Journal of Fiber Bioengineering and Informatics 6:2 (2013) 149–160
doi:10.3993/jfbi06201304

A 3D Finite Element Thermal Model for Clothed Human Body

Fengzhi Li [a,*], Yi Li [b], Yang Wang [a]

[a] *College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Yudao Street Nanjing, Jiangsu 210016, China*

[b] *Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hong Kong, China*

Abstract

A heat and moisture transfer model for the clothed human body is developed based on the 3-D scanning data of the human body. The whole passive clothed human body system is subdivided into four sub-systems which are the tissue system, the circulatory system, the respiratory system and the clothing system. The physical process of the heat and moisture transfer in the each sub-system is described by energy and mass balance equations. The Finite Element Method (FEM) is used to solve the governing equations for each sub-system. For a multi-layer clothing sub-system, a simple solution scheme is given by defining the air element. Also, the model is validated by comparing the simulation with experimental results from the literature. Finally, the 3-D simulation results are shown. The conclusion shows that the model has good prediction ability and it can be applied in the clothing design.

Keywords: Heat and Moisture Transfer; Human Body; Clothing; Model; Finite Element Method

1 Introduction

Modeling of the human body thermal response under various clothing and environmental conditions has drawn the attention of many researchers, because the model can be utilized in many fields such as the car industry, textile industry, aerospace, military and so on. Therefore, many human thermal response models have been developed based on the energy balance equations. According to the treating method for the passive system of the human body, the models can be classified into the lumped parameter thermal model, multi-node finite difference model and the multi-element model. The lumped parameter model such as two-node or multi-node model [1-3] can provide prediction result with certain accuracy, but the model assumes that each node has uniform temperature and the influence of spatial tissue temperature gradients in circumferential and height directions on heat transfer is ignored. The multi-node finite difference model uses the partial differential equations to describe heat transfer in human body issue. Then, the differential equations are discretized by the finite difference method, and the linear algebraic equation at

*Corresponding author.
Email address: helifz@nuaa.edu.cn (Fengzhi Li).

June 2013

each node can be obtained, such as Fiala multi-node thermoregulatory model [4, 5]. However, the finite difference method is difficult to utilize for discretizing the differential equations in the realistic human geometrical domain because of the limitation of the regular meth. In the multi-element thermal model, the human body is divided into several segments or elements, but no further nodes or layers are adopted in the elements, such as Smith's [6] and Fu's model [7]. In each element, the temperature gradient can be taken into account by the combination of shape function gradient and node temperatures. Therefore, the multi-element model usually gives more accurate result than the lumped parameter one, especially in the situation when a large temperature gradient exists in human body. However, the existed multi-element model assumes the human body can be simplified to different cylinder segments, which deviates from the realistic human body geometry. Study [8] shows that the geometry and anatomical structure of human body has a very important influence on heat exchange between the human body and environment, which also can be verified by the infrared thermography [9]. So a more realistic geometry of the human body for enhancing prediction accuracy of human body is necessary. Otherwise, predominant attention of these models mentioned above was paid to the physiological aspects of the human body, and the influence of spatial geometry on heat transfer and the dynamic coupled heat and moisture transfer from the clothing system has not received sufficient attention. For example, along the clothing thickness direction, only the thermal resistance is considered in Gagge's two-node model, while both thermal and moisture resistance were considered in Fu's one. The influence of spatial clothing temperature and moisture concentration gradients in the circumferential and height directions on heat and moisture transfer is ignored. The process of the moisture adsorption is assumed to be taken place at an instant. This assumption neglected the dynamic moisture adsorption process of the fiber. To consider the coupled heat and moisture transfer in the clothing, Li and his collaborators [10-13] developed a series of models, in which the water vapor diffusion, moisture absorption/desorption, liquid water penetration due to capillary pressure, evaporation/condensation, phase change heat generation, radiation and pressure gradient have been taken into account. These models [10-13] are 1-D, and some models have been used to simulate thermal responses of clothed human body model [14]. In recent years, Zhu *et al.* [15] developed a 3-D clothing heat and moisture model, in which the liquid water transfer has been emphasized. Hang *et al.* [16] use the finite volume method to solve the equations of heat and moisture transfer through 3-D textile materials. However, how the 3D dynamic coupled heat and moisture transfer in clothing can influence the human thermal responses is not reported in the literature.

The aim of this work is to extend Smith-Fu's bio-heat model for the human body by considering more realistic geometry and develop heat and moisture transfer model for the 3D single or multi-layer clothing by the Finite Element Method (FEM). Then, use the models to study the heat and moisture transfer in 3D clothed human body system.

2 Mathematical Models

The passive system of the whole clothed human body can be classified into four sub-systems which are the human body tissue sub-system, the circulatory sub-system, and the respiratory sub-system and clothing sub-system. In order to establish a heat and moisture transfer model for each sub-system, we must firstly determine the geometrical space, where the transfer phenomena will take place, and then pose the physical equations and boundary conditions. The schematics