A PREDICTIVE MODEL OF THERMAL CONDUCTIVITY OF PLAIN WOVEN FABRICS

by

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Original scientific paper
https://doi.org/10.2298/TSCI160805045W

This paper proposes an effective method to predict the thermal conductivity of plain woven blended fabric to optimize woven fabric structure, and to evaluate thermal comfort. The unit cell model of fabric is established for numerical simulation of heat transfer through thickness. The thermal conductivity of blended yarns is calculated by a series model. The temperature and heat flux distributions are verified experimentally.

Key words: *finite element method, geometric structure, thermal conductivity*

Introduction

The thermal property of textile materials has been widely recognized as one of the most important factors for wearing comfort [1, 2]. In recent years thermal theories have been profoundly studied, and several models for formulating the effective thermal conductivity of composite materials have been proposed, for example, the series model, the parallel model, the Pilling model, and the Clayton model, *etc.* [3, 4]. The practical applications of these models are limited since the characteristics of internal fabric structure of pore distribution have been ignored as fabric being a porous material with spatial distribution features. Therefore, some researchers investigated the relationship between fabric structure and thermal properties [5-7]. Several mathematical models based on the structure of fabric have been constructed. Bhattacharjee and Kothari [8] divided fabric to three components of porous yarns, interlacements between warp and weft yarns, and air pores, and established a mathematical model based on the Fourier law to predict thermal resistance of fabrics. Fan *et al.* [9] calculated the thermal resistance of a multilayer fabric based on its geometric feature by mathematical model.

Finite element analysis provides a simple and effective solution for these problems in complex calculation. Cimilli *et al.* [10] investigated the applicability of a finite element method (FEM) to heat transfer behavior of knitted fabrics developed by CATIA (computer aided 3-D interactive application) and imported it to ANSYS Workbench for further analysis, the results showed the potential of FEM for complex analysis on thermal properties of textiles. However, authors neglected the effect of the inter-yarn air on heat conduction in fabric. With the help of 3-D modeling software, some researchers further expanded the application of FEM to investigation of different textile materials such as new fibers, complex woven or knitted fabrics, coated fabrics, textile composites, *etc.* [11-13]. Fan *et al.* [14] promoted a model of three-layer branch-

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ing-structured bio-mimic woven fabric and predicted its thermal resistance based on FEM. Siddiqui and Sun [15] predicted the thermal conductivity and the thermal resistance of the plain woven Nomex® III fabric and the finite element model was validated by experiments. These studies are conducted on material properties and mechanisms of heat transfer, making further assumptions and setting boundary conditions combined with specific circumstances to solve mathematical models. Currently, fabrics composed of a single fiber are mainly investigated to modeling in these studies while studies on blended fabrics are not very common.

This paper aims to investigate the thermal properties of plain woven blended fabrics. The fabric geometric model was established based on its actual geometrical parameters, then it was imported to ABAQUS to simulate the process of heat transfer through the thickness to predict the temperature, heat flux distribution, and thermal conductivity in the steady-state.

Geometrical model

A geometrical model of plain woven fabric was established based on the actual geometrical structure parameters from microscopic images such as width and height of warp/weft, yarn spacing, yarn cross-section shape and thickness of fabric in fig. 1. The path of yarn could be determined by weave pattern and geometric parameters in TexGen [16, 17], and the cross-section shape of yarns was modified as ellipse proposed by Pierce* based on experimental images. This model can restore the real spatial distribution of yarns in fabric.

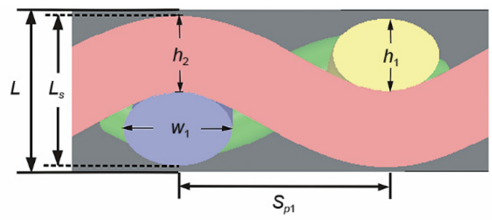


Figure 1. Geometric model of unit cell

Assumption

Since the vertical thickness of fabric is far less than transverse length and width, it is assumed that heat transfer through the direction of thickness and other directions of the unit cell are adiabatic boundaries, taking the conduction of ambient air and the surface convection between fabric and environment into consideration while neglecting the effect of radiation due to the small difference of temperature in fabric.

Thermal conductivity of yarn

Yarn is composed of solid fiber and air which have different thermal conductivities. The thermal conductivity of blended yarns were formulated based on the assumption that heat would transmit through two different fibers and air in series, thus the yarn effective thermal conductivity, K_y, can be expressed in the series model as the following formulas:

$$\frac{1}{K_y} = \frac{V_{m1}}{V_y}\frac{1}{K_{m1}} + \frac{V_{m2}}{V_y}\frac{1}{K_{m2}} + \varepsilon_y \frac{1}{K_a} \tag{1}$$

$$V_{m1} + V_{m2} = (1-\varepsilon_y)V_y \tag{2}$$

where K_{m1}, K_{m2} are the thermal conductivity of two fibers, V_{m1},V_{m2}, and V_y – the volume of two fibers and yarns, respectively, and ε_y is the yarn porosity which can be measured by experiments or calculated by:

