Effects of Zeta Potential and Fiber Diameter on Coupled Heat and Liquid Moisture Transfer in Porous Polymer Materials

Qing-Yong Zhu[*], Jing Yang, Ming-Hui Xie

School of Engineering, Sun Yat-sen University, Guangzhou, Guangdong, 510275, China

Abstract: This study is a theoretical investigation of the liquid water transport coupled with moisture and heat transfer in porous polymer materials. The solid surface zeta potential and the fiber diameter are investigated to reveal the mechanisms of the coupling effects. Based on the Poisson- Boltzmann equation for electric double layers and Navier-Stokes equation of liquid flows, a mathematical model to simulate the complex coupled heat and moisture transfer in porous polymer materials is reported in this paper.

Keywords: Electric double layer, coupled heat, liquid moisture transfer, porous polymer materials.

1. Introduction

Porous polymer materials are widely used in many fields, such as artificial skins in tissue engineering. So far, the coupled heat and liquid moisture transfer in porous polymer materials have aroused wide concern. Pores with various sizes, which can be considered as interconnecting micro-channels with different diameters, exist from the porous polymer materials. The flows in porous materials are generally a complex process which involves simultaneous, coupled heat and mass transfers. The heat transfer mechanisms in porous polymer materials include conduction by the solid material of the fibers, conduction by intervening air, radiation and convection. Meanwhile, the heat transfer process is coupled with phase changes, such as moisture sorption, moisture desorption, evaporation and condensation. Liquid and moisture transfer mechanisms include water vapor diffusion in the void spaces and liquid diffusion by capillary action. The rearrangement of the charges on the solid surface and the balancing charges in the liquid is called the electrical double layer (EDL). It has been proved that the flows in micro-scale are quite different from those in macro-scale. Generally for macro-channel flow the EDL can be neglected due to the very small thickness of the EDL compared with the characteristic size of macro-channels. However, for the micro-channel flow the thickness of the EDL is compared with the characteristic size of flow channels. It means that the EDL effects must be taken into account in micro-channel flow.

A couple of scholars, such as Li and Zhu , have made numerous research in this field [1-11]. A satisfactory model to simulate the couple heat and mass transfer in porous materials has been established by Li and Zhu and a great number of meaningful conclusions have been made. But the resistance effect of EDL on the coupled heat and liquid moisture transfer in porous polymer materials is seldom taken into account. The electroosmosis phenomenon of the electrolytic solution which flows through micro-channels comprising a bunch of cylinders was researched [12] and it was shown that the EDL has a significant effect on the flow field and the smaller the ratio of the channel diameter to the thickness of EDL is, the bigger the effect of EDL is. The heat effect of the electro osmotic flow in capillaries was studied [13] and it was pointed out that the EDL has a crucial effect on the heat transfer in capillaries as well.

In this paper, taking the resistance effect of the EDL into account, an improved model is deduced from the basic equations, including Poisson-Boltzmann equation for electric double layers and Navier-Stokes equation for liquid flows. The diffusion coefficient of the electrolytic solution and a dimensionless number that aims to describe the resistance effect of the EDL are obtained through theoretical derivation. With specification of initial and boundary conditions, the distribution of the moisture content and the temperature in the porous polymer materials with different solid surface zeta potentials and fiber diameters are numerically computed. Effects of the solid surface zeta potential and fiber diameter on the coupled heat and liquid moisture transfer in porous polymer materials are discussed. The comparison with a series of experimental measurements shows the superiority of this model in resolving the coupled heat and liquid moisture transfer in porous polymer materials. The results illustrate that the heat and moisture transfer process is influenced by the solid surface zeta potential and the fiber diameter of the porous polymer materials.

Nomenclature

C_a	[Kg/m^3]	water vapor concentration in the air filling the inter-fiber void space
C_f	[Kg/m^3]	water vapor concentration in the fiber
c_v	[KJ/m^{3}K]	volumetric heat capacity of the fabric
C^*	[Kg/m^3]	saturated water vapor concentration
D_a	[m^2/s]	diffusion coefficient of water vapor in the air of the fabric
D_f	[m^2/s]	diffusion coefficient of water vapor in the fibers of the fabric
D_l	[m^2/s]	diffusion coefficient of liquid water in the fabric
d	[m]	fiber diameter
d_{cmax}	[m]	maximal radius of the pores
e	[C]	fundamental charge
$h_{l\text{-}g}$	[m/s]	mass transfer coefficient
k_b	[-]	Boltzmann constant
K_{mix}	[W/mK]	thermal conductivity of the fabric
n_0	[-]	bulk number concentration of ions in the electrolyte solution
p	[N/m^2]	pressure in the capillary
S_v'	[m^{-1}]	specific volume of the fibers
T	[K]	absolute temperature
t	[s]	real time from change in conditions
x	[-]	X-coordinate

Greek symbols

ρ	[Kg/m3]	density of the fibers
ρ_e	[C/m3]	the net charge density per unit volume
ρ_l	[Kg/m3]	density of the liquid water
τ_a	[KJ/Kg]	latent heat of evaporation of water
τ_{al}	[KJ/Kg]	heat of sorption or desorption of liquid water by fibers
τ_{av}	[KJ/Kg]	heat of sorption or desorption of vapor by fibers
ω_1	[-]	proportion of the sorption of water vapor by fibers
ω_2	[-]	proportion of the sorption of liquid water by fibers
σ	[N/m]	surface tension
μ	[Kg/ms]	Dynamic viscosity
ε	[C/Vm]	permittivity of the electrolyte
ε_l	[-]	volume fraction of liquid phase

γ	[-]	the average angle of the capillaries in Fabrics
φ	[-]	contact angle
χ	[-]	valence of the ions of the electrolyte solution
Φ	[-]	porosity of the fabric
Ψ	[C]	local electrical potential

2. Numerical model

This paper lays emphasis on the porous polymer materials that is considered as containing a countless number of yarns woven out of fibers. The yarn is made up of a cluster of fibers twisted up. The capillaries are formed by these pores in yarns woven into porous polymer materials. The electrolyte solution flows from the regions of higher electrolyte solution concentration to regions of lower electrolyte solution concentration due to the fiber-liquid molecular attraction at its surface, which is determined by the surface tension and the effective capillary pore distribution. The liquid flow is coupled with heat transfer, moisture transfer and phase changes such as evaporation and condensation. The following assumptions are made in this model:

1. Local thermal is assumed to be equal among all phases due to the relatively low velocities considered and the small dimension of the constituting fibers.

2. The inertia of each phase in porous polymer materials is ignored because of the relatively low velocities.

3. Swelling of fibers while making porous polymer materials is neglected.
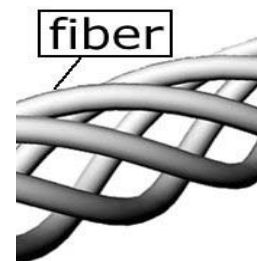

Figure 1 Structure of porous polymer materials.

When the electrolyte solution diffuses in porous polymer materials resulting from capillary action, the mass balance of the water vapor is established by equation (1), the mass balance of the liquid moisture is established by equation (2) and the energy balance is established by equation (3). The governing equations can be expressed as