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Effects of layering sequence on thermal response of multilayer fibrous materials: Unsteady-state cases

Mingwei Tian [a,b,d,*], Sukang Zhu [c], Ning Pan [c,d], Lijun Qu [a,b], Guangting Han [b], Fukui Pan [a]

[a] College of Textile and Clothing, Qingdao University, Qingdao 266071, PR China
[b] Laboratory of New Fiber Materials and Modern Textile, The Growing Base for State Key Laboratory, Qingdao University, Qingdao 266071, PR China
[c] Institute of Physics of Porous Soft Matters, Donghua University, Shanghai 200051, PR China
[d] Biological and Agricultural Engineering Department, University of California, Davis, CA 95616, USA

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ABSTRACT

Heat transfer between multilayer fibrous materials under unsteady-state conditions is regarded as an intricate and unpredictable process, and the system thermal response with different layer stacking sequences is investigated in this paper. All six possible sequences for three-layer fabrics are measured by an apparatus set up in our lab and simulated by the finite element method, taking account of the effects caused by the internal natural convection and boundary heat loss. It is found that the fabric contacting the hot heat source is the key layer in affecting the system thermal response during the dynamic unsteady-state conditions, and its volumetric heat capacity is the major factor in determining the results. In addition, the effect of the inner natural convection in the multilayer system resulted from the buoyancy is marginal, and negligible under common boundary conditions. In general this study demonstrates that the layer stacking sequences should be considered as an important factor in thermal response while designing a multilayer thermal protective suit.

1. Introduction

Clothing is generally made of fibrous materials and serves as the buffering zone between human body and the ambient to prevent the human body being injured from the mechanical actions, thermal (heat and flame) exposure, cold and cryogenic contact, and chemical and toxic etching, etc. So the abilities of heat and mass transfer of such fibrous materials are deemed as the critical factors, especially for thermal protective suits.

For single layer fabrics, researches have already been done extensively, such as on measurement of fabric effective thermo-physical properties [1–4], heat transfer [5,6] and thermal protective performance [7–11]. Recently, Pan et al. [12–14] proposed a new concept of "fibrous soft matter" to represent the fibrous materials by highlighting their multiphase nature, complex hierarchal structure and variable physical properties, including their thermal behaviors.

Then, for multilayer fabric cases, the combined heat transfer problems under radiation and conduction [15], structural optimization of the multilayer firefighter suit [7] and the thermal transport abilities [16–18] of given samples were also analyzed and investigated using both experimental and numerical methods. Nonetheless, most of such work studied the equivalent properties, such as the effective thermal conductivity [19], to reflect the overall thermal responses of the whole multilayer system under *steady-state* conditions. However, when a multilayer system is under *unsteady-state* conditions, its thermal response and effective properties changes with time and are often considerably different from those under the steady-state. In fact such unsteady-state heat transfer process is much variable and complex, describable only by sophisticated differential equations, than the steady ones defined with simple linear equations [20], therefore, the unsteady-state cases should be studied more carefully and thoroughly.

One related important issue in practical application of fibrous fabrics concerned the influence of the layer position or stacking sequence in a multiple layer system. Although, according to Ozisik [21], there was no net effect of the stacking sequence on the temperature response of a composite slab under steady-state conditions, no concluding results have demonstrated that such stacking sequence did not impact the thermal behaviors of a multilayer fabric system under unsteady-state conditions, where for instance multi-layered firefighter uniform was often experiencing. The purpose of this work was to conduct a study on the influence of such stacking sequence on the thermal response of a multilayer system composed of three different fabric layers. The thermal responses under all six possible stacking cases were measured by an experimental apparatus. Meanwhile, a theoretical model for such multilayer fibrous system, considering the inner natural con-

* Corresponding author at: Institute of Physics of Porous Soft Matters, Donghua University, Shanghai 200051, PR China.
E-mail address: tmw0303@gmail.com (M. Tian).

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vection and boundary heat loss, was also developed to numerically predict the same thermal properties for each case. Then the two results corresponding to each different sequence were compared, and the possible reasons where discrepancies stem from were discussed.

2. Experimental details

2.1. Materials

Three commercial fabrics, Fabrics 1, 2 and 3, with different constructions and fiber types were used. Based on the Fourier law, the sample total thickness seemed to be a significant parameter to affect the rate of heat flow through the sample, a single or multilayer. To make our measurements more comparable, we combined six pieces of Fabric 2 into one piece to form Sample B, and seven pieces of Fabric 3 into Sample C, so both of them had the similar thicknesses as Sample A (one piece of Fabric 1), around 2 mm for our experiments. The characteristics of the samples were all listed in Table 1, where the thickness of the samples were measured by the YG141 fabric thickness gauge under the same pressure 7.5 cN/cm^2 as in the other experiments; the thermophysical properties (thermal conductivity, thermal diffusivity and specific heat capacity) were simultaneously obtained by the transient approach proposed from Refs. [22,23] and then their bulk density could be easily calculated by using the fabric weight and volume. In addition, their porosities were measured by a porosity analyzer (ASAP 2020M, USA). The samples then cut into circular shape with radius r = 15 mm.