* Pierce, F., The Geometry of Cloth Structure, *J. Text. Inst., 28* (1937), pp. 45-96

$$\varepsilon_{\mathrm{y}} = \left(1 - \frac{\dfrac{M_{\mathrm{y}}}{\rho_{\mathrm{fiber}}}}{V_{\mathrm{y}}}\right)100 \tag{3}$$

$$V_{\mathrm{y}} = \pi a b l_{\mathrm{y}} \tag{4}$$

where M_{y} and l_{y} are the mass and length of yarn, respectively, ρ_{fiber} is the mass density of fiber, and a and b are the axial lengths of ellipse cross-section, respectively. The blended ration of two fibers was defined as $P/(1-P)$, according to eq. (2) we can obtain:

$$\frac{V_{m1}}{V_{\mathrm{y}}} = \frac{P\rho_2}{\rho_1 + (\rho_2 - \rho_1)P}(1-\varepsilon_{\mathrm{y}}) \tag{5}$$

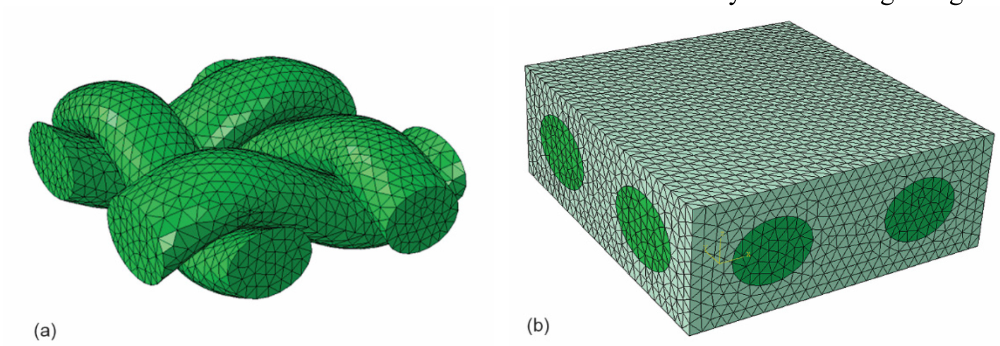
$$\frac{V_{m2}}{V_{\mathrm{y}}} = \frac{(1-P)\rho_1}{\rho_1 + (\rho_2 - \rho_1)P}(1-\varepsilon_{\mathrm{y}}) \tag{6}$$

where ρ_1 and ρ_2 are the mass density of two fibers, respectively, finally K_{y} can be calculated:

$$K_{\mathrm{y}} = \left[\frac{P\rho_2}{\rho_1 + (\rho_2 - \rho_1)P}\frac{1-\varepsilon_{\mathrm{y}}}{K_{m1}} + \frac{(1-P)\rho_1}{\rho_1 + (\rho_2 - \rho_1)P}\frac{1-\varepsilon_{\mathrm{y}}}{K_{m2}} + \frac{\varepsilon_{\mathrm{y}}}{K_a}\right]^{-1} \tag{7}$$

Meshing

After the unit cell model of yarn phase was completed, it was imported to ABAQUS/CAE, and the air model was created by Boolean operation, finally they were assembled into an overall unite cell. The overall model was meshed by free meshing as fig. 2.



Figue 2. Meshes of unit cell; (a) meshed model of yarn phase and(b) meshed model for unite cell

Boundary conditions

Set the initial temperature as 24.5 °C where the simulation environment equals to a comfortable air-conditioned indoor environment in summer. Boundary conditions determine the heat transfer process. The inner surface of fabric contacts human skin directly, and its temperature is almost equal to skin temperature, therefore set the inner surface of the unit cell as 32 °C. Except the thermal conduction of yarn and still air, free convection heat exchange occurred on the outer surface of fabric, the surface convection coefficient of heat transfer was set as 10 W/mK. Ultimately, the temperature and heat flux of the fabric unit cell can be calculated from the previous boundary conditions.

Samples

The experimental samples were selected arbitrarily for validation, for example a flax-cotton blended (70/30) fabric was chosen for testing. The area density of the fabric was 130 g/m^2. The warp/weft linear density was 18/35 Tex, and warp/weft set was 250/210 roots 10 cm^{-1}. Fabric geometrical parameters are listed in tab. 1. The thermal conductivity of yarns was defined by eq. (7), where ρ_1 and ρ_2 are 1540 and 1500 kg/m^{-3}, K_{m1}, K_{m2}, and K_a are 0.063, 0.053, and 0.026 W/mK.

