International Journal of Heat and Mass Transfer 60 (2013) 582–590

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Type design for bilayer textile materials under low temperature: Modeling, numerical algorithm and simulation

Dinghua Xu [a,*], Yuanbo Chen [a], Xiaohong Zhou [b]

[a] Department of Mathematics, College of Sciences, Zhejiang Sci-Tech University, Hangzhou 310018, Zhejiang, PR China
[b] Department of Textile Engineering, College of Materials and Textiles, Zhejiang Sci-Tech University, Hangzhou 310018, Zhejiang, PR China

ARTICLE INFO

Article history:
Received 28 January 2011
Received in revised form 1 March 2012
Accepted 10 December 2012
Available online 11 February 2013

Keywords:
Bilayer textile materials
Type design
Heat and moisture transfer
Inverse problems
Regularization method
Numerical solution

ABSTRACT

Based on the model of steady-state heat and moisture transfer through textiles, an inverse problem of type design (**IPTD**) for bilayer textile materials under low temperature is put forward. According to the idea of regularization method, the **IPTD** for bilayer textile materials can be formulated into a function minimization problem. By means of the finite difference algorithm for nonlinear ordinary differential equation and the direct search method of one-dimensional minimization problems, an iterative algorithm for the regularized solution of the **IPTD** is constructed. By analyzing the results of numerical simulation in different environmental conditions, some conclusions are obtained: Hooke–Jevees's direct search method can effectively solve the **IPTD** for bilayer textile materials, at the same time, numerical simulation shows the effectiveness of the algorithm and the validity of the proposed inverse problem.

1. Introduction

Simultaneous heat and moisture transfer in porous media is popularly discussed in a wide range of scientific and engineering fields, such as in civil engineering, energy storage and conservation, as well as functional clothing design, etc. [1–4]. For example, as for functional clothing design, there are many increasing requirements on human body comfort. We should develop healthier and safer textile based on heat and mass transfer characteristics [1]. As for the human body comfort textiles, it is hoped that the textiles are of fast decalescence, fast heat radiation, soft or stand-up apparel. Of course, clothing should be light and keeps body warm under lower temperature.

According to the above requirements, the physical characteristics (e.g., sorption, condensation characteristics), structure characteristic (e.g., porous media, multi-layered) of the textile materials and various heat and mass transfer, momentum transfer (e.g., conduction, convection, radiation and molecular diffusion, etc.) should be taken into account [1]. In practical applications, the mathematical modeling and numerical simulation becomes much more important since it provides an efficient way for evaluating new designs or testing new materials. The phenomena of coupled heat and mass transfer in porous media have been drawing the attention of research groups. From 1930s, researchers have discussed a few models of heat and moisture transfer and corresponding numerical simulations of thermal and water vapor concentration in porous media [2–14].

Henry first proposed a mathematical model to describe heat and moisture transfer in textiles in 1939 [2] and further analyzed the model in 1948 [3]. After his work, some coupled models of heat and moisture transfer were established or developed on the basis of partial differential equations in [2–12] or ordinary differential equations in [13]. Although considerable previous work had been carried out on the diverse aspects of simultaneous heat and moisture transfer both theoretically and experimentally, little had been done on the coupling of heat and moisture transfer with phase change and condensation before 2000. Some researchers, such as Fan and Li, have already put forward a few mathematical models of coupled heat and moisture transfer through porous clothing assemblies and porous insulation [4,6,7]. Based on these models, they have derived different numerical methods to solve these problems, such as finite difference method, finite volume method, finite element method, transfer function method and controllability volume-time-domain recursive method, and the numerical results are well matched with experimental results [4,6–9,11]. Some researchers, such as Cheng, had studied the natural convection of heat and mass transfer in porous media [5,10,12].

The computation of temperature and moisture content fields in porous media, from the knowledge of initial and boundary conditions, as well as of the thermal physical properties appearing in the formulation, constitutes a direct problem of heat and mass

---

* Corresponding author. Tel.: +86 136 6669 5270; fax: +86 571 86843000.
E-mail address: dhxu6708@zstu.edu.cn (D. Xu).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.12.063

