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Study of heat and moisture transfer within multi-layer clothing assemblies consisting of different types of battings

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Abstract

A theoretical model of simultaneous heat and moisture transfer is presented and applied to consider the moisture accumulation and thermal insulation performance of multi-layer clothing assemblies consisting of different types of fibrous battings. Concerning the boundaries with dramatic change in the multiple ply battings, the numerical model was solved using finite volume method. The computational results were first compared with the experimental measurements and then applied to evaluate whether and how the positions of different types of battings affect on the moisture accumulation and thermal insulation performance of the clothing assemblies. It was found that placing the hygroscopic wool batting in the inner region (i.e. closer to the body) and the non-hygroscopic polyester batting in the outer region (i.e. away from the body) could reduce the moisture accumulation within and the total heat loss through clothing assemblies. This provides potential to improve the performance of the clothing by optimizing the positions of the battings for the clothing having the same materials.

Keywords: Thermal comfort; Heat and moisture transfer; Condensation; Sorption; Clothing assembly; Multi-layer

1. Introduction

The moisture accumulation (i.e. absorption or condensation) within clothing is a serious problem for sportswear and clothing worn in cold climate [1–5]. As the wearer stops the exercise and his metabolic heat production reduces, the reduction of clothing thermal insulation due to condensates within clothing and the heat absorption by the moisture de-sorption re-evaporation of the condensates will cause "chilling" discomfort or even hypothermia. It is therefore important to optimize the construction of clothing assemblies so as to maximize the moisture transmission through clothing and minimize the moisture absorption and condensation within clothing.

In order to optimize the construction of clothing assemblies, it is essential to understand the heat and moisture transfer through fibrous materials. Coupled heat and moisture transfer through textile fabrics was first modeled by Henry [6], who considered the coupling effects of sorption/desorption in fabric textiles. Condensation/evaporation in textile fabrics was first considered by Ogniewicz and Tien [7], who developed a quasi-steady state model assuming condensate was in pendular state. Modeling in textile fabrics was further developed by considering the movement of condensates [8] and sorption transfer function [9], the effect of gravity [10,11], the frosting effect [12], the hygroscopic effect [13–15] as well as the variable permeability effect of the porous medium [16–18].

Recently, based on extensive theoretical modeling and experimental investigation, Fan et al. [4,19–24] established an integrated transient model of heat and moisture transfer through textile fabrics, which for the first time took into account of radiative heat transfer, condensations/evaporation, movement of liquid condensate, and the moisture bulk flow induced by the vapor pressure gradients. Very good agreements were found between the experimental results [25–27] and the numerical ones.

In the previous studies, the analysis of heat and moisture transfer was focused on a single type of fibrous batting sandwiched by an inner layer and an outer layer of covering fabric. In the present study, we consider whether and how the combi-

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Nomenclature

A	surface area of fiber covered by condensate	m^2
C_a	water vapor concentration in inter-fiber void space	$kg\,m^{-3}$
C_f	mean water vapor concentration in fiber	$kg\,m^{-3}$
C_v	effective volumetric heat capacity of fibrous batting	$kJ\,m^{-3}\,K^{-1}$
C_{va}	volumetric heat capacity of dry air	$kJ\,m^{-3}\,K^{-1}$
C_{vf}	effective volumetric heat capacity of fiber	$kJ\,m^{-3}\,K^{-1}$
C_{vw}	volumetric heat capacity of water	$kJ\,m^{-3}\,K^{-1}$
D_a	diffusion coefficient of water vapor in air	$m^2\,s^{-1}$
d_f	diffusion coefficient of moisture in fiber	$m^2\,s^{-1}$
d_l	dispersion coefficient of free water in fibrous batting	$m^2\,s^{-1}$
E	condensation or evaporation coefficient, dimensionless	
F_L	total thermal radiation incident traveling to the left	W
F_R	total thermal radiation incident traveling to the right	W
h_c	convective mass transfer coefficient	$m\,s^{-1}$
h_t	convective thermal transfer coefficient	$W\,m^{-2}\,K^{-1}$
k	effective thermal conductivity of fibrous batting	$W\,m^{-1}\,K^{-1}$
k_D	permeability of porous batting	m^2
k_{D0}	initial permeability of porous batting	m^2
k_{Dr}	relative permeability of porous batting	
L	thickness of sing layer batting	m
L_0	thickness of inner or outer covering fabrics	m
M	molecular weight of evaporating substance, $M = 18.0152$ for water	$g\,mol^{-1}$
p	pressure of water vapor in inter-fiber void	Pa
p_{sat}	saturated water vapor pressure at temperature T_s	Pa
p_v	vapor pressure in vapor region at T_v	Pa
R	the universal gas constant, $R = 8.31$	$J\,K^{-1}\,mol^{-1}$
R_{ti}	resistance to heat transfer of inner or outer covering fabric (i.e. $i = 0$: inner fabric, $i = 1$: outer fabric)	$K\,m^{-2}\,W^{-1}$
R_{di}	diffusion resistance to water vapor (i.e. $i = 0$: inner fabric, $i = 1$: outer fabric)	$s\,m^{-1}$
RH	relative humidity	
t	time	s
T	temperature	K
T_i	temperature of the boundaries (i.e. $i = 0$: surface next to human body, $i = 1$: surrounding air)	K
T_s	temperature at the interface of condensates and vapor	K
T_v	temperature in the vapor region	K
u	velocity of water vapor	$m\,s^{-1}$
W	total water content of the fibrous batting, which is defined as the weight of water divided by the weight of the dry fibrous batting	%
W_f	content of free water in batting	
$\tilde{W}$	content of water absorbed in fiber	
x	distance from the inner covering fabric (the warm side)	m

