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Numerical Study of Heat and Moisture Transfer in Textile Materials by a Finite Volume Method

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Abstract. This paper focuses on the numerical study of heat and moisture transfer in clothing assemblies, based on a multi-component and multiphase flow model which includes heat/moisture convection and conduction/diffusion as well as phase change. A splitting semi-implicit finite volume method is proposed for solving a set of nonlinear convection-diffusion-reaction equations, in which the calculation of liquid water content absorbed by fiber is decoupled from the rest of the computation. The method maintains the conservation of air, vapor and heat flux (energy). Four types of clothing assemblies are investigated and comparison with experimental measurements are also presented.

AMS subject classifications: 78M20, 65N22, 65N06

Key words: Fibrous porous medium, multi-component flow, clothing assemblies, finite volume method, condensation/evaporation.

1 Introduction

Heat and mass transfer in fibrous porous media attracts considerable attention since it can be found in a wide range of industrial and engineering domains, such as paper and pulp [7], building materials [1] and more recently, textile [17, 21]. Heat and moisture transfer with phase change is coupled in rather complicated mechanisms. Henry started to investigate the diffusion of moisture into bales of cotton in 1939 [9] and again in 1948 [10]. Later, David and Nordon [2] improved this model by incorporating several features omitted by Henry. Ogniewicz and Tien [19] proposed a quasi-steady state model to

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describe heat and mass transfer with immobile condensation in porous insulation (building material). This model was extended by Shapiro and Motakef [20] to analyze unsteady heat and mass transfer. Recently, Fan et al. [3–5] introduced dynamic moisture absorption and radiation heat transfer into the existing models for clothing assemblies. In their model, the mixture velocity is determined by the vapor pressure. A more realistic mathematical model for moisture transport in clothing assemblies was proposed by Huang et al. [11]. Their model is a generalization of a single-component model used in [5] to a multi-component model by treating air and vapor separately.

This paper focuses on the numerical investigation of heat and moisture transfer in clothing assemblies, based mainly on the model proposed in [11] with several further modifications. Since the volume fraction of water is relative small, a simplified water equation is introduced in this paper by neglecting convection and diffusion (capillary effect) for liquid water. Therefore, liquid water is immobile and stays at the condensation site. Heat conductivity depends upon the conductivity of each material in the clothing assemblies and their suitable combination. The effective heat conductivity is obtained by a combination of parallel and serial distributions, depending on the amount of water/ice. The capacity of mixture is treated in the same way. Since the model consists of a system of nonlinear equations, to maintain the conservation of air, vapor and energy, a splitting semi-implicit finite volume method is used. In addition, liquid water content absorbed by fiber is obtained directly from the scaled water content which is computed by solving an evolution equation along the fibre radius with a Dirichlet boundary condition.

The rest of the paper is organized as follows. In Section 2, we introduce the mathematical model of moisture transport in textile materials in a one dimensional setting and a class of physical boundary conditions for a typical clothing assembly, a porous batting sandwiched by two covering layers. The model consists of a system of nonlinear evolution transport equations. In Section 3, we propose a splitting semi-implicit scheme for this system of nonlinear equations using a finite volume method. Numerical results are presented in Section 4. Clothing assemblies with two different batting materials (polyester and viscose) and two different cover materials (nylon and laminated) are investigated numerically by the proposed method and the results are compared with experimental observations [6], which reveal distinct characteristics due to the fact that the two batting materials have different rates of absorption and the two covers have different resistance to air and vapor. Numerical test shows that the proposed method is efficient and numerical results are in better agreement with the experimental data than previous numerical simulations, indicating that the current model is more realistic than the previous ones reported in the literature.

2 Mathematical model

Here we consider a model problem of heat and moisture transfer in textile materials, which consists of a three-layer porous clothing assemblies as illustrated in Fig. 1. The