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Heat and moisture transfer from skin to environment through fabrics: A mathematical model

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Abstract

A mathematical model is set up to simulate the heat and moisture transfer from skin to environment through fabrics by including the radiation heat transfer between surfaces and the surface diffusion along fibers. The result shows that the contributions of radiation and conduction through air are approximately 20% each of the total heat flux. The surface diffusion does not play a significant role in the total moisture transport if the surface diffusion is restricted to the chemisorption of water molecules onto fiber surfaces. It is concluded that the microclimate plays the most significant role in the heat and moisture transfer from skin to environment.

Keywords: Surface diffusion; Radiation; Natural convection; Howard model; Microclimate

1. Introduction

The transport of heat and moisture through fabrics is one of the major concerns in the design of functional clothing such as sports wears and military uniforms for extremely cold or hot conditions. In the clothing research, they usually assess the transport of heat and moisture through fabrics by using a sweating hot plate [1–4] or a thermal manikin [5–10]. Even though the transport of heat and vapor through fabrics is a classical chemical-engineering problem, there has been no rigorous treatment of the problem despite its practical importance. There have been some researches on the heat and moisture transport through fibrous media [11,12]. But these studies may not be directly applicable to clothing systems. Recently, Sobera et al. [13] considered a convective heat and moisture transfer problem to a cylinder sheathed by a porous layer modeling a clothed human limb. In their studies a turbulent flow due to forced convection was considered and an empirical correlation was proposed. Ghali et al. [14] considered heat and moisture transport by periodic ventilation of cotton by modeling. We believe that such systematic and theoretical studies are required to design functional clothing properly and to achieve the comfort and protection at severe conditions.

To understand the heat and moisture transfer in clothing systems, we need to have the proper mechanism for heat and moisture transport from skin to environment through fabrics. Until now, the mathematical models developed for the heat transport through fabrics have been restricted to the cases of conduction through fabrics, conduction and convection within the microclimate (a space between skin and fabric, see Fig. 1) and heat transfer concomitant with the vapor transport. In the case of vapor transport, only the diffusion of vapor through pores of fabrics together with the adsorption and desorption of vapor onto fabrics was considered [15–17]. The radiation term was considered already [17,18], but systematic studies have been still lacking. In this study, we consider a more realistic model for the transport of heat and moisture through

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Nomenclature

C_p	heat capacity at constant pressure
D	diffusion coefficient
D_{sur}	surface diffusion coefficient
e	emissivity
g	gravitational acceleration
h	heat transfer coefficient
ΔH_{vap}	enthalpy change of vaporization
j	mass flux
k	thermal conductivity
K	equilibrium constant between the surface concentration and bulk concentration
K_{w}	mass transfer coefficient of moisture
l	length
q	heat flux
T	temperature
v	mass average velocity
w	vapor fraction

Greek symbols

β	thermal coefficient of volume expansion
ε	porosity
μ	viscosity
ρ	density
σ	Stefan–Boltzmann constant
τ	tortuosity
ζ	concentration coefficient of volume expansion

Subscripts

air	air
con	conduction
diff	moisture diffusion
eff	effective variable
rad	radiation
vap	H_2O vapor (moisture)
MF	boundary between microclimate and fabric
FE	boundary between fabric and environment
F	fabric
MC	microclimate
E	environment
x, y, z	x-, y-, z- coordinates

Dimensionless groups

Gr	Grashof number
Gr_{w}	diffusional Grashof number
Pr	Prandtl number
Ra	Rayleigh number
Sc	Schmidt number
Sh	Sherwood number

fabrics by including the effect of radiation of heat between the skin and fabric and fabric and environment and the effect of surface diffusion along fiber surfaces. Even though the importance of surface diffusion was raised from many years ago [15], there has been no attempt to include the effect quantitatively. In this research we have included the surface diffusion term in the model by adopting an idea from the solid catalysis on the chemisorption. The model calculation shows that the radiation plays an important role in heat transfer even at the ambient temperature level. However, the surface diffusion may not play a significant role in the total moisture transport if the surface diffusion is restricted to the chemisorption of water molecules onto fiber surfaces. Therefore, we have concluded that surface diffusion may play a significant role when the surface diffusion is caused by multilayer physisorption.

2. Formulation of the problem

Let us consider a system that consists of human skin, fabric and an air layer between the skin and fabric as shown in Fig. 1. The outer surface of fabric is exposed to the environment extended to infinity. The fabric and the skin are placed perpendicular to the direction of gravity. This lay-out will be called a horizontal system. The problem of a vertical problem will be also considered later. The air layer between the skin and fabric will be called microclimate. The gap distance of microclimate has an order of millimeters while the size of fabrics and skin is sufficiently large compared to the gap distance of microclimate. Hence it is assumed that the heat and moisture transport are basically one-dimensional. In this lay-out, the air layer between skin and fabric (microclimate) when the temperature difference is small is stagnant without natural convection. The fabric is essentially a porous medium with porosity ε.

The heat and moisture originated from human skin are delivered to environment through the microclimate, the fabric and the boundary layer adjacent to the fabric. In the microclimate moisture is transferred to the surface of the fabric according to Fick's law. Here it is assumed that the Rayleigh number is below the critical value for the onset of natural (Benard) convection not to have a convective motion of air in the microclimate. The validity of this assumption will be considered later. The route of heat transfer is more complex. Heat is transferred to the surface of fabric (1) by the conduction through the air layer, (2) by the radiation between skin and fabric surface and (3) by the transport of vapor through the microclimate. Then the total heat transfer through the microclimate is expressed as follows

$$q_{\mathrm{MC}} = -k_{\mathrm{MC}}\frac{\mathrm{d}T}{\mathrm{d}x} + \frac{\sigma(T_{\mathrm{S}}^4 - T_{\mathrm{MF}}^4)}{(1/e_{\mathrm{S}} + 1/e_{\mathrm{MF}} - 1)} + j_{\mathrm{MC}}(\Delta H_{\mathrm{vap}}), \tag{1}$$

where the first term represents the thermal conduction through the air layer, the second term represents the

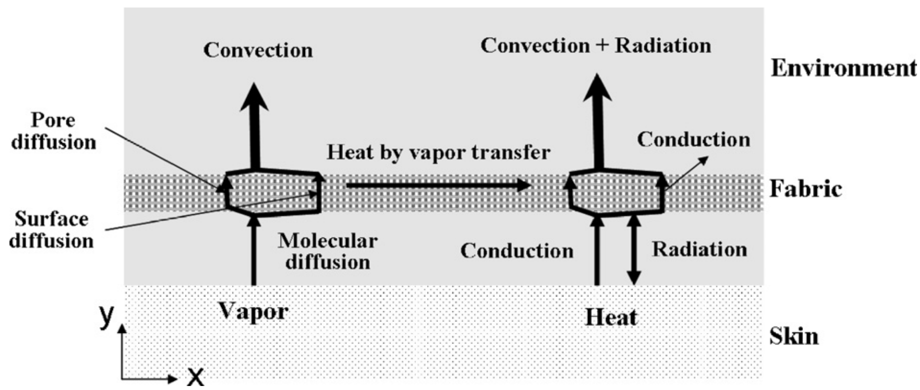

Fig. 1. Pathways of the heat and moisture transfer from skin to environment through fabric: horizontal system. Radiation and surface diffusion are considered in addition to conduction and convection.

radiative heat transfer between two grey surfaces (skin and fabric) and the third term represents the heat transfer by the moisture diffusion through the air layer. The diffusion flux is given by the Fick's law

$$j_{\mathrm{MC}} = -\rho D_{\mathrm{vap}} \frac{\mathrm{d}w}{\mathrm{d}x}. \tag{2}$$

At the steady state the temperature and moisture concentration satisfy

$$k_{\mathrm{air}} \frac{\mathrm{d}^2 T}{\mathrm{d}x^2} = 0 \tag{3}$$

and

$$D_{\mathrm{vap}} \frac{\mathrm{d}^2 w}{\mathrm{d}x^2} = 0, \tag{4}$$

respectively.