Greek symbols

β	radiative sorption constant of the fibers	m^{-1}
ε	porosity of fibrous batting considering condensates (liquid water, or ices) in the batting	
ε_0	porosity of the dry fibrous batting without condensates	
λ	latent heat of (de)sorption of fibers or condensation of water vapor	$kJ\,kg^{-1}$
μ	dynamic viscosity of water vapor	$kg\,m^{-1}\,s^{-1}$
μ_0	initial dynamic viscosity of water vapor at T_0	$kg\,m^{-1}\,s^{-1}$
ρ	density of the fibers	$kg\,m^{-3}$
ρ_w	density of liquid water or ice	$kg\,m^{-3}$
σ	Boltzmann constant, $\sigma = 5.6705 \times 10^{-8}$	$W\,K^{-4}\,m^{-2}$
τ	effective tortuosity of the fibrous batting	
Γ	total rate of (de)sorption, condensation, freezing and/or evaporation	$kg\,s^{-1}\,m^{-3}$
Γ_{ce}	rate of condensation, freezing and/or evaporation	$kg\,s^{-1}\,m^{-3}$
Γ_S	rate of (de)sorption	$kg\,s^{-1}\,m^{-3}$

nation of different types of fibrous battings affect the heat and moisture transfer through the clothing assemblies. In this work, the previously presented model [19–24] is further developed and solved in consideration of the effects of changes of permeability, viscosity, boundary conditions in the combinations of different types of battings on the performance of clothing assemblies. The computational results will be compared with experimental results produced using the method of Fan et al. [4,27]. The computational and experimental investigations will be applied to evaluate whether and how the positions of different types of battings affect the moisture accumulation and thermal insulation performance of the clothing assemblies.

2. Theoretical analysis

A clothing assembly as illustrated in Fig. 1 consisting of an inner lining fabric, a layer of inner fibrous batting, a layer of outer fibrous batting and an outer lining fabric was considered in a cold climate in the paper. On the assumptions that each fibrous material is isotropic; there is no change of volumes; there is only sublimation or ablimation in the frozen region; local thermal equilibrium exists among all phases and the moisture content at the fibre surface is in sorptive equilibrium with that of the surrounding air, we can have the following governing equations.

