EFFECTIVE THERMAL CONDUCTIVITY OF COMPLICATED HIERARCHIC MULTILAYER FABRIC

by

Jie FAN [a,b,c]***, Na ZHU*** [b]***, Zhi LIU*** [b]***, Qian CHENG*** [b]***, and Yong LIU*** [a,b]*

[a] Key Laboratory of Advanced Textile Composites, Ministry of Education of China, Tianjin, China
[b] School of Textiles, Tianjin Polytechnic University, Tianjin, China
[c] National Engineering Laboratory for Modern Silk, College of Textile and Clothing Engineering, Soochow University, Suzhou, China

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Warm retention property of fabric is one of the most important factors for clothing comfortability. The worm retention efficiency of a multilayer fabric with hierarchic inner structure was investigated based on its geometric feature. The thermal resistance of the multilayer fabric increases as the layer of the fabric increases.

Key words: *thermal conductivity, complicated fabric, hierarchic*

Introduction

Thermal transfer property of textile fabrics has a close relationship with the warm retention performance of garment and has received much attention in the design of functional clothing [1]. Woven fabric is a porous media constructed by fiber and gas. The unique inner structure of the fabric has a great effect on its heat transfer performance [2, 3].

Much research work has been carried out to improve the warm retention property of fabric. Bedek *et al.* [4] concluded that the relative porosity of a fabric would affect the first thermal contact feeling. Majumdar *et al.* [5] reported that fabric texture has an influence on the thermal resistance of fabric. Fibers with better water management property could help reducing fabric thermal conductivity. Ozdil *et al.* [6] found that the thermal resistance values decreases while the yarn twist and yarn count increase. Previous research suggests that yarn as well as fiber assembly in the fabric are significant for warm retention property of fabric. Superior warm retention property can be obtained by optimizing the fabric structure.

In this presentation, we promote a multilayer fabric composed of single layer fabrics with different weave structure. The thermal conduction property of the fabric was investigated based on the multi-scale anisotropic structure of the fabric using thermal-electrical analogy.

Depiction of the complicated hierarchic multilayer fabric

The hierarchic inner structure of multilayer fabric is constructed by an assembly of a series of single layer fabrics. Each single layer fabric has the same porosity but different in texture. The hierarchic multilayer fabric is fabricated according to the principle that the single pore area in the upper layer is one half of that in the next lower layer. The single layer fabrics are combined in sequence by binding weave to form the hierarchic multilayer fabric, shown in fig. 1.

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* Corresponding author; e-mail: fanjie@tjpu.edu.cn, liuyong@tjpu.edu.cn

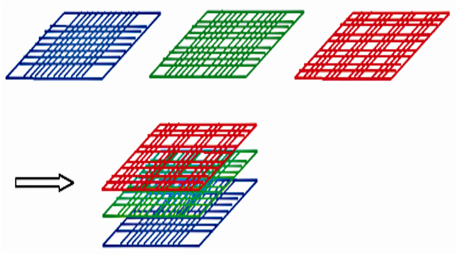

Figure 1. Structure diagram of hierarchic multilayer fabric

Model for thermal conductivity of the complicated hierarchic multilayer fabric

A well-organized assembly of single layer fabrics endows the hierarchic multilayer fabric with an anisotropic configuration in the fabric's thickness direction. Heat conduction through the fabric is mainly due to the heat conduction through the interlacing points between the warp yarns and weft yarns, and the convective heat transfer by the hierarchic continuous air path.

Heat conduction through the solid yarn touch points

According to Fourier's law, heat conduction through the solid yarn touch points can be expressed as:

$$R = \frac{L}{A\lambda} \tag{1}$$

where R is the thermal resistance, L – the channel length of thermal conduction, A – the contact area of the interlacing point, and λ – the thermal conductivity.