The heat transfer within the fabric is also composed of the conduction and the heat transfer due to the transport of vapor. The conduction is composed of the conduction through solid fibers and the conduction through the air filling the interstices between fibers. In this case an average conductivity may be introduced thus

$$k_{\mathrm{F,eff}} = (1-\varepsilon)k_{\mathrm{fabric}} + \varepsilon k_{\mathrm{air}}, \tag{5}$$

where ε is the porosity of fabric. Then the conduction of heat through the fabric can be written as follows

$$q_{\mathrm{F,con}} = -k_{\mathrm{F,eff}} \frac{\mathrm{d}T}{\mathrm{d}x}. \tag{6}$$

In the fabric moisture is transferred by two independent mechanisms of pore diffusion through the interstices between fibers and surface diffusion along the surface of fibers. Heat is transferred toward the outer surface of fabric by conduction through fibers and the air in pores and by the transfer concomitant with the moisture transport. Then the heat and moisture fluxes can be written as follows

$$q_{\mathrm{F}} = -k_{\mathrm{F,eff}} \frac{\mathrm{d}T}{\mathrm{d}x} + j_{\mathrm{F}} \Delta H_{\mathrm{vap}}. \tag{7}$$

The radiation heat flux inside the fabric is not explicitly included in the above equation, since the fabric is densely packed with fibers, and hence, the radiation effect is already included in the effective thermal conductivity term. Fan et al. [17] included the radiation effect inside the fibrous bat with the porosity of 0.87–0.915. But in this research the penetration depth will be very shallow, since the fabric is densely packed and opaque. The surface diffusion is governed by the surface concentration which is determined by the adsorption and desorption processes between water vapor in pores and liquid water on fiber surfaces. In this research we assume that the adsorption and desorption are in the local equilibrium state. Then we can write surface diffusion in terms of the moisture concentration in pores rather than moisture concentration at the surface assuming a linear adsorption isotherm. Then we can write the diffusion within the fabric as follows [19]

$$j_{\mathrm{F}} = -D_{\mathrm{F,eff}} \frac{\mathrm{d}w}{\mathrm{d}x}, \tag{8}$$

where

$$D_{\mathrm{F,eff}} = \left(D_{\mathrm{vap}} \frac{\varepsilon}{\tau} + K D_{\mathrm{sur}}\right) \tag{9}$$

is the effective diffusivity, τ is the tortuosity of fabric and K is the equilibrium constant. Therefore, the governing equations for heat and vapor transport within the fabric are written as follows assuming that physical properties are constant:

$$D_{\mathrm{F,eff}} \frac{\mathrm{d}^2 w}{\mathrm{d}x^2} = 0, \tag{10}$$

$$k_{\mathrm{F,eff}} \frac{\mathrm{d}^2 T}{\mathrm{d}x^2} = 0. \tag{11}$$

In the environment region, basically, temperature and humidity are assumed to be uniform except the boundary layer adjacent to the fabric. In the environmental region there is no length scale, hence the Rayleigh number cannot be properly defined. Since it is assumed that the temperature of fabric surface placed in the lower position than the environment is higher than the temperature of the environment, there should a natural convection with mushroom type plumes [20]. In this case we adopt the Howard model [20] to predict the boundary layer structure and heat and moisture transfer coefficient. According to the Howard theory, the Nusselt number is expressed by the following relationship based on a boundary layer thickness, l

$$Nu = \frac{hl}{k} = \left(\frac{Ra}{Ra_c}\right)^{1/3} = 0.1\left(\frac{C_p\rho^2 g\beta(T_{FE} - T_E)l^3}{k\mu}\right)^{1/3}, \tag{12}$$

where Ra_c has the value of 1000. In the above equation, the length scale is cancelled at both sides which cannot be defined explicitly as already stated. The heat transfer coefficient h is then

$$h = 0.1\left[\frac{C_p k^2\rho^2 g\beta(T_{FE} - T_E)}{\mu}\right]^{1/3}, \tag{13}$$

which is independent of the length scale of the environment. In the present study natural convection can be also induced due to the inhomogeneity in moisture concentration. Since the molecular weight of water vapor is smaller than the molecular weight of air and the moisture content is higher near the fabric surface, the average density is smaller at the fabric surface than at the environment. This also induces the natural convection which reduces the thickness of boundary layer. The combined effect of density gradient due to the difference in temperature and moisture content can be treated by the method suggested by Bird et al. [21] as follows

$$h = 0.1\left[\frac{C_p k^2\rho^2 g\beta(T_{FE} - T_E)}{\mu} + \frac{C_p k^2\rho^2 g\zeta(w_{FE} - w_E)}{\mu}\right]^{1/3}. \tag{14}$$

In addition to the natural convection, heat is also transferred from the fabric surface to the environment with moisture transport and by radiation as in the case of microclimate, thus

$$q_E = h(T_{FE} - T_E) + j_E\Delta H_{vap} + \sigma e_F(T_{FE}^4 - T_E^4). \tag{15}$$

Similarly we can deduce the moisture transfer coefficient and rate of transport as follows:

$$K_w = 0.1\left[\frac{\rho^4 D_{vap}^2 g\beta(T_{FE} - T_E)}{\mu} + \frac{\rho^4 D_{vap}^2 g\zeta(w_{FE} - w_E)}{\mu}\right]^{1/3}, \tag{16}$$

$$j_E = K_w(w_{FE} - w_E). \tag{17}$$

The analogy between heat and mass transfer in the natural convection system where heat and moisture are transferred simultaneously has also been found to be valid in a similar system where heat and moisture are transferred from a thin film of water [22]. El-Riedy [23], Sheridan and Williams [24], Tan [25] and Schrage [26] have used the analogy successfully for various natural convection systems. We also note that even though there is a substantial difference in the heat or moisture transport coefficients the change in the heat or moisture transport would not be that large. This argument will be confirmed from the fact that even though the heat and mass transfer coefficients are twice in the vertical system compared to the horizontal system, the total heat or moisture transport changes by less than 10% in heat and moisture fluxes.

At the steady state heat and moisture fluxes through microclimate, fabric and environment should be balanced, thus:

$$q_{MC} = q_F = q_E, \tag{18}$$

$$j_{MC} = j_F = j_E. \tag{19}$$

At the skin surface and in the environment the temperature and relative humidity are assumed to be constant

$$T_S = \text{const}, \quad w_S = \text{const},$$
$$T_E = \text{const}, \quad w_E = \text{const}.$$

Also, the temperature and moisture content are continuous at the microclimate–fabric interface and fabric–microclimate interface.

3. Results

3.1. Steady state analysis

Before we begin to describe the numerical result, we need to describe the physical system we chose for the numerical calculation. We selected three representative fabrics: cotton, PET (polyethylene terephthalate) and wool. In addition to the type of fabrics, the woven structure is also an important factor. We assumed that the woven structure is basically the same and used the data in Layton [27]. In Table 1, we listed the physical properties of fabrics. Even though the surface diffusion term is included in the model, the values of surface diffusivity of fabrics are not known in the literature as far as the authors are aware of. Therefore, we performed simulations without including the surface diffusion term first and then we included the surface diffusion term by varying the surface diffusivity as a parameter. We performed simulations by assuming that there is no convective motion in the microclimate. The validity of this assumption will be discussed after setting up the reference set of parameters. In Fig. 2, we have plotted the cumulative heat fluxes due to conduction, radiation and moisture diffusion for cotton, PET and wool. Contrary to the common

Table 1
Physical properties of fabrics used in the simulation (Layton [27])

	Cotton	Wool	PET
Porosity	0.591	0.691	0.707
Tortuosity	2.21	2.35	1.5
Emissivity	0.95	0.95	0.8
k, mW m/K	$29.45 + 27W$	$44.1 + 63W$	$40.4 + 23W$
C_p, J/kg K	1380	1338	1255
ρ, kg/m^3	1350	1310	1220

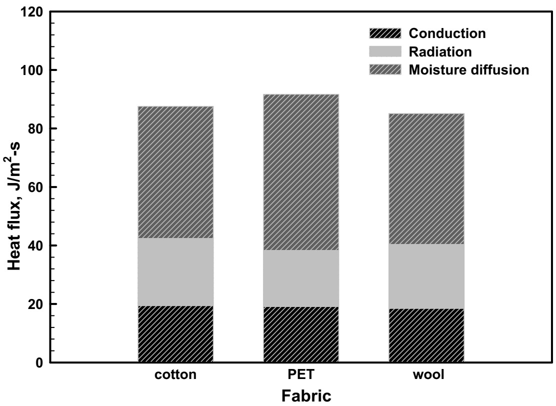

Fig. 2. Cumulative heat fluxes due to each heat transfer mechanism for various fabrics without surface diffusion of moisture.