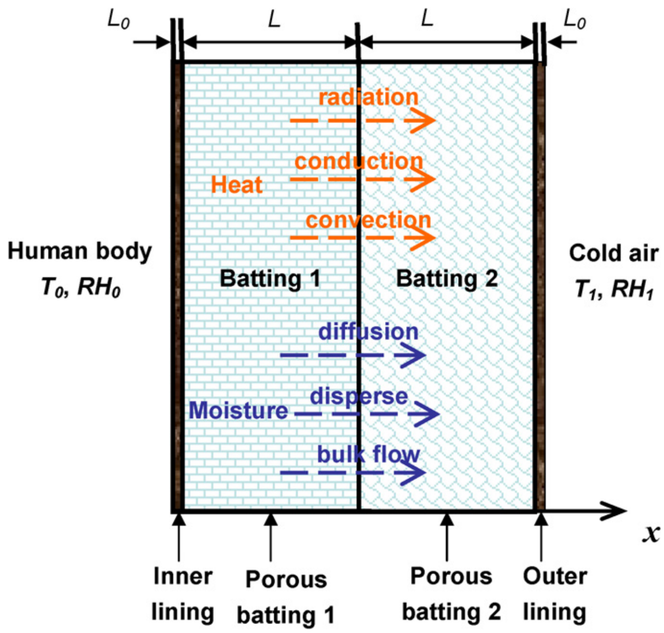

Fig. 1. Schematic diagram of the clothing assembly system.

2.1. Mass conservation equations

For the water vapor in the void space of the fibrous battings, we have:

$$\varepsilon\frac{\partial C_a}{\partial t}=-\varepsilon u\frac{\partial C_a}{\partial x}+\frac{D_a\varepsilon}{\tau}\frac{\partial^2 C_a}{\partial x^2}-\Gamma(x,t) \tag{1}$$

where, $\Gamma(x,t)$ is the source term of water vapor including the moisture accumulation due to absorption or desorption by fibers (Γ_S) and the water condensation or evaporation (Γ_{ce}):

$$\Gamma(x,t)=\Gamma_S(x,t)+\Gamma_{ce}(x,t) \tag{2}$$

The water vapor due to the adsorption or desorption in the fibers may be calculated according to the following equation:

$$\Gamma_S(x,t)=\rho(1-\varepsilon)\frac{\partial C_f(x,t)}{\partial t} \tag{3}$$

The water vapor due to condensation or evaporation can be modeled using the Hertz–Knudsen equation on the assumption that the fibers are assumed to be in an ideal cylinder shape [28]. The condensation or evaporation rate covered with condensates (liquid water or ice) can be calculated by:

$$\Gamma_{ce}(x,t)=-AE\sqrt{M/2\pi R}\left(P_{\mathrm{sat}}/\sqrt{T_s}-P_v/\sqrt{T_v}\right) \tag{4}$$

For the free water among the fabrics, the mass conservation equation can be expressed as:

$$\rho(1-\varepsilon)\frac{\partial\tilde{W}}{\partial t}=\rho(1-\varepsilon)d_l\frac{\partial^2\tilde{W}}{\partial x^2}+\Gamma_{ce}(x,t) \tag{5}$$

$$\tilde{W}=W(x,t)-W_f(x,t) \tag{6}$$

where, W is the total water content of the fibrous batting. W_f and $\tilde{W}$ are the content of free water in the battings and the content of absorbed in the fiber, respectively.

$$W_f=\frac{C_f}{\rho} \tag{7}$$

$$W(x,t)=\frac{1}{\rho(1-\varepsilon')}\int_0^t\Gamma(x,t)\,\mathrm{d}t \tag{8}$$

2.2. Energy conservation equation

For heat transfer through the fibrous battings, we have:

$$C_v(x,t)\frac{\partial T}{\partial t}=-\varepsilon uC_{va}(x,t)\frac{\partial T}{\partial x}+\frac{\partial}{\partial x}\left(k(x,t)\frac{\partial T}{\partial x}\right)-\frac{\partial F_R}{\partial x}+\frac{\partial F_L}{\partial x}+\lambda(x,t)\Gamma(x,t) \tag{9}$$

where

$$\frac{\partial F_L}{\partial x}=\beta(x)F_L-\beta(x)\sigma T^4(x,t) \tag{10}$$

$$\frac{\partial F_R}{\partial x}=-\beta(x)F_R+\beta(x)\sigma T^4(x,t) \tag{11}$$

where, $k(x,t)$ is the effective thermal conductivity of the fabric, which can be calculated by $k(x,t)=\varepsilon k_a+(1-\varepsilon)(k_f+\rho Wk_w)$. Similarly, the effective volumetric heat capacity and the porosity of the fabric are calculated by $C_v=\varepsilon C_{va}+(1-\varepsilon)(C_{vf}+\rho WC_{vw})$, and $\varepsilon=\varepsilon_0-(\rho/\rho_w)W(1-\varepsilon_0)$, respectively.

