Development of Computational Algorithms for Clothing Thermal Functional Simulation

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Abstract: This paper focuses on the development of a multi-structural computational scheme for textile thermal engineering design, which plays an important role in translating complex mathematical models into computational algorithms and to implement computational simulation of clothing wearing system consisting of human body, clothing and external environment. In this paper, the integrated models for simulating the clothing wearing system is introduced and the descretization process of the partial differential equations involved in the mathematical models is reported. Based on the descretized equation assemblies, the multi-dimensional algorithms for computational simulation are developed for clothing thermal engineering design. Furthermore, the influence of the physical properties of clothing on the simulation results is analyzed to guide the user to design the thermal performance of clothing.

Keywords: Computational algorithms, simulation models, clothing thermal function.

1. Introduction

Clothing thermal engineering design is a model-based and simulation-based technique to develop the thermal performance of clothing meeting with the thermal biological requirements of the human body for various wearing situations. It is the application of a systematic and quantitative way of designing and engineering of clothing with the inter-disciplinary combination of physical, physiological, mathematical, computational software science, and engineering principles [1]. The key part of this technique is the simulation capacity to computationally simulate the thermal behaviors involved in the clothing wearing system consisting of wearer, clothing and wearing scenario. With the simulation capacity, the CAD system can be developed and offered to the users to design, simulate, view and evaluate the thermal performance of clothing during the wearing period, and thus to obtain feedback to iteratively improve their designs before making any real samples. This innovative technique has many advantages, which can not be obtained from the conventional design approach. Clothing thermal engineering design is based on the scientific models and computational simulation, which offers much more reliance than the experience-based conventional approach. Meanwhile, clothing thermal engineering design can greatly speed up the design cycle by virtual simulation and preview of the thermal performance of designed clothing.

This paper focuses on the development of a multi-structural computational scheme for clothing thermal engineering design. This scheme is applied to translate the mathematical models describing the thermal behaviors in the clothing wearing system into computational algorithms and to implement the computational simulation in the clothing thermal engineering design. Firstly, the integrated mathematical models describing the clothing wearing system are introduced, and then the partial differential equations in the mathematical models are descrtized. Based on the solution of the models, a multi-structural scheme is developed for clothing thermal engineering design. Furthermore, the influence of the physical properties of clothing on the simulation results is analyzed to guide the user to design the thermal performance of clothing.

2. Integrated Mathematical Models

The thermal behaviors, which happen in the clothing wearing system, involves various heat and moisture transfer process in textile materials and biological thermoregulations in human body. Specifically, they may be regarded as follows [2].

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1) Heat and moisture transfer behaviors in fibers, fabrics and garments including their interactions and the influence of phase change materials and various functional treatments;

2) Thermoregulatory behaviors of human body responding to various external environments;

3) Interactions between the boundaries of clothing, human body and environment.

Before the development of the simulation capacity for clothing thermal engineering design, the mathematical models is necessary to be developed and integrated to numerically express these thermal behaviors. There have been many mathematical models reported in the literatures for simulating the heat and moisture transfer processes in textile materials and the thermal biological regulation behaviors of the body [3-10]. By judging the potential/suitability of these models to be directly integrated to the engineering design process for general application purposes [11], such as, whether the model was developed with clear physical meanings and the parameters in the models are related to the real structural and physical properties/process of the materials, and whether there is close interactions between the human body models and clothing models so as to enable the integration between them with smooth communication sockets, the mathematical models are selected and integrated to simulate the clothing wearing system for clothing thermal engineering design. The main equations of them are listed as follows:

Fabric vapour moisture governing equation

$$\frac{\partial(\varepsilon_a C_a)}{\partial t} = \frac{D_a \varepsilon_a}{\tau_a}\frac{\partial^2 C_a}{\partial x^2} + G_a \frac{\partial^2 p_s}{\partial x^2} + \varpi_a \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{\lg} \tag{1}$$

Fabric liquid water governing equation

$$\frac{\partial(\rho_l \varepsilon_l)}{\partial t} = \frac{1}{\tau_l}\frac{\partial}{\partial x}\left(D_l \frac{\partial(\rho_l \varepsilon_l)}{\partial x}\right) + G_l \frac{\partial^2 p_s}{\partial x^2} + \varpi_l \frac{\partial C_f}{\partial t} - \Gamma_{\lg} \tag{2}$$

Fabric heat transfer governing equation

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K_t \frac{\partial T}{\partial x}\right) + \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x} + (\omega_a \lambda_v + \omega_l \lambda_l)\varepsilon_f \frac{\partial C_f}{\partial t} - \lambda_{\lg} h_{\lg} \Gamma_{\lg} + \dot{q}(x,t) + W \tag{3}$$

Fabric dry air pressure governing equation:

$$\frac{M_g \varepsilon_a}{RT}\frac{\partial p_s}{\partial t} - \frac{p_s \varepsilon_a M_g}{RT^2}\frac{\partial T}{\partial t} - \frac{M_g p_s}{RT}\frac{\partial \varepsilon_l}{\partial t} = \frac{\partial}{\partial x}\left[G_s \frac{\partial p_s}{\partial x}\right] - \varpi_1 \varepsilon_f \frac{\partial C_f}{\partial t} + \Gamma_{\lg} \tag{4}$$

Fiber moisture absorption/desportion model:

$$\frac{\partial C_f(x,r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_f(x,t)\frac{\partial C_f(x,r,t)}{\partial r}\right) \tag{5}$$

Human body thermal regulatory model:

$$\begin{aligned} S_{cr} &= M - E_{res} - C_{res} - W - (K_{\min} + c_{pbl}V_{bl})(T_{cr} - T_{sk}) \\ S_{sk} &= (K_{\min} + c_{pbl}V_{bl})(T_{cr} - T_{sk}) - E_{sk} - R - C \end{aligned} \tag{6}$$

The detailed descriptions of the development and integration of these mathematical models can be found in the literatures [7,8,12]. The human body thermal regulatory model is one-dimensional considering the body as two-node concentric shells (core and skin). The partial differential equations in these models are required to be discretized firstly to obtain their numerical solutions, while the algebraic equations do not need special solution method.

3. Discretization of the Partial Differential Equations

The finite volume method is adopted to spatially discretize these partial differential equations. In this method, the volume integrals in a partial differential equation that contain a divergence term are converted to surface integrals and the equation is always kept conservative during the discretization process. In order