understanding, the result shows PET fabrics transport the largest amount of heat and moisture, and therefore, a human body would feel most comfortable with PET fabrics. The authors believe that this contradiction is caused by neglecting the surface diffusion term in the calculation. Surface diffusion is a transport of adsorbed vapor on the fiber surfaces. Depending upon the hydrophilic nature, tortuosity, pore size and the total surface area of the fabric, the amount of adsorbed water varies, hence the surface diffusivity. As far as the authors are aware of, the surface diffusivities of water molecules on fabric surfaces are not reported. In the case of porous catalysis, there was a report that the surface diffusion could have 5–14 times the pore diffusion [28]. We expect that the surface diffusion through fabrics may not have the same order of magnitude compared to the pore diffusion in the case of man-made fibers, since the surface area of most man-made fibers is 1 m^2/g and is much less than the surface area of most solid catalysts used in the petrochemical industry (100 m^2/g). However, in the case of cotton, water molecules can be adsorbed by multilayer physisorption rather than by single layer chemisorption only due to the hydrophilic nature of the fabric, and hence, the effect of surface diffusion should be much larger. In the following we will describe the parametric studies with some sets of parameters related to the model. We will describe mostly on the heat and moisture fluxes and temperature and moisture concentration at the fabric–microclimate interface that are known to be the important properties which relate the human comfort.

The major parameters related to the problem are microclimate thickness, fabric thickness, environment temperature and humidity, and kind of fabrics. In this study we chose a representative set of parameters first and performed parametric studies while varying one of the parameters. In Table 2, we listed the reference condition for parametric studies.

First we checked the validity of assumptions introduced in the formulation of problems using the reference set of parameters. We checked the Rayleigh number for the microclimate region and found that Ra was 60 when the reference set of conditions was used. This value is far below the critical value of 1700 and, in fact, Ra did not go over 1700 for most of the simulating conditions. Therefore, the validity of the assumption that '*there is no convective motion in the microclimate*' is confirmed. In the parametric studies we did not perform the simulations when Ra became larger than the critical value. The boundary layer is approximately 15 mm thick. Next we checked the contribution of each heat transfer mechanism to the total heat flux in the microclimate region, i.e., heat conduction, radiation between skin and fabric surfaces and heat transfer due to vapor transport without surface diffusion together with other related results and showed the values in Table 3. At the reference set of conditions the contributions of conduction, radiation and moisture diffusion are approximately 17.6%, 21.0% and 61.4%, respectively. We note that the vapor diffusion plays the most significant role in the total heat transfer even without surface diffusion. One may think that the non-negligible effect of radiation is quite surprising because it is usually thought that radiation has significant effect only when the temperature is very high. The large effect of radiation results from the smallness of heat conduction through the stagnant air layer. A similar effect of radiation is observed for the heat transfer between

Table 2
The reference set of simulation condition

Fabric type	Cotton
Environment temperature	298 K
Environment moisture fraction	0.012
Thickness of fabric	2 mm
Thickness of microclimate	5 mm
Surface diffusivity, KD_{sur}	10^{-4} m^2/s

Table 3
Numerical results when the reference condition is used

Physical variables	Numerical value
Temperature at the boundary between microclimate and fabric, T_{MF}	305.72 K
Temperature at the boundary between fabric and environment, T_{FE}	303.19 K
Moisture fraction at the boundary between microclimate and fabric, w_{MF}	0.0275
Moisture fraction at the boundary between fabric and environment, w_{FE}	0.0269
The total heat flux, q_{total}	111.5 W/m^2
Conduction heat flux at the boundary between microclimate and fabric, $q_{MC,con}$	19.6 W/m^2
Radiation heat flux at the boundary between microclimate and fabric, $q_{MC,rad}$	23.5 W/m^2
Heat flux by moisture transport at the bound. between microclimate and fabric, $q_{MC,vap}$	68.4 W/m^2
Conduction heat flux at the boundary between fabric and environment, $q_{FE,con}$	12.7 W/m^2
Radiation heat flux at the boundary between fabric and environment, $q_{FE,rad}$	30.4 W/m^2
Moisture transport hear flux at the boundary between fabric and environment, $q_{FE,diff}$	68.4 W/m^2
The moisture flux, j_{total}	2.75×10^{-5} kg/m^2s

the outer fabric surface and the environment (27.3% of the total heat flux is due to radiation). This means that the heat transfer due to the natural convection is not large enough from the surface kept near the ambient temperature.

In Fig. 3, we have plotted the temperature and moisture fraction profiles from the skin surface to the environment for three differing values of surface diffusivity. In plotting the temperature and moisture profiles at the environment region we have assumed that the two profiles follow the Howard model. The temperature profiles are almost indistinguishable for differing surface diffusivity while the moisture fraction profiles are strongly affected by the surface diffusivity. As expected from the weak coupling of heat and moisture transfer equations, the temperature profile has the same shape regardless of the kind of fabrics. Since the values of the surface diffusivity of commercial fabrics are not known as far as the authors are aware of, we performed simulations by varying the value until the heat transfer due to moisture transfer term becomes saturated. In Fig. 4, we have plotted the total heat and moisture fluxes from the skin surface to the environment for widely differing values of surface diffusivity (five decades). As surface diffusivity becomes larger the total moisture flux becomes larger as it should be. On the other hand the contribution of pore diffusion becomes negligibly small. This is because,

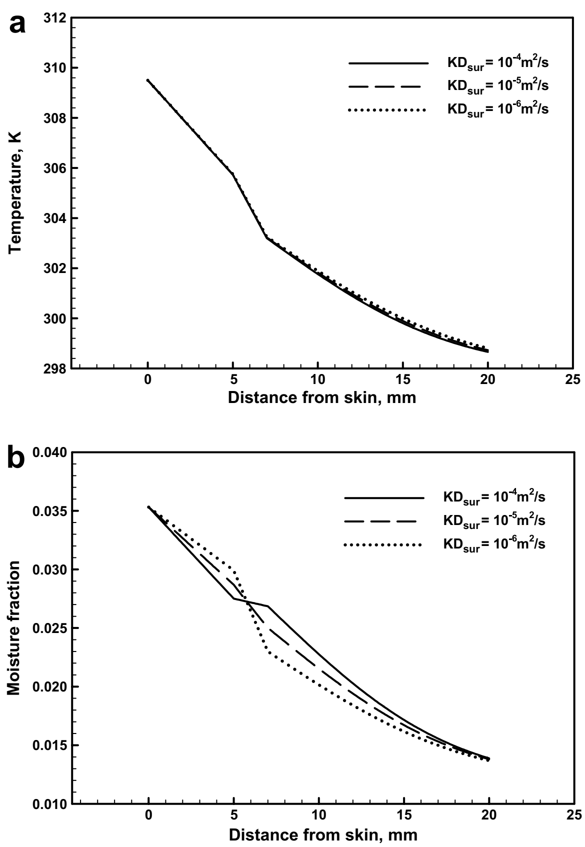

Fig. 3. (a) Temperature and (b) moisture fraction profiles for three different levels of surface diffusion through cotton. The temperature and moisture profiles in the environment are calculated from the Howard's model.