Nomenclature

T	temperature, K
p_v	pressure of the water vapor, Pa
m_v	mass flux of water vapor, kg m^{-2} s^{-1}
r_1,r_2	radius of the inner and outer textile's cylindrical pore, respectively, m
L	thickness of the inner textile, m
L_o	thickness of the outer textile, m
R_{t0}	resistance to heat transfer in the outer textile material, K W^{-1} m^2
h_t	convective heat transfer coefficient on the surface between the outer textile material and the environment, W K^{-1} m^{-2}
k_1, k_2, k_1', k_2'	constants which are related with molecular weight and gas constant
$T_{\min}$	minimum temperature at a specific place during a specific time period, K
$T_{\max}$	maximum temperature at a specific place during a specific time period, K
$RH_{\min}$	minimum relative humidity at a specific place during a specific time period
$RH_{\max}$	maximum relative humidity at a specific place during a specific time period
T_0	temperature on the boundary between microclimate area and inner porous batting, K
T_R	temperature on the boundary between outer textile material and environment, K
T^e	environmental temperature, K
RH^e	environmental relative humidity
$m_{v,L}$	mass flux of water vapor on the boundary between inner textile material and outer textile material, kg m^{-2} - s^{-1}
$p_{v,R}$	water vapor pressure on the out boundary of outer textile material, Pa
$RH^0_{i,j}$	relative humidity in the microclimate area when a person stays in the environmental conditions$\{T^e_i, RH^e_j\}$
RH^*_0	experience value of relative humidity in comfortable state
h_1	thickness difference of the inner textile, m
h	thickness difference of the outer textile, m

Greek symbols

Γ	rate of condensation, kg m^{-3} s^{-1}
ε_1,ε_2	porosity of the inner and outer textile surface, respectively
τ_1,τ_2	effective tortuosity of the inner and outer textile, respectively
κ	thermal conductivity of the inner textile material, W K^{-1} m^{-1}
κ_o	thermal conductivity of the outer textile material, W K^{-1} m^{-1}
$\Delta\kappa_i$	searching step, W K^{-1} m^{-1}
λ	latent heat of sorption and condensation of water vapor, J kg^{-1}
α	acceleration factor
β	reduced rate
γ	iteration step length
δ^2	regularization parameter
ε	permissible error

Subscripts

o	out
e	environment
L	left
R	right

transfer [2–14]. On the other hand, according to the environmental temperature and humidity and the body comfort index, simultaneous estimation of physical parameters and thickness of textiles are inverse problems for coupled heat and mass transfer process [15,16].

The inverse problems of textile materials design based on heat and moisture transfer properties have played important roles in many applied fields. By using the theories and methods of inverse problem to study textile materials design, it can scientifically predict and guide the textile design and clothing equipment design, at the same time, it can also have significance for the development of advanced textile materials and protecting human health in harsh environment. Therefore it necessary that we should study that the conditional well-posedness and numerical methods mathematically for the inverse problems of textile design.

Recently, Xu studied the model of stationary heat and moisture transfer through parallel pore textiles by means of theoretical analysis and numerical simulations [13]. For dynamic model of heat and mass transfer, we can see [14] for example. Based on the model, the formulation of inverse problems of textile material design for single-layer textile materials under low temperature was first put forward and different numerical methods were applied to solve these inverse problems, such as Hooke–Jeevees's pattern search method, Golden section method and the other direct search method [15,16].

In the real life, people usually enjoy wearing light bilayer dresses (for example underwear and a outer garment). For this reason, we extend our previous works [16] and propose an inverse problem of type design (**IPTD**) for bilayer textile materials under low temperature. That is to say, according to the environmental temperature and humidity and the body comfort index, from the knowledge of the textile geometry structure and thickness of the inner and outer material, as well as the heat conductivity of outer textile material, we shall determine the type of the inner material.

The paper is composed of the following sections: In Section 2, we will introduce a mathematical model of stationary coupled heat and moisture transfer through parallel pore bilayer textiles. In Section 3, based on the model in Section 2, an **IPTD** for bilayer textile materials under low temperature is put forward. In Section 4, by means of the finite difference method, numerical computation of the direct problem is carried out. In Section 5, according to the idea of regularization methods, we establish iteration schemes to numerically solve the **IPTD**. In Section 6, we make numerical simulation under two different low temperature conditions and obtain the thermal conductivity of different materials by using Hooke–Jeeves's pattern search algorithm. In Section 7, some conclusions and prospects are given.

2. Mathematical formulation of a heat and mass transfer process in textiles

2.1. The schematic diagram and assumptions

In the body-clothing-environment system, we consider a model consisting of a thick outer textile material and a thin inner textile material as shown in Fig. 1. The inner textile material is close to