For a control unit area of a n-layer hierarchic multilayer fabric, the thermal resistance of a repeated fabric unit caused by the solid yarn is:

$$R_{\text{inter}} = \frac{k3nd}{A_{\text{inter}}(\delta)\lambda_s} \tag{2}$$

where k is the correction factor of the conductive distance, and $A_{\text{inter}}(\delta)$ – the contact area between the warp yarn and weft yarn, which depends on the stiffness of yarn δ.

Figure 2. Schematic diagram of the hierarchic continuous tortuous channel path in the multilayer fabric

Convective heat transfer through continuous air channel

Single layer fabrics are pile up in sequence in the hierarchic multilayer fabric. The fabrics with smaller pores locate at the upper layers, while the fabrics with larger pores lie in the lower layers. The size decreasing pores connect to form a hierarchic continuous tortuous channel path for heat conduction, shown in fig. 2.

Here we introduce the Kozeny-Carman equation to investigate the convective heat transfer process in the hierarchic multilayer fabric by analogy method. Kozeny-Carman equation depicts the pressure drop of air flux through a packed fiber plug:

$$Q = \frac{1}{K}\frac{A\Delta P}{S_S^2 \mu L}\frac{\varepsilon^3}{(1-\varepsilon)^2} \tag{3}$$

where ΔP is the pressure drop, L – the total height of the fiber plug, A – the cross-section area of the fiber plug, μ – the viscosity of air, ε – the porosity of the fiber plug, S_S^2 – the specific surface area of the fiber plug, K – the structural parameter related with the shape of pore and the variation of the path length.

According to eq. (3), the air-resistor of the n-layer hierarchic multilayer fabric's control unit is:

$$R = \frac{\Delta P}{Q} = K\frac{S_S^2 \mu L}{A}\frac{(1-\varepsilon)^2}{\varepsilon^3} \tag{4}$$

Here, the control unit of the hierarchic multilayer fabric is regarded as a fiber plug with a constant mass W, and eq. (4) can be rewritten as:

$$R = \frac{\Delta P}{Q} = K\frac{4W^2 \mu L}{Ar^2\gamma^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} \tag{10}$$

where r is the pore radius, and γ – the density of fiber.

Since convective heat transfer is due to the thermal motion of air in the continuous air channel. The efficiency of convective heat transfer has a relationship with the size of convective heat transfer channel path. The thermal resistance of convective heat transfer will increase with decrease of the channel path's diameter. Thus, the convective thermal resistance of the fabric can be treated as the air-resistor of the fiber plug. The convective thermal resistance of the hierarchic multilayer fabric can be regarded as the cascade of the orderly packed single layer fabric.

The convective thermal resistance of the i^{th} fabric layer is depicted as:

$$R_{gi} = \frac{\Delta T}{Q} = K\frac{4W^2 \mu L}{Ar_i^2\gamma^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} \tag{10}$$

where ΔT is the temperature difference, L – the height of the i^{th} fabric layer, A – the area of the fabric repeated unit, r_i – the radius of air path in the i^{th} fabric layer, μ – the viscosity of air, ε – the porosity of the fabric layer, W – the mass of the i^{th} fabric layer, and K – the structural parameter related with the shape of pore and the variation of the path length.

As each fabric layer has the same porosity, area, mass, and similar height, but different structural parameter. The convective thermal resistance of each fabric layer depends on the radius of the air path.

$$R_{gi} \infty \frac{1}{r_i^2} \tag{11}$$

Since the porosity of each fabric layer is a constant, the single pore area of a certain fabric layer has a relationship with the number of pore in the layer:

$$\frac{r_i^2}{r_{i+1}^2} = \frac{N_{i+1}}{N_i} = 4 \tag{12}$$

where N_i is the number of pore in the i^{th} fabric layer.