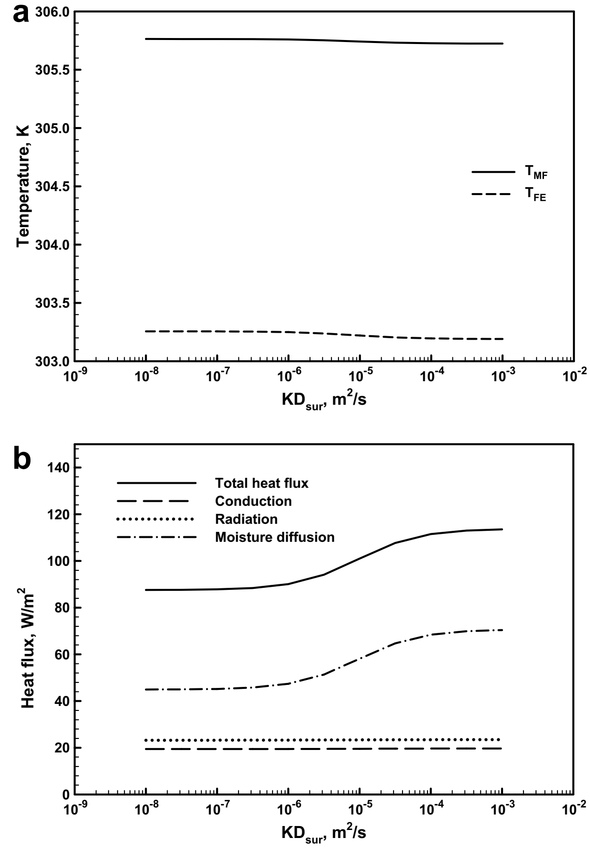

Fig. 4. The effect of surface diffusion on the temperature and heat flux through the microclimate. (a) temperatures at the microclimate–fabric boundary (T_{MF}) and fabric–environment boundary (T_{FE}) and (b) the total heat flux and the contributions from each heat transfer mechanism.

as surface diffusivity becomes sufficiently large, the moisture transfer is limited by the molecular diffusion through the microclimate, and therefore, the moisture gradient in the fabric merges to zero due to the large value of surface diffusivity, hence the molecular diffusion through the fabric becomes negligible. In Fig. 5, we have plotted the temperature and moisture fraction at both sides of fabric. The moisture fractions are significantly affected by surface diffusivity between 10^{-6} and 10^{-4} m^2/s. Even when surface diffusivity becomes sufficiently large, the moisture transfer is limited by the molecular diffusion at the microclimate and convective mass transfer from the fabric surface to the environment. This means that even when the surface diffusion is originated from multilayer physisorption rather than monolayer-chemisorption, the effect of surface diffusion has to be limited. This further means that fabric type should have limited influences when the steady state is considered. In the theory on solid catalysis, the surface diffusivity is proportional to the surface area and the surface diffusion in solid catalysis is about 10 times the pore diffusion [19,28]. Then the order of magnitude of KD_{sur} in Eq. (9) will be 10^{-6} m^2/s. In this range of surface diffusivity the contribution of surface diffusion appears to be not large enough. To have a larger contribution we need to have far larger surface diffusivity, say larger than 10^{-5} m^2/s. It may

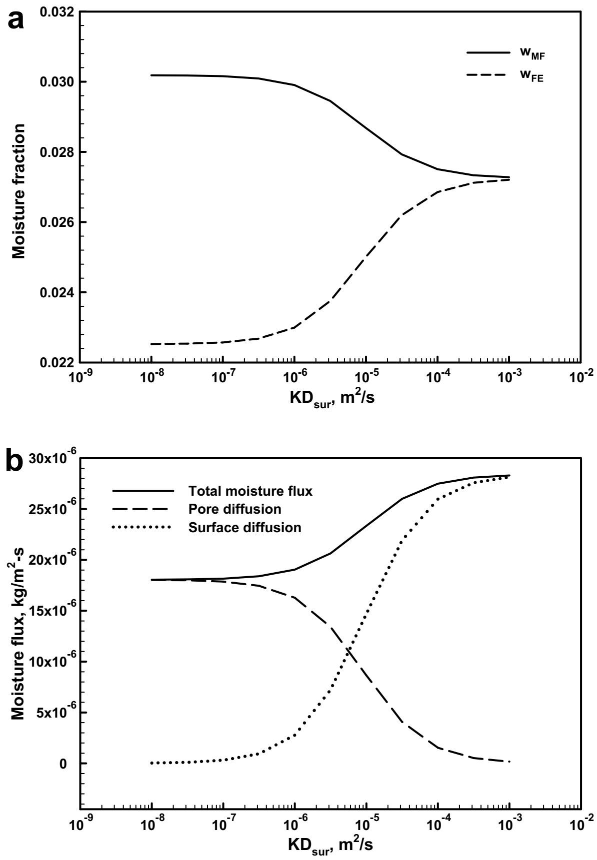

Fig. 5. The effect of surface diffusion on the moisture concentration and moisture flux through the fabric. (a) Moisture concentration at the microclimate–fabric boundary (w_{MF}) and fabric–environment boundary (w_{FE}) and (b) the total moisture flux and the contributions from each moisture transfer mechanism.

be probable that the surface diffusion in the cotton should be caused by the multilayer physisorption rather than chemisorption.

3.2. Effect of environment temperature

In Fig. 6, the effects of environment temperature on heat and moisture transfer are shown. All the individual mechanisms of heat transfer decrease with the increase in environment temperature, hence with the decrease in the driving force. Since we have chosen that the environment moisture is below the saturated vapor pressure at the temperature in the simulation, the heat flux due to moisture transfer does not drop down to zero while heat flux due to radiation and heat conduction decreases to zero when environment temperature approaches to the skin temperature. In the case of fabric surface temperatures, the inner surface is less sensitive than the outer surface.

3.3. Effect of microclimate thickness

In Fig. 7, the effect of microclimate thickness on heat fluxes is shown. The total heat flux decreases with the increase in microclimate thickness. Also temperatures and moisture fractions at fabric surfaces are also lowered. The decrease in heat flux is the result of increased air layer which behaves like an insulating material. The contribution of radiation increases with the increase in microclimate thickness, since radiation is independent of microclimate thickness while the fabric surface temperature is lowered.

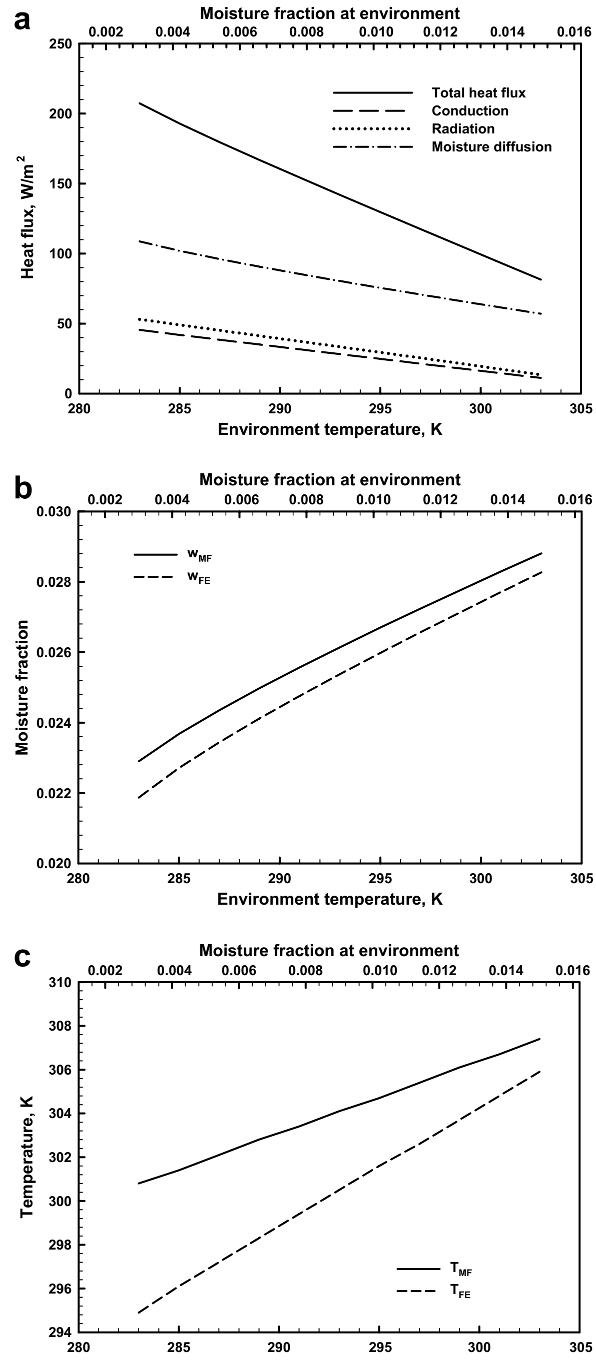

Fig. 6. The effect of environment temperature on: (a) the total heat flux and individual heat transfer mechanisms, (b) moisture fraction at the inner and outer fabric surfaces and (c) temperature at the inner and outer surfaces. The upper scale of each curve represents the moisture fraction at the environment.