2.3. Generalized Darcy's law

The moisture bulk flow within the fibrous insulations can be expressed using the Darcy's law,

$$u=-\frac{k_D}{\mu}\frac{\partial p_v}{\partial x} \tag{12}$$

where $\partial p_v/\partial x$ is the pressure gradient in the flow direction and μ is the dynamic viscosity of the water vapor.

$$\mu=\mu_0\left(\frac{T_0}{T}\right)^{1.25} \tag{13}$$

where, T_0 is the initial temperature, and μ_0 is the initial dynamic viscosity of the water vapor at T_0. k_D is the permeability of the fibrous batting, which is calculated from the initial permeability k_{D0} and the relative permeability k_{Dr},

$$k_D=k_{D0}\cdot k_{Dr} \tag{14}$$

The relative permeability varies with the change of porosity and may be calculated according to Carman–Kozeny model [29]:

$$k_{Dr}=\frac{(\frac{\varepsilon}{\varepsilon_0})^3}{(\frac{1-\varepsilon}{1-\varepsilon_0})^2} \tag{15}$$

2.4. Thermodynamic relations

The partial pressure of the water vapor is equal to its equilibrium pressure

$$p_v=p_{v\,\mathrm{eq}}(T,RH) \tag{16}$$

The gaseous mixture (including water vapor and air) is supposed to be an ideal mixture of perfect gases:

$$p_i = \rho_i RT/M_i; \quad i = a, v \tag{17}$$

2.5. Boundary and initial conditions

Since, on the inner face ($x = 0$) and the outer face ($x = 2L_0 + 2L$) of the clothing assemblies, the heat fluxes are continuous, we have:

$$k(0,t)\frac{\partial T}{\partial x}\bigg|_{x=0} = \frac{1}{R_{t0}}(T|_{x=0} - T_0) \tag{18}$$

$$k(L,t)\frac{\partial T}{\partial x}\bigg|_{x=2L_0+2L} = \frac{T_1 - T|_{x=2L_0+2L}}{R_{t1} + (1/h_t)} \tag{19}$$

Similarly, the boundary conditions for the moisture transfer on the inner and outer faces of the battings can be expressed as:

$$\frac{D_a\varepsilon}{\tau}\frac{\partial C_a}{\partial x}\bigg|_{x=0} = \frac{C_a|_{x=0} - C_{a_0}}{R_{d0}} \tag{20}$$

$$\frac{D_a\varepsilon}{\tau}\frac{\partial C_a}{\partial x}\bigg|_{x=2L_0+2L} = \frac{C_{a_1} - C_a|_{x=2L_0+2L}}{R_{d1} + (1/h_c)} \tag{21}$$

For the radiative heat transfer on the inner and outer faces, the boundary conditions can be expressed as

$$(1-\zeta_1)F_L|_{x=0} + \zeta_1\sigma T^4\big|_{x=0} = F_R|_{x=0} \tag{22}$$

$$(1-\zeta_2)F_L|_{x=2L_0+2L} + \zeta_2\sigma T^4\big|_{x=2L_0+2L} = F_R|_{x=2L_0+2L} \tag{23}$$

Initially, the clothing assembles are transferred from the normal room environment. Therefore, the initial conditions are

$$T|_{t=0} = 25; \qquad RH|_{t=0} = 65\% \tag{24}$$

2.6. Numerical solution with finite volume scheme

The governing equations and described boundary conditions are discretized and solved using the FVM [23,30,31]. Using the FVM as shown in Fig. 2, the vector quantities (i.e. moisture bulk flow velocity, heat resistance, vapor resistance and Darcy flow resistance) are calculated on the boundaries of the elements, while the scalar quantities (i.e. temperature, moisture pressure, vapor concentration and free water content) are placed on the centers of the elements. Compared to the finite difference method (FDM) in previous studies [19–22,24], FVM is helpful in better dealing with the boundary of dramatic change especially in the fibrous combinations of multiple types of fibrous battings. Therefore, the treatment using FVM is advantageous to a more accurate physical representation of the heat and liquid moisture transfer.