Thus, we obtained:

$$r_i^2 = \frac{r_1^2}{4^{i-1}} \tag{13}$$

The convective thermal resistance of the hierarchic multilayer fabric’ control unit by air phase can be analogized to the series resistance:

$$R_g = \sum_{i=1}^{n} R_{gi} = \sum_{i=1}^{n} K \frac{4W^2 \mu L}{A r_i^2 \gamma^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} = K \frac{4W^2 \mu L}{A \gamma^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} \sum_{i=1}^{n} \frac{1}{r_i^2} \tag{14}$$

For the fabric which has n layers, we have:

$$L = 3d \tag{15}$$

$$A = (2d\, 2^{n-1})^2 \tag{16}$$

$$W = AL(1-\varepsilon)\gamma \tag{17}$$

$$r_i = \frac{2^{n-2} d}{2^{i-1}} = 2^{n-1-i} d \tag{18}$$

Submit eqs. (15)–(18) into eq. (14), we obtained:

$$R_g = \sum_{i=1}^{n} R_{gi} = \frac{108 \mu K (1-\varepsilon)^4 d^3 2^{2n}}{\varepsilon^3} \sum_{i=1}^{n} \frac{1}{2^{2(n-1-i)}} \tag{19}$$

Heat resistance of the complicated hierarchic multilayer fabric

The thermal resistance of the fabric’s control unit equals to the touch points between the warp yarns and weft yarns and convective thermal resistance by air motion in the branching air phase, and can be expressed as:

$$\frac{1}{R_f} = \frac{1}{R_{\text{inter}}} + \frac{1}{R_g} = \frac{A_{\text{inter}}(\delta)\lambda_s}{k\,3nd} + \frac{\varepsilon^3}{108 \mu K (1-\varepsilon)^4 d^3 2^{2n} \displaystyle\sum_{i=1}^{n} \frac{1}{2^{2(n-1-i)}}} \tag{20}$$

Effective thermal conductivity of the complicated hierarchic multilayer fabric

Effective thermal conductivity of the complicated hierarchic multilayer fabric is obtained by comparing its thermal conductivity with that of a complicated basket weave multilayer fabric. The two multilayer fabrics have the same number of layer, but each layer of the complicated basket weave multilayer fabric has same dominant structure with the middle layer of complicated hierarchic multilayer fabric.

As each fabric layer of the complicated basket weave multilayer fabric is composed of the same number of warp yarns and weft yarns, the complicated basket weave multilayer fabric’ s control unit has the same thermal resistance expression as that of the complicated hierarchic multilayer fabric:

$$R_{\text{interc}} = \frac{k\,3nd}{A_{\text{inter}}(\delta)\,\lambda_s} \tag{21}$$

The convective thermal resistance of the complicated basket weave multilayer fabric's control unit by air phase can expressed as:

$$R_{gc} = nR_{gic} = K\frac{4nW^2\mu L}{Ar_{ic}^2\gamma^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} = K\frac{4nW^2\mu L}{A\gamma^2}\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{1}{r_{ic}^2} \tag{22}$$

where

$$r_{ic} = r_{(n+1)/2} \tag{23}$$

Submit eq. (18) into eq. (23), we got:

$$r_{ic} = 2^{(n-3)/2}d \tag{24}$$

Submit eqs. (15)–(17) and eq. (24) into eq. (22), we got:

$$R_{gc} = nR_{gic} = \frac{864nK\mu d^3 2^n (1-\varepsilon)^4}{\varepsilon^3} \tag{25}$$

Thus, the total thermal resistance of the complicated basket weave multilayer fabric's control unit is:

$$\frac{1}{R_{fc}} = \frac{1}{R_{\text{interc}}} + \frac{1}{R_{gc}} = \frac{A_{\text{inter}}(\delta)\lambda_s}{k3nd} + \frac{\varepsilon^3}{864nK\mu(1-\varepsilon)^4 d^3 2^n} \tag{26}$$

