Computational and Experimental Investigation of Moisture Transport of Spacer Fabrics

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ABSTRACT
This paper investigates the moisture transfer behavior of spacer fabrics. Spacer structures are knitted fabric constructions comprising two separate fabrics which are joined together by spacer threads. In order to investigate the dynamic moisture transfer of spacer fabrics, an experimental apparatus was developed which made the simulation of human body sweating possible.

In the experimental section, the influence of some parameters such as the kind of spacer threads and also heat setting under drawing on moisture transport properties is investigated. Heat setting under drawing affects air permeability, thickness and porosity of spacer fabrics. The Results showed that water vapor produced by sweating can be easily and quickly transferred from the skin to the outer surface to keep the skin dry. In the computational section, a mathematical model was developed to describe moisture transport behavior of spacer fabric. The model was in high good agreement with the observations in the experiments.

INTRODUCTION
The creation of clothing which surrounds the body with a microenvironment and function under physiological conditions has made it possible for us to live in conditions as extreme as the hot desert or the cold polar area. Textiles have been developed to improve their physiological functions for thousands years. The ability of clothing to transport heat and moisture vapor, produced by human body, with high water vapor permeability is one of the most important factors allowing the human body to provide cooling due to evaporation [1]. Transfer moisture vapor of clothing has a critical role in wear comfort, especially in conditions that involve sweating. The moisture transfer properties of clothing materials contribute to determining the thermal and sensorial comfort of garments made from them [2]. In fact, an important purpose for clothing designers is keeping the skin dry after physical activity by rapid transport of liquid perspiration away from the skin, because of the role of humidity next to the skin in determining comfort levels [3].

The wear comfort of clothing is affected by physical processes include heat transfer by conduction, convection and radiation. Meanwhile, moisture transfer by diffusion, sorption, wicking and evaporation, and mechanical interactions in the form of pressure, friction, and dynamic irregular contact. The main interests of research in the field are the dynamic heat and moisture transport behavior of clothing and their influence on clothing comfort in the last decade [4].

There are three possible ways the moisture may migrate along the direction of the concentration gradient, when a water vapor concentration gradient is applied across a fabric: travelling of the water moisture through the fiber interiors, along the surfaces of the fibers, or through the air spaces between the fibers and the yarns.

As long as the water remains in the vapor state, bulk transport of liquid by capillary action can be neglected, and these routes may be described by the following three mechanisms: a) molecular diffusion through the polymeric phase, b) surface diffusion of absorbed molecules along the fibers and c) molecular diffusion through the air spaces of the fabric [5].
Perspiration moisture collects in and passes through clothing as worn. Both the collection and passage of

this moisture is influenced by the properties of clothing fabrics. The measurement of moisture properties related to comfort in wear is very important [6].

Generally, in responding to external humid transients; a piece of dry fabric exhibits three stages of transport behavior. Two fast processes are dominated in the first stage: water vapor diffusion and liquid water diffusion in the air filling the interfiber voids, which new steady states can be reached in a fraction of a second. Throughout this period, water vapor diffuses into the fabric because of the concentration gradient across the two surfaces. In the meantime, due to the surface tension force, the liquid water starts to flow out of the regions of higher liquid content to the drier regions.

The second stage, which is a relatively slow process features the moisture sorption of fibers and takes a few minutes to a few hours to be completed, depending on the hygroscopicity of the fibers. In this period, water diffuses into the fabric by sorption of water into the fibers, which increases the relative humidity at the fiber surfaces. After liquid water diffuses into the fabric, the surfaces of the fibers are saturated because of the film of water on them, which again enhances the sorption process. Throughout these two transient stages, the heat transfer process is coupled with the four different forms of moisture transfer due to the heat release or absorption during sorption/desorption and evaporation/condensation, which, in turn, are affected by the efficiency of heat transfer.