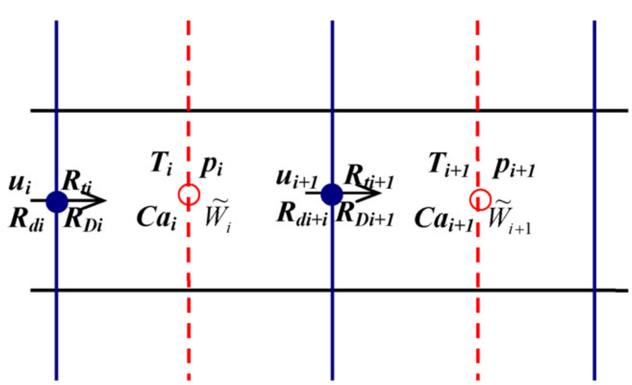

Fig. 2. Schematic of grid partition and quantities placement using FVM.

Table 1
Parameters used in the numerical calculation

ρ_w	k_w	C_{vw}	ρ_a	k_a	C_{va}	D_a
990	0.57	4200	1.205	0.026	1013	2.5×10^{-5}
ξ_1	ξ_2	σ	λ(dry)	λ(wet)	τ(freezing)	τ
0.9	0.9	5.672×10^{-8}	2522.0	2260.0	2593.0	1.2

In the calculation, we assume the temperature and relative humidity at the inner side were preset at 35 °C and 96%, respectively, simulating the sweating condition of human body. The temperature and the relative humidity in environment were preset at −20 °C and 95%, respectively, simulating a cold subzero condition. The parameters used in the numerical calculation are listed in Table 1.

3. Experimental investigation

The sweating guarded hot plate previously developed by Fan et al. [4,27] on the basis of ISO/EN31092 was used to test two types of clothing assemblies: (1) Goretex inner fabric + multiple ply wool battings + multiple ply polyester battings + Goretex outer fabric and (2) Goretex inner fabric + multiple ply polyester battings + multiple ply wool battings + Goretex outer fabric. The samples were first placed in the air-conditioned room with the temperature of 25 ± 1 °C and RH of $65 \pm 5\%$ for at least 24 h before being placed onto the sweating hot plate, which is placed in a cold chamber of -20 ± 1 °C. The temperatures between the plies were recorded by RTD sensors.

Each fabric ply was weighed before and after a pre-determined time period (e.g., 8 hours and 24 hours) to determine the water accumulated in the clothing assemblies. The mass of water accumulated in the ith ply batting ($m_{w,i}$) can be calculated with the following equation:

$$m_{w,i} = m_{i,t} - m_{i,0} \tag{25}$$

where, $m_{i,t}$ and $m_{i,0}$ are the weights of the ith batting at time t and at the start, respectively.

As the present investigation is aimed at examining whether alternating the positions of multiple ply wool battings and multiple ply polyester battings has any effects, the multiple ply wool battings and multiple ply polyester battings were made to have the same thickness of 1.5 cm and almost the same initial mass. The multiple ply wool batting consisted of two plies of batting, and the multiple ply polyester batting consisted of three plies of battings. The properties of the multiple ply wool and polyester battings are listed in Table 2, and those of the cover Goretex fabric are listed in Table 3. In order to compare with the clothing assemblies consisting of different types of battings, the combinations consisting of a single type of batting (i.e. all-wool

Table 2
Properties of fibrous battings

Composition	Multiple ply wool battings	Multiple ply Polyester battings
	Made of two single plies	Made of three single plies
Thickness (cm)	1.50	1.50
Mass ($kg\,m^{-2}$)	0.145	0.153
Fibre density ($kg\,m^{-3}$)	1310	1390
Volumetric heat capacity ($kJ\,m^{-3}\,K^{-1}$)	1600	1300
Diffusion coefficient of moisture ($m^2\,s^{-1}$)	6.0×10^{-13}	6.0×10^{-13}
Disperse coefficient of free water ($m^2\,s^{-1}$)	5.4×10^{-11}	1.35×10^{-13}

Table 3
Properties of the inner and outer Goretex cover fabric

Composition	Three layer laminated fabric
Construction	Woven + membrane + warp knit
Mass ($kg\,m^{-2}$)	0.22
Thickness (m)	5.15×10^{-4}
Thermal resistance ($m^2\,K\,W^{-1}$)	0.0316
Water vapor resistance ($m^2\,Pa\,W^{-1}$)	8.6
Resistance to air penetration	Impermeable
Coefficient of Darcy's law ($m^2\,Pa^{-1}\,s^{-1}$)	5.21×10^{-11}