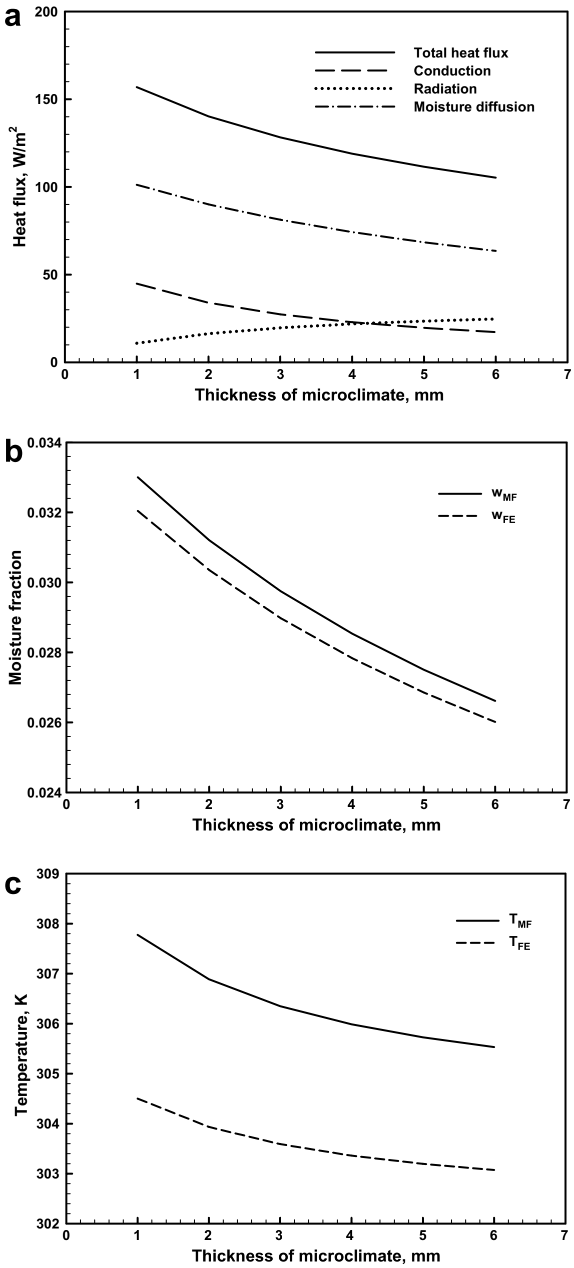

Fig. 7. The effect of microclimate thickness on: (a) the total heat flux and individual heat transfer mechanisms, (b) moisture fraction at the inner and outer fabric surfaces and (c) temperature at the inner and outer surfaces.

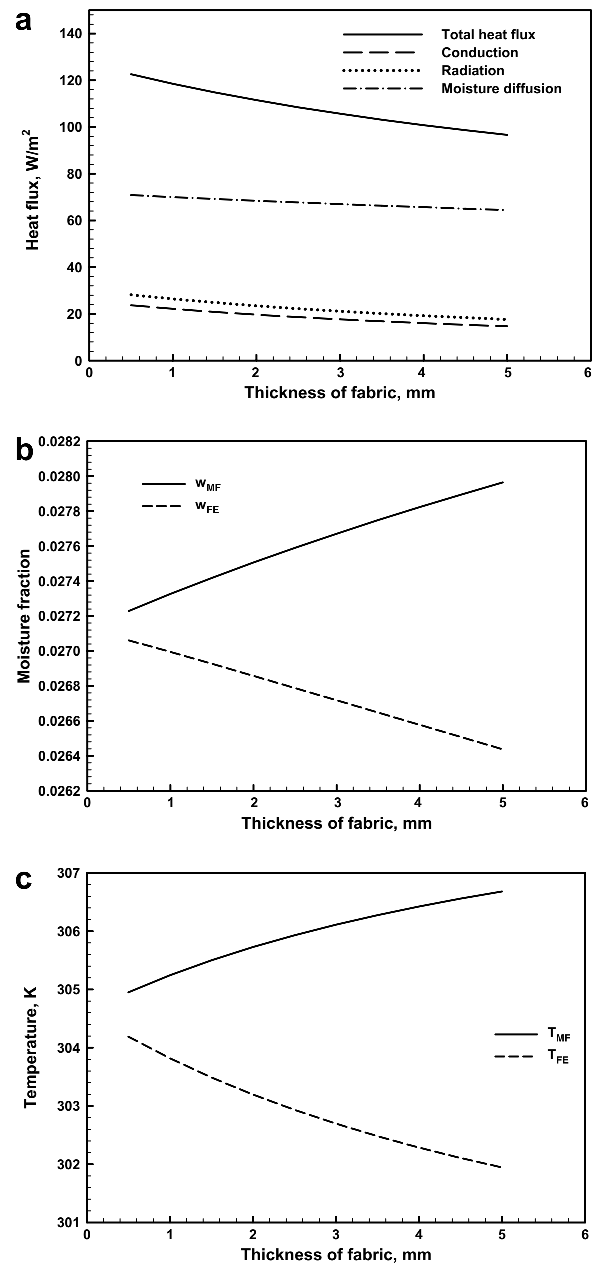

Fig. 8. The effect of fabric thickness on: (a) the total heat flux and individual heat transfer mechanisms, (b) moisture fraction at the inner and outer fabric surfaces and (c) temperature at the inner and outer surfaces.

3.4. Effect of fabric thickness

In Fig. 8, the effect of fabric thickness on total heat flux is shown. In the figure, the total heat flux varies about 20% when fabric thickness changes from 0.5 to 5 mm. The smaller variation compared to the variation in microclimate thickness comes from the fact that the thermal conductivity of fabric is larger than the air layer (microclimate), and hence, the result is less sensitive to fabric thickness than microclimate thickness. The effect of fabric thickness will be larger when the thickness of microclimate is smaller.

3.5. Vertical geometry

Let us consider a vertical geometry with a length L as shown in Fig. 9. When the fabric and the skin surface are vertically placed, the system behaves differently in many senses. In the case of vertical geometry, there is always a convective motion in the microclimate and the pattern of the convective motion is strongly dependent on Ra in the slot. Ra for the present problem on the vertical geometry is found to be less than 5000, and therefore, the motion is laminar and one-dimensional for the most part of the slot

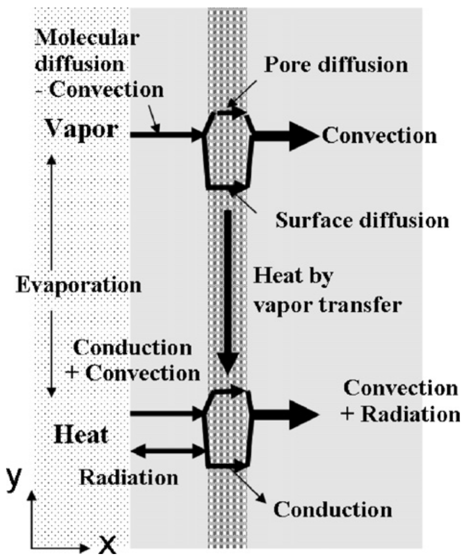

Fig. 9. Pathways of the heat and moisture transfer from skin to environment through fabric: vertical system. Radiation and surface diffusion are considered in addition to conduction and convection.