Table 1. Geometrical structure parameters of plain fabric

Warp width, w_1 [mm]	Weft width, w_2 [mm]	Warp height, h_1 [mm]	Weft height h_2 [mm]	Warp spacing, S_{p1} [mm]	Weft spacing, S_{p2} [mm]	L [mm]	L_s [mm]
0.205	0.255	0.140	0.150	0.400	0.422	0.295	0.285

Model validation

The simulated results of temperature and heat flux distribution in plain woven flax-cotton blended fabrics are shown in figs. 3 and 4. It can be found that the temperature was decreasing in the direction along the thickness, the temperature of inner surface was defined constant as 32 °C, the outer surface temperature was lower because heat exchange occurred on it with the environment. Heat flux through the yarn phase was larger than air and the largest area was the interlacements of yarn, indicating that the yarn phase serves as the main thermal conductor in fabric.

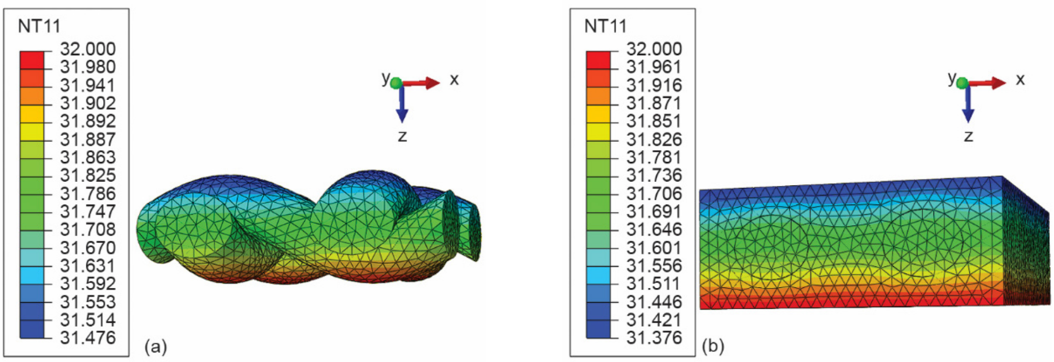


Figure 3. Temperature distribution [°C]: (a) temperature distribution of yarn phase and (b) temperature distribution of overall unit cell

The temperature and heat flux of fabric unit cell was simulated by the previous model. The thermal conductivity of fabric in heat transfer steady-state can be calculated by Fourier law:

$$q = -K_f \frac{\Delta T}{L} = \frac{Q}{A} \tag{8}$$

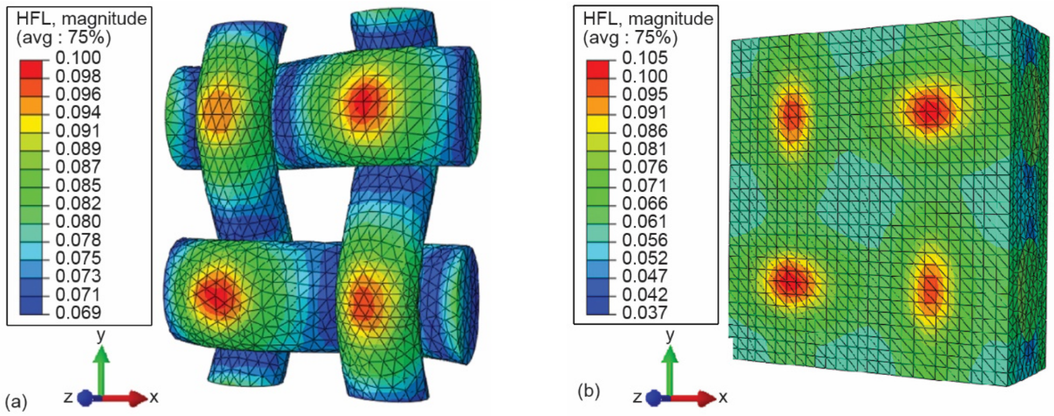


Figure 4. Heat flux (HFL) distribution 10^3 [W/m^2]; (a) heat flux of yarns phase and (b) heat flux of overall unit cell

where q is the heat flux density, ΔT – the temperature difference between inner and outer surface, L – the thickness of fabric, Q – the total heat flux through the fabric unit cell, A – the area vertical to the direction of heat flux, and K_f – the thermal conductivity of the fabric and calculated as 0.0355 W/m^2 from simulation results. The experimental one was measured as 0.0365 W/m^2 according to the standard ASTM D1518-2011. These two values of simulations and experiments are very close to each other suggesting that this finite element model can successfully predict the thermal conductivity of fabrics.

Conclusion

In this paper a finite element model of plain woven blended fabric was successfully established to simulate the heat transfer process through thickness. The thermal conductivity of blended yarns were calculated by the series model and submitted to the fabric model. The thermal conductivity of fabric was calculated based on the simulated results of temperature and heat flux. The comparison between the experimental results and the simulated one indicated the effectiveness of this model. Furthermore, this heat transfer model can be expanded to other textile materials to predict their thermal properties.

Acknowledgment

This work was supported by Industry-University-Research Union Innovation Found, Prospective Joint Project (*Research and development on the key technologies in manufacturing cool and excellent moisture permeability fabrics*, BY2014081-04).

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Paper submitted: August 5, 2016
Paper revised: August 23, 2016
Paper accepted: August 25, 2016