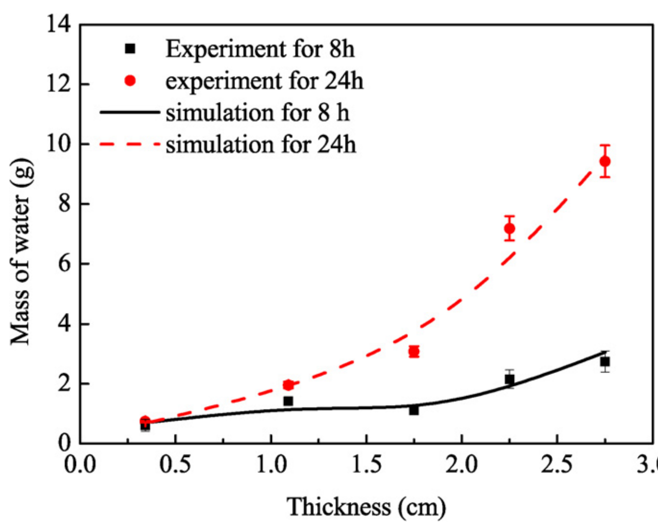

Fig. 3. Distribution of mass of water in Goretex + wool + polyester + Goretex.

and all-polyester) were also tested in the experiments. Three repeated measures were carried out at each combination for the error analysis of the experimental tests.

4. Results and discussion

Fig. 3 presents the comparison of the mass of water accumulated in the clothing assembly consisting of Goretex + wool + polyester + Goretex between the numerically calculated and experimentally measured results at 8 h and 24 h. Accordingly, Fig. 4 shows the comparison of the mass of water accumulated in the Goretex + polyester + wool + Goretex assembly between the numerical and experimental results. The error bars in Figs. 3 and 4 are the standard deviations of the three repeated measures. From Figs. 3 and 4, it could also be observed that

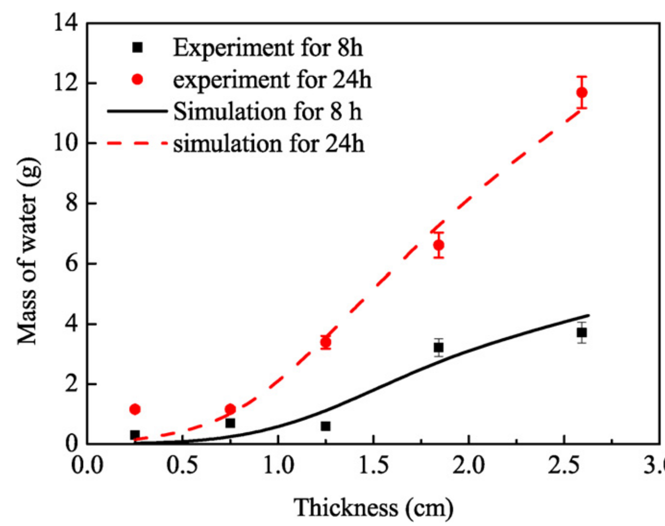

Fig. 4. Distribution of mass of water in Goretex + polyester + wool + Goretex.

numerical calculations agree well with the experimental measurements for both the clothing assemblies.

As a comparison of the mass of water between the two clothing assemblies shown in Figs. 3 and 4, there was less water in the inner region but faster increase in the middle region when the polyester battings were placed in the inner region and the wool battings are placed in the outer region. It is understandable as the polyester battings absorb little moisture, but wool battings are highly hygroscopic.