Divide eq. (26) by eq. (20), the effective thermal resistance of the complicated hierarchic multilayer fabric is:

$$R^* = \frac{R_f}{R_{fc}} = \frac{\dfrac{A_{\text{inter}}(\delta)\lambda_s}{k3nd} + \dfrac{\varepsilon^3}{864nK\mu(1-\varepsilon)^4 d^3 2^n}}{\dfrac{A_{\text{inter}}(\delta)\lambda_s}{k3nd} + \dfrac{\varepsilon^3}{108\mu K(1-\varepsilon)^4 d^3 2^{2n}\displaystyle\sum_{i=1}^{n}\frac{1}{2^{2(n-1-i)}}}} \tag{27}$$

Result and discussion

Suppose the yarn is a rigid body with round cross-section, the contact area between warp yarn and weft yarn is very small. Thus, the heat conduction item through the fabric interlacing points can be omitted. Heat convection in the fabric performs as the dominant thermal conduction mode, eq. (27) became:

$$R^* = \frac{R_f}{R_{fc}} = \frac{2^n\displaystyle\sum_{i=1}^{n}\frac{1}{2^{2(n-1-i)}}}{8n} \tag{28}$$

The effective thermal resistance curve shown in fig. 3 suggests that the effective thermal resistance of the complicated hierarchic multilayer fabric exhibits significant increase with increase of the fabric layer, indicating that the complicated hi-

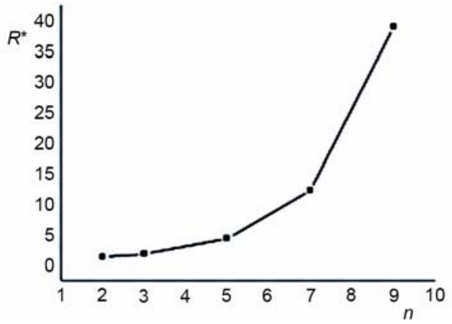

Figure 3. Effective thermal resistance of the complicated hierarchic multilayer fabric

erarchic multilayer fabric performs a much better warm retention property comparing with the complicated basket weave multilayer fabric. This is due to the unique hierarchic thermal convective path constructed by orderly assemble of single layer fabrics with different pore size. It is the hierarchic structure along the fabric thickness direction which causes the anisotropic thermal conduction property inside the fabric. The complicated hierarchic multilayer fabric provides a novel designing approach to manufacture functional thermal protective material.

Conclusions

In this study, effective thermal resistance of a complicated hierarchic multilayer fabric is calculated. Theoretical analysis suggests that the effective thermal resistance of the complicated hierarchic multilayer fabric shows geometric growth with increase of fabric layer, indicating that the complicated hierarchic multilayer fabric has a better warm retention performance due to its hierarchic inner construction.

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References

[1] Ran, X. J., *et al.*, Investigation on Heat and Mass Transfer in 3D Woven Fibrous Material, *International Journal of Heat and Mass Transfer*, *54* (2011), 15-16, pp. 3575-3586

[2] Du, N., *et al.*, Optimum Porosity of Fibrous Porous Materials for Thermal Insulation, *Fibers and Polymers*, *9* (2008), 1, pp. 27-33

[3] Fan, J., He, J. H., Biomimic Design of Multi-Scale Fabric with Efficient Heat Transfer Property, *Thermal Science*, *16* (2012), 5, pp. 1349-1352

[4] Bedek, G., *et al.*, Evaluation of Thermal and Moisture Management Properties on Knitted Fabrics and Comparison with a Physiological Model in Warm Conditions, *Applied Ergonomics*, *42* (2011), 6, pp. 792-800

[5] Majumdar, A., *et al.*, Thermal Properties of Knitted Fabrics Made from Cotton and Regenerated Bamboo Cellulosic Fibres, *International Journal of Thermal Sciences*, *49* (2010), 10, pp. 2042-2048

[6] Ozdil, N., *et al.*, Effect of Yarn Properties on Thermal Comfort of Knitted Fabrics, *International Journal of Thermal Sciences*, *46* (2007), 12, pp. 1318–1322

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