2.1.1. Construction of multilayer systems

We then used the samples as individual layers to designate the stacking sequence of the three layers. There were six possible arrangements for layers A, B and C [ABC/ACB/BCA/BAC/CAB/CBA]. For instance in the ABC system shown in Fig. 1, the 1st layer, Sample A, was contacting the hot plate; the 2nd layer, Sample B, was referred to as the filling hereafter, and the 3rd layer, Sample C, was contacting the cold plate. The other five combinatory sequences followed the same rule.

2.1.2. Influence of sample heterogeneity and anisotropy

It was a simple and common approach to assume porous materials as both homogeneous and isotropic while investigating their thermal properties. Under the assumption, the porous materials could be represented by their equivalent homogenous systems and their thermophysical properties could be depicted by the corresponding effective properties (i.e. effective thermal conductivity) as in Ref. [13], provided that the systems were at local thermal equilibrium (LTE). If at local thermal non-equilibrium (LTNE), the local temperatures of fiber and air phases had then to be defined based on the local constant porosity in the representative elementary volume (REV) [24,25]. We have conducted some research [2] to demonstrate that under the conditions associated with our research, the fibrous materials we dealt with were indeed under LTE state so that they could be treated as homogeneous materials.

The samples we used for this study also had some directionality and not strictly isotropic. Again during our investigation, the sample directionality was never brought into play, i.e., all samples were loaded onto the instrument the same way, maintained the same orientation through the entire test. We could thus ignore the anisotropy or the direction-property dependence in each sample for our present study.

2.2. The experimental method

In order to investigate the thermal response of the samples under unsteady-state conditions, a test apparatus was set up in our lab and its main features were illustrated in Fig. 1. The heat flowed downwards from the hot plate through the multilayer system consisted of three layers (1st, 2nd, 3rd layer) to an isothermal cold plate maintained at a lower temperature. These two isothermal plates were both made of copper, the hot plate was kept at an approximately constant value by the electrical heating system while the cold plate was maintained by the cold circulating water so that the temperature variation of these two plates were both maintained within ±0.1° during the whole measurements respectively. The guarded hot plate is equipped to surround the hot plate to minimize the heat loss to their boundaries. Perspex was applied to form another accessory, the thin edge-guard cylinder, used as a high-visibility enclosure to wrap the samples so as to prevent the air from leaking to the ambient. Additionally, the upper hot plate can be raised to the right position to contact with the sample without causing excessive deformation. Moreover, the pressure detection system was employed to monitor and adjust the pressure on the sample. Also there is a pressure sensor installed to record the pressure during the entire process. A heat flux sensor (HS-10, sensitivity 0.3 μV/(W/m^2)) was embedded at the center of the interface between the hot plate and the sample to measure the heat flux through it and transmit the data to the computer control system.

The multilayer samples of six sequences were pre-conditioned under the standard experimental conditions of temperature 20° and relative humidity 65% for 24 h before testing. In each test, the cold plate and the hot plate were conditioned and maintained at their corresponding temperatures, T_0 = 20° and T_H = 30° respectively. Then a multilayer sample was placed on the upper side of the cold plate, and the hot plate was then moved down with the edge-guard cylinder until touching the upper surface of the sample. Meanwhile, the pressure and heat flux sensors captured the signals to monitor the starting position. For all the tests, the pressure was adjusted to the same level at 7.5 cN/cm^2 and the heat fluxes were recorded at a sampling frequency 1 s. Each layer sequence was measured five times in turn and then their mean value and the coefficient of variation (CV) value were computed.

Table 1
The parameters of fabric samples.

	Sample A	Sample B * 6[1]	Sample C * 7[2]
Construction	Needle punched nonwoven	Thermal bonded nonwoven	Plain weave fabric
Fiber	PET (poly ethylene terephthalate)	PP (polypropylene)	Cotton
Thickness (mm)	2.044	2.040	1.930
Thermal conductivity (W/mK)	0.047	0.025	0.040
Thermal diffusivity (m^2/s)	1.500e−7	0.980e−7	0.925e−7
Bulk density (kg/m^3)	199	120	406
Specific heat capacity (J/m^{3}K)	1575	2129	1070
Porosity (%)	80	86	78

1:6 Pieces of fabric 2 are stacked and sewed into sample B
2:7 Pieces of fabric 3 are stacked and sewed into sample C