The comparison of the water accumulated in the two clothing assemblies (i.e. Goretex + wool + polyester + Goretex and Goretex + polyester + wool + Goretex) between the computational and experimental results is shown in Fig. 5. It can be observed that the computational results are slightly smaller than but very close (the differences below than 3%) to the experimental results for the two clothing assemblies consisting of different battings. Fig. 5 also presents the experimental results of the water amount accumulated in the clothing assemblies consisting of a single type of batting (i.e. Goretex + all-wool + Goretex and Goretex + all-polyester + Goretex). As can be observed from the comparison of the amounts of water accumulated within the above four combinations in Fig. 5, placing wool battings in the inner regions and polyester in the outer regions resulted the lowest moisture accumulation after 24 hours of testing. Therefore, the combination of wool (in the inner region) + polyester (in the outer region) could reduce the water accumulation noticeably compared to the clothing assemblies consisting

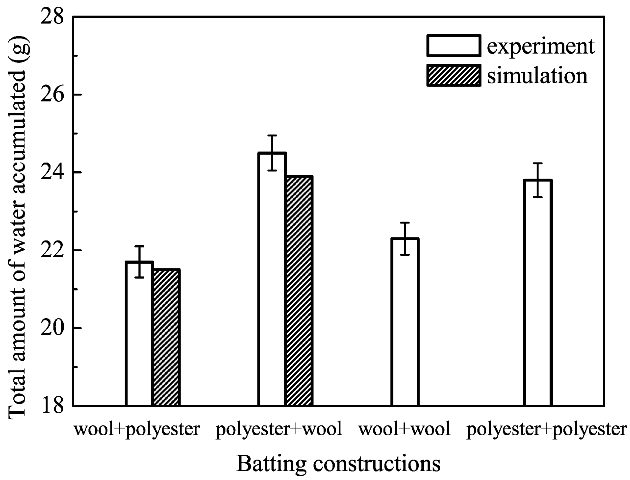

Fig. 5. Comparison of total amount of water accumulation after 24 h.

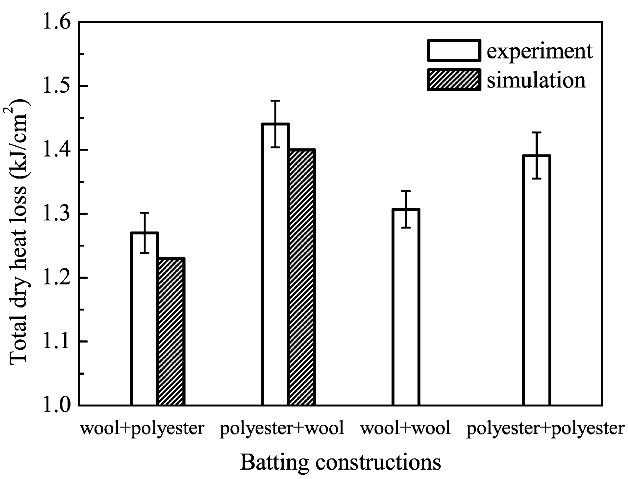

Fig. 6. Comparison of total dry heat loss during 24 h.

of a single type of batting as well as the combination of polyester + wool. For example, the amount of water accumulated in the combination Goretex + wool + polyester + Goretex was approximately 7% less than that in Goretex + polyester + wool + Goretex. Since the wool and polyester battings were fully saturated in both the clothing assemblies, the difference in the total water accumulation must be caused by the reduced condensation within the clothing assembly having wool battings in the inner region. The difference in condensation affected the dry heat loss through the clothing assemblies. As can be observed from Fig. 6, the total dry heat loss through the clothing assembly consisting of Goretex + wool + polyester + Goretex is about 10% less than that through the clothing assembly consisting of Goretex + polyester + wool + Goretex. In Fig. 6, the amount of heat loss is the total heat loss through the clothing assemblies from the start to the 24 h, which is an integral of the dry heat flux versus time from 0 to 24 h. Fig. 6 also presents the experimental results of the total dry heat through the clothing assemblies consisting of a single type of batting from 0 to 24 h. It can be observed that the combination Goretex + wool + polyester + Goretex has noticeably lowest amount of total dry heat than the other three combinations.

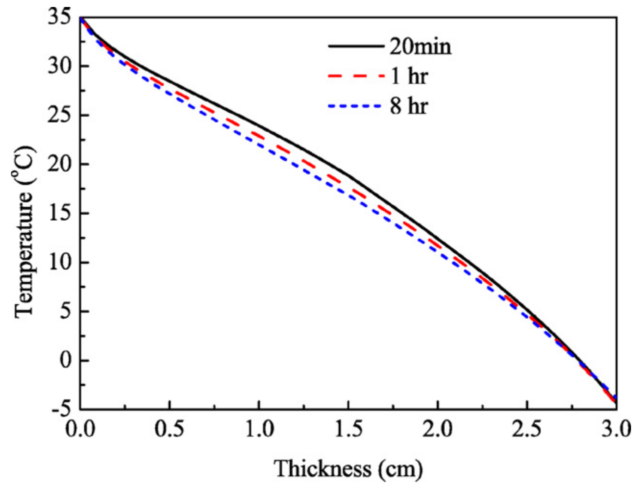

Fig. 7. Temperature distribution of Goretex + wool + polyester + Goretex.