[20]. Two-dimensional flow can be seen only in the region of turn-around of flow at the top and the bottom of the geometry. To take into account for the convective motion we need to use the two-dimensional governing equations in two-dimensional geometry. In the microclimate, these are

$$\text{Continuity: } \nabla \cdot \mathbf{v} = 0, \tag{20}$$

$$\text{Motion: } \rho(T,w)(\mathbf{v}\cdot\nabla\mathbf{v}) = -\nabla p + \mu\nabla^2\mathbf{v} + \rho(T,w)\mathbf{g}, \tag{21}$$

$$\text{Energy: } \rho(T,w)\widehat{C}_P(\mathbf{v}\cdot\nabla(T-T_{\mathrm{MF}})) = -k_{\mathrm{MC}}\nabla^2 T + \rho_{\mathrm{vap}}(T)D_{\mathrm{vap}}\nabla^2 w\Delta H_{\mathrm{vap}}, \tag{22}$$

$$\text{Diffusion: } \rho(T,w)(\mathbf{v}\cdot\nabla w) = \rho_{\mathrm{vap}}(T)D_{\mathrm{vap}}\nabla^2 w. \tag{23}$$

Note here that we did not use the Boussinesque approximation in solving the natural convection problem. We rather formulate the problem by using a variable air density to use a commercial software package. The total heat and moisture fluxes in the microclimate are determined from the following relations as in the case of horizontal system:

$$\text{Heat flux: } q_{\mathrm{MC}} = -k_{\mathrm{MC}}\nabla T + \frac{\sigma(T_{\mathrm{S}}^4 - T_{\mathrm{MF}}^4)}{(1/e_{\mathrm{S}} + 1/e_{\mathrm{MF}} - 1)} + j_{\mathrm{MC}}\Delta H_{\mathrm{vap}}, \tag{24}$$

$$\text{Mass flux: } j_{\mathrm{MC}} = -\rho_{\mathrm{vap}}(T)D_{\mathrm{vap}}\nabla w. \tag{25}$$

Within the fabric, we also write the equations in two dimensions, since the flow and temperature distribution in the microclimate are two-dimensional, thus:

$$\text{Energy: } \nabla^2 T = 0, \tag{26}$$

$$\text{Diffusion: } \nabla^2 w = 0. \tag{27}$$

The heat and moisture fluxes in the fabric are written as follows:

$$\text{Heat flux: } q_{\mathrm{F}} = -k_{\mathrm{F,eff}}\nabla T + j_{\mathrm{F}}\Delta H_{\mathrm{vap}}, \tag{28}$$

$$\text{Mass flux: } j_{\mathrm{F}} = -\rho_{\mathrm{vap}}D_{\mathrm{F,eff}}\nabla w. \tag{29}$$

The boundary conditions for the momentum equation is the no-slip conditions, thus: $\mathbf{v} = 0$. The boundary condition for the energy and diffusion equations at the microclimate–fabric interface is that the fluxes are continuous, thus:

$$-k_{\mathrm{MC}}\nabla T + \frac{\sigma(T_{\mathrm{S}}^4 - T_{\mathrm{MF}}^4)}{(1/e_{\mathrm{S}} + 1/e_{\mathrm{MF}} - 1)} = -k_{\mathrm{F,eff}}\nabla T, \tag{30}$$

$$-\rho_{\mathrm{vap}}(T)D_{\mathrm{vap}}\nabla w = -\rho_{\mathrm{vap}}D_{\mathrm{F,eff}}\nabla w. \tag{31}$$

At the skin surface and in the environment the temperature and relative humidity are assumed to be constant as in the case of horizontal problem:

$$T_{\mathrm{S}} = \text{const}, \quad w_{\mathrm{S}} = \text{const},$$
$$T_{\mathrm{E}} = \text{const}, \quad w_{\mathrm{E}} = \text{const}.$$

The boundary conditions at the upper and lower ends are no flux conditions. Except at both ends of the channel, it is a one way diffusion problem across the gap and only the moisture moves through the boundary. The moisture movement will not change the velocity profile inside the microclimate significantly because the amount of moisture is less than 3 vol%. Therefore, the assumption that the air does not move across the microclimate–fabric boundary will be sufficiently close to the physics of the problem.

The heat and mass transfer coefficients between the fabric and the environment are also modified as follows:

$$\text{Heat flux: } q_{\mathrm{E}} = h(T_{\mathrm{FE}} - T_{\mathrm{E}}) + j_{\mathrm{E}}\Delta H_{\mathrm{vap}} + e_{\mathrm{F}}\sigma(T_{\mathrm{FE}}^4 - T_{\mathrm{E}}^4), \tag{32}$$

$$\text{Mass flux: } j_{\mathrm{E}} = K_{\mathrm{w}}(w_{\mathrm{FE}} - w_{\mathrm{E}}), \tag{33}$$

where heat and moisture transfer coefficients are determined from

$$h = 0.518\left[\frac{C_p k^3\rho^2 g\beta\Delta T}{\mu l} + \frac{C_p k^3\rho^2 g\zeta\Delta w}{\mu l}\right]^{1/4}, \tag{34}$$

$$K_{\mathrm{w}} = 0.518\left[\frac{D_{\mathrm{vap}}^3\rho^5 g\beta\Delta T}{\mu l} + \frac{D_{\mathrm{vap}}^3\rho^5 g\zeta\Delta w}{\mu l}\right]^{1/4} \tag{35}$$

by using the relationship on Nusselt and Grashof numbers as follows [21]:

$$Nu = 0.518[PrGr + PrGr_{\mathrm{w}}]^{1/4}, \tag{36}$$

$$Sh = 0.518[ScGr + ScGr_{\mathrm{w}}]^{1/4}. \tag{37}$$

The above system of equations was solved using a commercial software package (Fluent Version 6.2.16). The number of meshes was chosen to place 4 meshes per millimeter after checking the convergence and accuracy of the solution.

When the skin and fabric are placed vertically, there is always a natural convection in the microclimate. The flow pattern is strongly dependent on Rayleigh number, ranging from a laminar flow to a fully turbulent flow. When the reference condition was used Rayleigh number for the system was found to be 60. In this range of Rayleigh number there is no horizontal motion of air except the upper and lower ends and in most part of the flow channel the flow is unidirectional [20]. In Fig. 10, we have plotted the flow pattern in the microclimate region and confirm that the end effect is only limited to the region at both ends of the channel with an approximate length comparable to the width of the channel. Also when we vary the parameters as in the case of horizontal problems, the flow pattern remains the same. Therefore, in the following we will compare the simulation results for the vertical geometry with the result on the horizontal system.

Fig. 11 shows that both the total heat and moisture fluxes of vertical system are larger than that of horizontal system. This is because the heat transfer between the fabric surface and environment is larger for the long channel. (horizontal case: $h = 2.6\ \mathrm{W/(m^2\,K)}$; vertical case: $h = 5.9\ \mathrm{W/(m^2\,K)}$). The radiation is still an important factor. In Fig. 12, the fabric surface temperatures of the microclimate and environment sides (T_{MF} and T_{FE}) are lower by a fraction of a degree in the vertical system than in the horizontal system to accommodate the slightly higher heat flux. Here we plotted the temperature of the fabric surface at the middle of the channel. Since the lengthwise non-uniformity is as small as 0.01 K at the fabric surface except at the top and bottom of the channel, the mid-point temperature well represents the surface temperature of the fabric. The moisture level at the middle of the channel is lower by 10% approximately in vertical system as in the case of temperature. In the field of clothing research the differences in temperature and moisture fraction can be regarded meaningful because human sensation is sensitive enough to recognize the small difference.

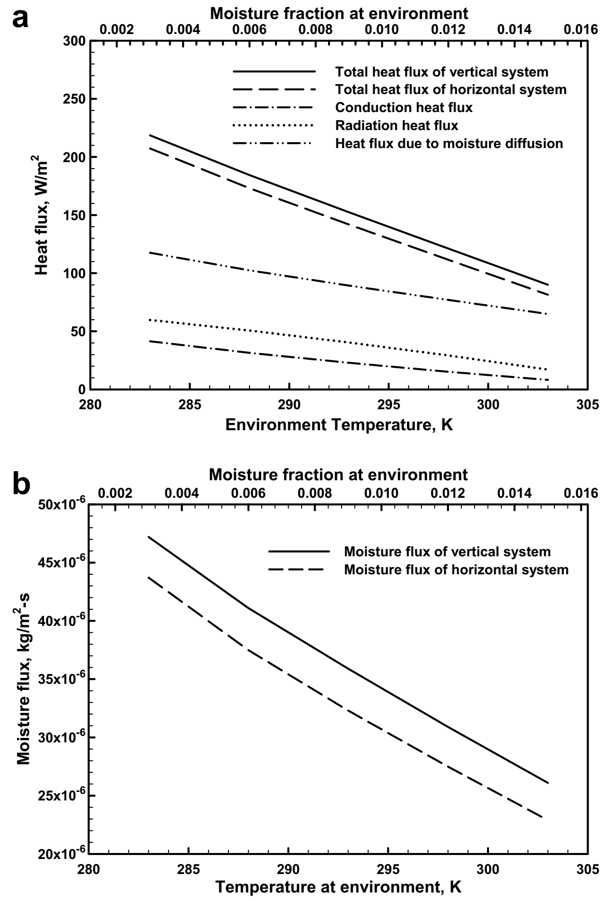

Fig. 11. Comparison of (a) heat and (b) moisture fluxes for the horizontal and vertical lay-outs when the environment temperature varies. The upper scale of each curve represents the moisture fraction at the environment. In (a) the individual heat flux for the vertical lay-out is also shown.

