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Heat Transferring Mechanism through Interlacing Structure Using Finite Element Analysis ⋆

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Abstract

Heat transmission in the fabric is strongly related to the thermal comfort, which plays an important role when designing fabrics. In this work, a heterogeneous model constructed according to the internal structure of five woven fabrics was developed to study the heat transmission through fabrics. In this model, heat can transfer along the longitudinal and transverse direction of warp and weft yarn at different rate base on the inputted boundary conditions and constants, such as mass density, specific heat and thermal conductivity. In addition, heat transmission occurring in the contacting interface between the warp and weft yarn was also considered. The validity of this model was then confirmed by the high consistency between the thermal resistance obtained from experiment and simulation. The simulation results suggested that heat mainly transfers inside the same yarn, with only a very small portion of heat exchange between the warp and weft yarn via their contacting region. Besides, the calculated fabric thermal resistance is obviously affected by the size of contacting area between fabric and heat source.

Keywords: 3D heterogeneous model; Heat transfer; Textile; Heat flow

1 Introduction

It is widely recognized that the heat transfer through fabrics is important for understanding the thermal comfort of clothing [1, 2]. Lots of efforts have been devoted to investigate the heat transfer in fabrics to find the relationships between thermal properties and fiber properties, yarn properties and fabric structures [3-7]. However, the interwoven structure and fibrous material make it difficult to understand the heat transfer behavior in fabrics by experimental approach.

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Mathematical model, which widely used in the natural sciences, engineering disciplines and social sciences, is a method of simulating real-life situations with mathematical equations, and then predicting their future behavior. In recent years, mathematical modeling has become a popular method for investigating the heat transmission in textiles, especially for the case of coupled heat and moisture transmission [8-10]. The first mathematical model, in which the heat and moisture transfer in textiles were simultaneously considered, was proposed in 1939 by Henry [11]. In his model, a bale of cotton fiber was regarded as a continuous network with a large portion of pores, and during the process of heat transmission, some of water vapor may get through the pores and become immobilized along with the heat. While, this model was limitedly applied due to the fact that some assumptions used in the model were too far from the actual moisture sorption process. For the purpose of improving this model, David and Nordon derived a numerical solution, providing a space-time relationship for moisture concentration and temperature [12]. They conducted experiment on wool and cotton fabrics, and measured the temperature and regain during the process of heat flow through the fabric. Good agreement was found between the predictions from the model and the experimental observations, indicating the reliability of their model. Li and Holcombe developed an extended mathematical model, in which the water vapor uptake rate of the fiber was assumed to be associated with two stages of sorption and the coupled heat and moisture transport in a wool fabric was presented by the water vapor sorption kinetics [13]. The result suggested that their two-stage model exhibited the best agreement with the experimental observations from the sorption cell tests than the previous models. After that, an improved mathematical simulation model with higher resolution and more detailed physical meanings was proposed by Li and Luo [14, 15]. They verified their model by comparing the simulation and experimental results.

The Finite Element Method (FEM) is popular for solving problems of engineering and mathematical physics. The advantage of using FEM is that it can divide very complex problem into many simple parts and provide compact, visible and result-oriented analyse. Researchers in textile field have widely employed FEM for analyzing the mechanical properties of fabrics, such as bending, shear and compression [16, 17]. While, it has been rarely used for the heat transmission analyse in fabrics due to its complicated geometrical structure and heterogeneous composition. Cimilli S. has made an attempt to investigate the heat transferring performance by a FEM model of plain knitted fabric, in which the internal structure of fabric was considered [18]. This FEM model demonstrated excellent applicability to simulate heat transfer behavior in fabric and to achieve effective thermal conductivity of fabrics, with good agreement between simulated and experimental results. However, in this FEM model, the cross section of yarn was constructed in round shape, which was much different from that in a real fabric, thus resulting in a limited application of complex textiles. The micro-CT (computed tomography) is extensively used to generate the fabric structure model [19-23]. While the limited resolution of the CT image data was insufficient for accurate simulation of heat transfer in FEM model.

In our previous work, we have developed heterogeneous models according to the observed structure by a 3D microscope for analyzing the heat transmission in the cross section and surface of textiles [24-26]. In this work, we improved our model and the heat transmitting along the longitudinal and transverse directions of yarn was considered simultaneously. In addition, the heat transfer at the contact area between warp yarn and weft yarn was also included. Five plain weave fabrics were chosen as samples and their detailed structure was used for model construction. Then the heat transfer was simulated in the model and the heat flow in warp yarn and weft yarn was compared. In addition, the relationship between contact area with heat source and heat flow