At last, the third stage is reached as a steady state, in which all four forms of moisture transport and the heat transfer process become steady and the coupling effects among them become less significant [7]. Spacer fabrics are much like a sandwich, which have two complementary slabs of fabric with a third layer tucked in between. Spacer fabrics are essentially pile fabrics that have not been cut and consist of two layers of fabric separated by yarns at a 90 degree angle. Spacer structures are knitted fabric constructions comprising two separate fabric webs which are joined together and kept apart by spacer threads. The spacer threads are generally made of PET or PA monofilament yarns. This creates a ventilated space of 1.5 to 60 mm of air, allowing heat and moisture to escape. The amount of air incorporated in the assembly can be altered by modifying the structure of the knitted construction [8]. Thermal regulation properties and active breathing properties of spacer fabrics are due to three-dimensional construction and special properties such as high porosity and high air permeability. They also transport moisture. In the 3-D structure of the textile an insulating layer of air is formed between the two outer surfaces of the textile, which protects the wearer from the effects of heat, while at the same time, guarantees that the garment is both breathable and comfortable [9].

Measuring of the local moisture content of fabric surfaces next to the skin in a real wearing experiment was studied by researchers. To provide a method for measurement of moisture transport of spacer fabrics during sweating conditions, we developed a dynamic sweating hot plate instrument to simulate the conditions in which clothing fabrics are placed over a sweating skin. The sweating guarded hot plate apparatus, simulating the heat and moisture transfer from the body surface through clothing material to the environment, was designed for the measurement of water vapor transfer of fabrics, relating to comfort characteristics of the garment [10].

Background

A mathematical model to describe coupled heat and moisture transfer into an assembly of textile fibers was first proposed and analyzed by Henry in 1939. In this model a system of differential equations was developed to describe the processes involved, derived from the conservation of mass and energy. In a small element of fabric with unit area and thickness *dx,* homogeneously packed with fibers, and exposed to a moisture gradient, water vapor is assumed to diffuse through the interfiber spaces and to be absorbed or desorbed by the fibers. Volume changes of the fibers due to changing moisture content are neglected. Because the diffusion coefficient of water through fibers is negligible compared with that through air, moisture transport through fibers is also ignored. A mass balance on the basis of the above assumption leads to Eq. (1):

$$\varepsilon \frac{\partial C_a}{\partial t} + (1-\varepsilon)\frac{\partial C_f}{\partial t} = \frac{D_a \varepsilon}{\tau}\frac{\partial^2 C_a}{\partial x^2} \qquad (1)$$

Where ε is the porosity; C_a and C_f are the moisture concentration in the air and fibers respectively. D_a is the diffusion coefficient of water vapor in air; and τ is the effective tortuosity of the fabric [4].

Sorption kinetics for cylindrical fibers is described by diffusion process, which is governed by Eq. (2) [4]:

$$\frac{\partial C_f(x,r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left\{ r D_f(x,t)\frac{\partial C_f(x,r,t)}{\partial} \right\} \qquad (2)$$

TABLE I: Numerical values of fiber-fabric structural and physical properties

parameters	**symbol**	**unit**	**Values for polyester fiber**
Density of fibers	ρ	Kg/m^3	1.38×10^3
Radius of fibers	R_f	m	1.0×10^{-5}
Diffusion coefficient of water vapor in fiber[4]	D_f	m^2/s	3.9×10^{-13}
Diffusion coefficient of water vapor in air[4]	D_a	m^2/s	2.49×10^{-5}
Porosity of fabric	ε	——	0.92
Effective tortuosity of fabric	τ	——	1.2
Regain[4]	R	%	$0.006244\ H_a$
Mass transfer Coefficient (inner surface)[12]	h_{c0}	m/s	8.8×10^{-3}
Mass transfer Coefficient (outer surface)[13]	h_{c1}	m/s	0.137
thickness	L	m	0.00461

In this equation r is the radial distance from the center of the fiber (m). It was assumed the moisture content at the surface of fiber reach instantaneous equilibrium with the moisture content of the adjacent air, as Eq. (3):

$$C_{sf}(x,R_f,t)=f'\{W_C(H_a)\}=f\{C_a(x,t)\} \tag{3}$$

Where R_f is the mean radius of the fibers (m); W_c is the fractional water content at the fiber surface; and H_a is the fractional relative humidity in the adjacent air.