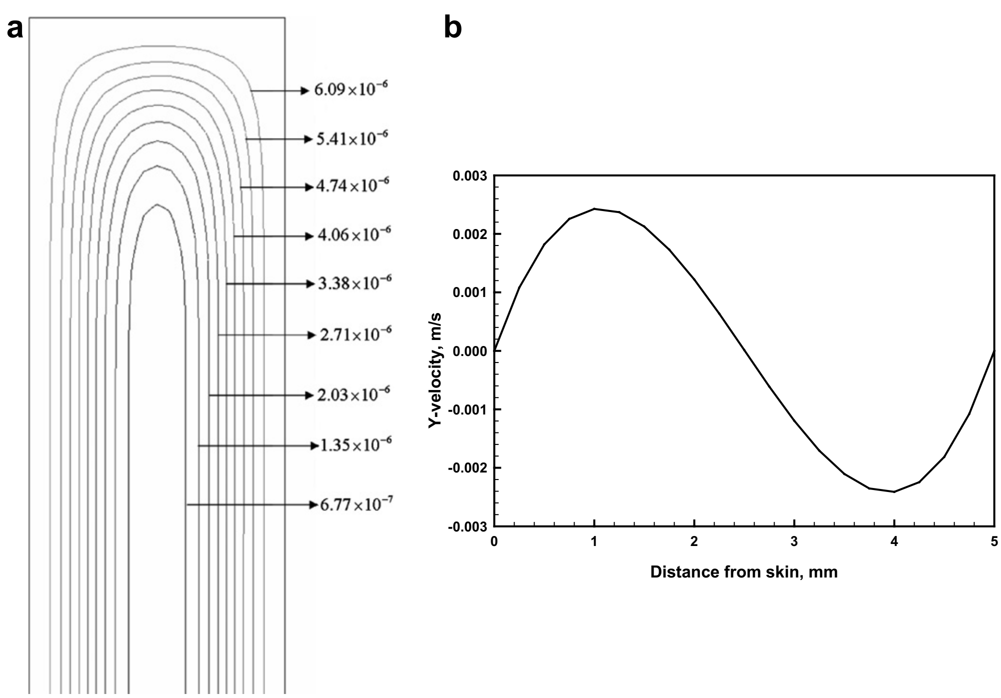

Fig. 10. (a) Streamlines at the upper part of the microclimate. The left side is the skin and the right side is the fabric. The unit of the streamlines is $\mathrm{m^2/s}$. (b) The y-component velocity profile at the middle of the microclimate.

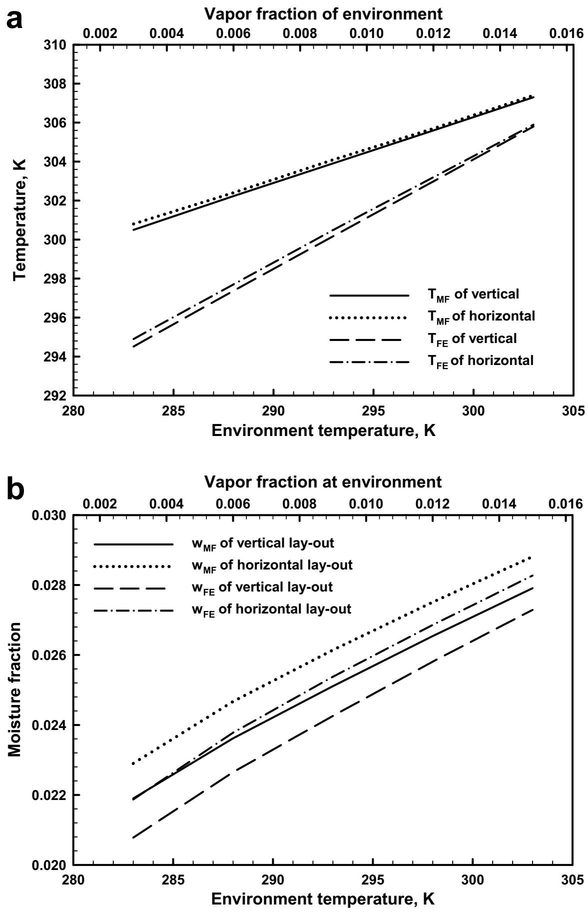

Fig. 12. Comparison of (a) temperature (T_{MF} and T_{MF}) and (b) moisture fractions (w_{MF} and w_{MF}) at the microclimate–fabric interface for the horizontal and vertical lay-outs when the environment temperature varies. The upper scale of each curve represents the moisture fraction at the environment.

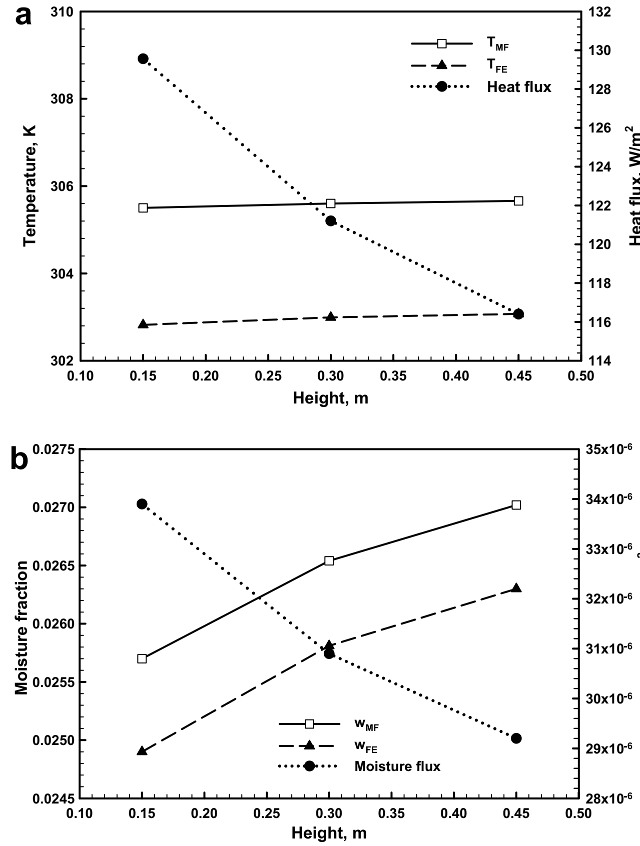

Fig. 13. The effect of the height of the microclimate in the vertical lay-out on: (a) heat flux and temperatures at the inner and outer boundaries and (b) moisture flux and moisture fractions at the inner and outer boundaries.

In the case of the vertical system, heat and moisture transfer coefficients are dependent on the length of the channel. In Fig. 13, we plotted the moisture fraction and temperature variation with height. As seen in the figure there are about 10% variations in moisture fraction and heat flux and 0.2 °C in fabric surface temperature when the length varies threefolds.

4. Discussion and conclusions

In the present study we have set up a mathematical model to simulate the heat and moisture transfer from skin to environment through a fabric. First we considered a horizontal lay-out in which there was no convective motion of air between skin and fabric (microclimate). We assumed constant temperature and moisture fraction at the skin surface and environment. For three kinds of fabrics (cotton, wool and PET), we first determined the heat and moisture transfer characteristics without including the surface diffusion term and found that we needed to include the surface diffusion to properly account for the difference among fabrics. Since we did not have the numerical values of surface diffusivity we performed simulations by keeping the surface diffusivity as a parameter and found that chemisorption was still not enough and physisorption would be required to account for the higher transfer rate through cotton. There is also the limit of large physisorption because the resistances of the microclimate and the boundary layer still exist. We found that the contributions of radiation and conduction through air were about 20% of the total heat flux. This value may be underestimated for non-severe conditions since the moisture fraction at the skin surface was assumed to be 95% of the saturation vapor pressure.