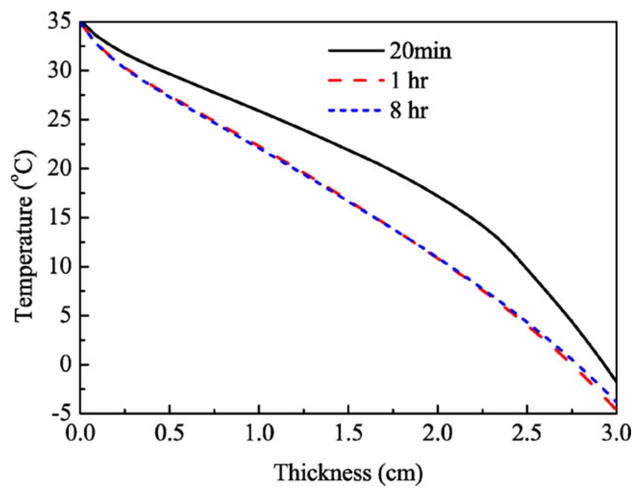

Fig. 8. Temperature distribution of Goretex + polyester + wool + Goretex.

The differences in the water accumulation due to the alternating position of wool and polyester battings may affect the changes in temperature distributions within the clothing assemblies. Figs. 7 and 8 plot the numerical results of the changes of temperatures for the two types of clothing assemblies, Goretex + wool + polyester + Goretex and Goretex + polyester + wool + Goretex, respectively. As can be observed, the clothing assembly having the wool battings in the inner region and polyester battings in the outer region approached a steady temperature distribution at a slower pace than that having the wool battings in the outer region. It is because the wool battings release heat when absorbing moisture. Fig. 9 showed the computational results of the water vapour concentrations within the two clothing assemblies. It can be observed that the water vapour concentration in the clothing assembly having wool battings in the inner region is lower, which is a further explanation for the reduced condensation.

5. Conclusions

Both theoretical analysis and experimental measurements were carried out to examine the effects of the positions of dif-

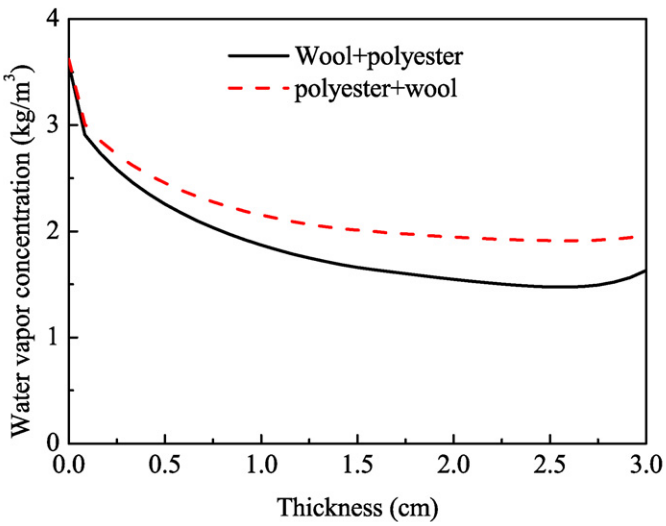

Fig. 9. Water vapor concentration distributions at 24 h.

ferent types of fibrous battings on condensation within and dry heat transfer through clothing assemblies. Theoretical results showed very good agreement with the experimental ones. The results further demonstrated that placing the hygroscopic battings in the inner region and non-hygroscopic battings in the outer region of clothing assembly is advantageous in terms of thermal comfort as it would reduce condensation and associated dry heat loss. The effects of locations of batting layers have significant practical implications, as it means, we can optimize the performance of the clothing having the same materials, but optimally construct the materials into clothing system.

Acknowledgements

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