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Numerical simulation of multiscale heat and moisture transfer in the thermal smart clothing system

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ABSTRACT

Simulation capacity is essential to the engineering design of industrial products with complex functions. This paper discusses a numerical algorithm to simulate the multiscale heat and moisture transfer in the thermal smart clothing system. A group of multiscale nonlinear models are proposed to describe the mix-type coupled heat and moisture transfer in the human body, fabrics, fiber material, and phase change material (PCM) particles. The dynamic thermal boundary conditions among individuals are considered and described to integrate the multiscale models. The coupled partial differential equations of the models are discretized by the finite volume method, and the numerical scheme for the thermal smart clothing simulation are developed considering the specification of wearing scenarios. To validate the models and simulation scheme, the simulation results and experimental results with the same clothing and wearing conditions are compared and discussed. Furthermore, a series of simulation cases are made to present the application of this numerical algorithm in practical design by expressing a sequence of design issues through the simulation results for the designers. This simulation scheme is helpful in the engineering design process of thermal smart clothing to identify the thermal quality of the clothing in advance and thus reduce the design cost.

1. Introduction

Being regarded as an innovative product with great commercial prospect, thermal smart clothing is characterized by its capability to quantify the thermal performance of clothing to provide high-quality thermal protection for the human body under various wearing situations, such as extremely hot or cold environment. During the design process, the textile material is usually integrated with phase change material (PCM) particles or subjected to moisture management treatment or electrical heating technology. In contrast to traditional design, the engineering design method should to be utilized. In this case the complex thermal and fluid flow among the human body, clothing, and the environment (called clothing wearing system) should be systematically considered to quantify the thermal quality of the clothing. However, these thermal and fluid flows are in different scales due to the different dimensions of the human body, fabric, fibers and PCM particles. It is difficult to have accurate analysis of the thermal performance of individual entity with numerical simulation only in one scale.

In the literature, interest is continuing on the mathematics of describing the heat and moisture transfer through porous textile materials. Theoretically, the involved heat transfer mechanisms include the conduction by the fibers and the intervening air,

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Nomenclature

$B_{i,j}$	heat loss by blood flow in the *j*th body node in the *i*th segment (W)
C_a	water vapor concentration in the air filling the inter-fiber void space (kg/m^3)
C_f	water vapor concentration in the fiber (kg/m^3)
$C*$	saturated water vapor concentration at the local temperature (kg/m^3)
c_v	volumetric heat capacity of the fabric (J/m^3.K)
$c_{i,j}$	thermal capacity of the *j*th body node in the *i*th segment (J/m^3.K)
$Ch_{i,j}$	heat production by muscle shivering of the *j*th body node in the *i*th segment (W/m^2)
D_a	diffusion coefficient of water vapor in the air of the fabric (m^2/s)
D_l	liquid diffusion coefficient in fabric (m^2/s)
D_f	diffusion coefficient of water vapor in the fiber (m^2/s)
$D_{i,j}$	heat loss by radiation and convection of the *j*th body node in the *i*th segment (W/m^2)
$E_{i,j}$	heat loss by evaporation of the *j*th body node in the *i*th segment (W/m^2)
F_R	thermal radiation flux on a tiny volume element to the left direction
F_L	thermal radiation flux on a tiny volume element to the right direction
G_a	coefficient of pressure gradient to water vapor flux
G_l	coefficient of pressure gradient to liquid water flux
G_s	coefficient of pressure gradient to air flux.
H_m	convection mass transfer coefficient (m/s)
H_c	convection heat transfer coefficient (W/m^2.K)
$m_{s,i}$	sweating secretion rate of the *i*th body segment (g/s.m^2)
$m_{rsw,i}$	regulatory sweating of the *i*th body node (g/s.m^2)
Γ_f	effective moisture sorption rate of the fiber
Φ_{lg}	evaporation/condensation rate of the liquid/vapor
L	thickness of the fabric (cm)
$M_{i,j}$	metabolic heat of the *j*th body node in the *i*th segment (W/m^2)
$Mb_{i,j}$	basal metabolic rate of the *j*th body node in the *i*th segment (W/m^2)
M_g	mole mass of air molecule (kg/mol)
h_{lg}	mass transfer coefficient for evaporation and condensation (m/s)
h_r	radiative heat transfer coefficient (W/m^2.K)
h_T	heat transfer coefficient between PCM particles and surrounding flow (W/m^2.K)
K_t	thermal conductivity of the fabric (W/m^2.K)
K_m	thermal conductivity of the PCM particle (W/m^2.K)
$K_{i,j}$	thermal conductivity of the *j*th body node in the *i*th segment (W/m^2.K)
P_s	pressure of dry air in the fabric (Pa)
$P_{c,i}$	pressure of the clothing close to the skin of the *i*th body node (Pa)
$P_{sat,i}$	saturated vapor pressure of the skin of the *i*th body node (Pa)
$P_{sk,i}$	water vapor pressure of the skin of the *i*th body node (Pa)
P_e	pressure of the environment (Pa)
p_m	pumping ratio of water vapor loss from the skin
p_h	pumping ratio of heat loss from the skin
q_m	energy released/absorbed rate of PCM particle
R	general gas constant
R_{esk}	water vapor resistance of the skin (m^2.Pa.s/kg)
R_{va}	water vapor resistance of the air layer (m^2.Pa.s/kg)
R_{ta}	thermal resistance of the air layer (m^{2}K/W)
R_n	heat transfer resistance of waterproof membrane (m^{2}K/W)
RH_f	relative humidity of the fiber surface
r_f	fiber radius in radial coordinate (m)
r_m	PCM particle radius in radial coordinate (m)
S_i	area of the skin of the *i*th body node (m^2)
S_v	surface volume ratio of the fiber (1/m)
T	temperature of the fabric (K)
$T_{i,j}$	temperature of the *j*th body node in the *i*th segment (K)
$T_{sk,i}$	skin temperature of the *i*th body node (K)
T_e	temperature of the environment (K)
$T_{c,i}$	temperature of the clothing close to the *i*th body node (K)