Next we considered a vertical system. In this case we needed to consider the convective motion inside the microclimate. The model calculations showed that the qualitative nature of heat and moisture transfer characteristics was the same. Quantitatively the total heat flux was 10% larger in the vertical system than in the horizontal system and the fabric surface temperature was 0.2 °C lower. Since the seemingly slight differences may play a significant role in the human comfort research, in the assessment of heat and moisture transfer through fabrics, the geometry effect should be properly taken into account for more accurate results.

In the heat and moisture transfer model from skin considered in the present study we fixed skin temperature and moisture fraction regardless of the environment conditions.

Therefore, the result obtained here may not explain the human sensation quantitatively during wearing a different kind of fabrics because, in real systems, skin temperature is not fixed and is dependent on the heat flux. Another factor which we need to consider in the heat and mass transfer from skin is the unsteadiness of the system. In real systems, temperature and moisture fraction of human skin and the environment change continuously. In this case the pseudo steady state assumption cannot be applied and most of all, depending upon the capability of holding heat and moisture by the fabric, the temperature and moisture fraction at the microclimate change appreciably. As usually recognized, cotton can hold more water than PET (2 g water/100 g PET vs. 8 g water/100 g cotton) due to the hydrophilic nature of cotton. The reason why we feel comfortable when wearing cotton fabric may not be solely due to higher transfer rate of heat and moisture resulted from the larger surface diffusion of moisture and should be explained by the interplay of larger transfer rate and larger capacity for holding moisture. At any rate, in a more realistic model we need to include the skin and the physiological characteristics of human body in the model. Li and Holcombe [16] considered a mathematical model to describe the dynamic heat and moisture transport behavior of clothing and its interaction with the human thermoregulation system under transient wear conditions. We may extend our model to a more practical one using their idea. But this kind of research is out of scope of the present journal and should be considered elsewhere.

Recently, textiles coated with nanoporous materials have been considered to be useful in multifunctional clothing [29]. The nanoporous structure is known to change the hydrophilic nature of the fabric and even has anti-microbacterial activity. In such porous materials with high surface area, surface diffusion plays an important role. If they are coated in a small amount, the effect will be small. If they are too much coated, we do not expect a proportionally large increase in transport rates due to saturation. The result of present research can be a useful guideline in determining the range surface diffusivity of fabrics (hence the amount of nanoporous material) coated with nanoporous materials, for example.

In the field of clothing science, it has been a question of longtime standing to understand the detailed mechanism of heat and vapor transports through fabrics. We believe that this research shed a light on understanding the mechanism. Especially we first report here the role of radiation and surface diffusion. We hope that this research can induce experimental studies on measuring the surface diffusivity to measuring the heat and moisture fluxes through various kinds of fabrics.

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References

[1] B. Farnworth, P.A. Dolhan, Heat and water transport through cotton and polypropylene under wear, J. Text. Inst. 55 (1985) 627–630.
[2] E.A. McCullough, M. Kwon, H. Shim, A comparison of standard methods for measuring water vapour permeability of fabrics, Meas. Sci. Technol. 14 (2003) 1402–1408.
[3] J.T. Fan, X.Y. Cheng, Heat and moisture transfer with sorption and phase change through clothing assemblies. Part I: Experimental investigation, Text. Res. J. 75 (2005) 99–105.
[4] C. Prahsarn, R.L. Barker, B.S. Gupta, Moisture vapor transport behavior of polyester knit fabrics, Text. Res. J. 75 (2005) 346–351.
[5] H.O. Nilsson, I. Holmer, Comfort climate evaluation with thermal manikin methods and computer simulation models, Indoor Air 13 (2003) 28–37.
[6] D. Quintela, A. Gaspar, C. Borges, Analysis of sensible heat exchanges from a thermal manikin, Eur. J. Physiol. 92 (2004) 663–668.
[7] M.B. Ducharme, P. Tikuisis, P. Potter, Selection of military survival gears using thermal manikin and computer survival model data, Eur. J. Physiol. 92 (2004) 658–662.
[8] M.G.M. Richards, D. Fiala, Modelling fire-fighter responses to exercise and asymmetric infrared radiation using a dynamic multi-mode model of human physiology and results from the sweating agile thermal manikin, Eur. J. Physiol. 92 (2004) 649–653.
[9] T. Fukazawa, G. Lee, T. Matsuoka, et al., Heat and water vapour transfer of protective clothing systems in a cold environment, measured with a newly developed sweating thermal manikin, Eur. J. Physiol. 92 (2004) 645–648.
[10] I. Holmer, Thermal manikin history and applications, Eur. J. Physiol. 92 (2004) 614–618.
[11] C.V. Le, N.G. Ly, R. Postle, Heat and mass transfer in the condensing flow of stream through an absorbing fibrous medium, Int. J. Heat Mass Transfer 38 (1995) 81–89.
[12] P.W. Gibson, M. Charmchi, Modeling convection/diffusion processes in porous textiles with inclusion of humidity-dependent air permeability, Int. Commun. Heat Mass Transfer 24 (5) (1997) 709–724.
[13] M.P. Sobera, C.R. Kleijn, H.E.A. Van den Akker, convective heat and mass transfer to a cylinder sheathed by a porous layer, AIChE J. 49 (2003), 3018-3-28.
[14] K. Ghali, N. Ghaddar, B. Jones, Modeling of heat and moisture transport by periodic ventilation of thin cotton fibrous media, Int. J. Heat Mass Transfer 45 (2002) 3703–3714.
[15] K. Hong, N.R.S. Hollies, S.M. Spivak, Dynamic moisture vapor transfer through textiles, Text. Res. J. 58 (1988) 697–706.
[16] Y. Li, B.V. Holcombe, Mathematical simulation of heat and moisture transfer in a human–clothing–environment system, Text. Res. J. 68 (6) (1998) 389–397.
[17] J. Fan, Z. Luo, Y. Li, Heat and moisture transfer with sorption and condensation in porous clothing assemblies and numerical simulation, Int. J. Heat Mass Transfer 43 (2000) 2989–3000.
[18] W.A. Lotens, Heat transfer from humans wearing clothing, Doctor Dissertation, Delft, The Netherlands, Technische Universiteit Delft, 1993.
[19] T.K. Sherwood, R.L. Pigford, C.R. Wilke, Mass Transfer, McGraw Hill, New York, 1975, pp. 39–43.
[20] J.S. Turner, Buoyancy Effects in Fluids, Cambridge University Press, Cambridge, 1973, pp. 207–246.
[21] R.B. Bird, W.E. Stewart, E.N. Lightfoot, Transport Phenomena, second ed., John Wiley & Sons, Inc., Hoboken, N.J, 2002, pp. 698–699.
[22] G. Desrayaud, G. Lauriat, Heat and mass transfer analogy for condensation of humid air in a vertical channel, Heat Mass Transfer 37 (2001) 67–76.
[23] M.K. El-Riedy, Analogy between heat and mass transfer by natural convection from air to horizontal tubes, Int. J. Heat Mass Transfer 24 (1981) 365–369.

[24] J. Sheridan, A. Williams, D.J. Close, An experimental study of natural convection with coupled heat and mass transfer in porous media, Int. J. Heat Mass Transfer 35 (1992) 2131–2143.
[25] K.K. Tan, Predicting Marangoni convection caused by transient gas diffusion in liquids, Int. J. Heat Mass Transfer 48 (2004) 135–144.
[26] D.S. Schrage, A simplified model of dendritic growth in the presence of natural convection, J. Cryst. Growth 205 (1999) 41–426.
[27] J.M. Layton, The science of clothing comfort, Textile Progress, vol. 31, No. 1/2, The Textile Inst., Oxford, 2001.
[28] H. Komiyama, J.M. Smith, Interparticle mass transport in liquid filled pores, AIChE J. 20 (1974) 728–734.
[29] D. Hegemann, M. Hossain, D.J. Balazs, Nanostructured plasma coatings to obtain multifunctional textile surfaces, Prog. Org. Coat. 58 (2007) 237–240.