The relationship between moisture content of fibers and relative humidity of the adjacent air is commonly described by the sorption isotherm. For instance, the sorption isotherm for polyester can be expressed as Eq. (4) [11]:

$$W_c = 0.006244\ H_a \tag{4}$$

Numerical Solution of the Model

The finite difference scheme is used to numerical solution of Eq. (1) and (2). The parameters of polyester fabric (sample 1); that was needed to solve Eq. (1) and (2) are listed in *Table I*. A single set of properties is assumed for the entire thickness.

Initial and Boundary Conditions

To find a solution to Eq. (1) and (2), it was needed to specify boundary and initial conditions for humidity and moisture content. It is assumed that, initially a fabric is equilibrated to a given humidity (C_{a0} and H_{a0}). The moisture content is uniform throughout the fabric at known values, as Eq. (5) [14]:

$$\begin{aligned} C_a(x,0) &= C_{a0} \\ C_f(x,0) &= f(H_{a0},T_0) \end{aligned} \tag{5}$$

The fabric then undergoes a change to a different atmosphere, inner surface of fabric faced the sweating skin but does not contact it (at $x=0$), and the outer surface is exposed to the controlled environment (at $x=L$). The boundaries are exposed to a new moisture concentration C_{sk} and C_{env}. Considering the connective nature of the boundary air layers, the boundary conditions can be described by Eq. (6) [12]:

$$\begin{aligned} D_a\varepsilon\left.\frac{\partial C_a}{\partial x}\right|_{x=0} &= h_{c0}(C_a-C_{sk}) \\ D_a\varepsilon\left.\frac{\partial C_a}{\partial x}\right|_{x=L} &= -h_{c1}(C_a-C_{env}) \end{aligned} \tag{6}$$

EXPERIMENT

Four spacer fabrics were used. Specifications and properties of the samples are listed in *Tables II*, *III*.

TABLE II: Properties of the spacer fabrics

Sample code	Weight (kg/m^2)	Thickness (mm)	Air permeability ($L/m^2.s$)	porosity
1	0.316	4.61	2092	0.92
2	0.276	2.9	2875	0.95
3	0.432	4.74	1310	0.95
4	0.350	4.53	1320	0.93

TABLE III: Physical Properties of the spacer fabrics

Sample code	The kind of top and bottom layer and their denier	The kind of spacer threads and their denier	Heat setting	dyed
1	Bottom layer polyester, 70 Top layer polyester, 100	Polyester 20 den	——	——
2	Bottom layer polyester, 70 Top layer polyester, 100	Polyester 20 den	yes	yes
3	Bottom layer polyester, 70 Top layer polyester, 100	Polyester 30 den	——	——
4	Bottom layer polyester, 70 Top layer polyester, 100	Nylon 30 den	——	——

Samples were squares with the size of 5×5 inches, and then put into a conditioning room at $25^{+}_{-}1°C$ and $65^{+}_{-}2\%$ RH for at least 24 hours prior to testing to reach equilibrium regain. In order to investigate the dynamic moisture transfer of spacer fabrics, we developed an experimental apparatus on the basis of the work reported by Prahsarn et al. [10]. This device made the simulation of sweating of human body possible and consisted of a controlled environmental chamber, sweating guarded hot plate and data acquisition system. The instrument for the experiments is shown schematically in *Figure 1*. The guarded hot plate, maintained at 35°C and used as a heat source, is housed in an environmental chamber in which ambient conditions are: (25°C, 65%RH). The diffusion cell consists of a water container, a piece of animal skin for simulating human skin and eight humidity sensors.

Inner side of fabric faces the sweating skin but does not contact it, while the outer side is exposed to the controlled environment. Four humidity sensors are put on the sample and four humidity sensors are put under the sample. The temperature and vapor gradients maintained between the points where the moisture vapor emerges from the simulated skin (35°C, 90%RH) and the ambient environment controlled at 25°C and 65%RH are driving forces for the movement of moisture vapor.

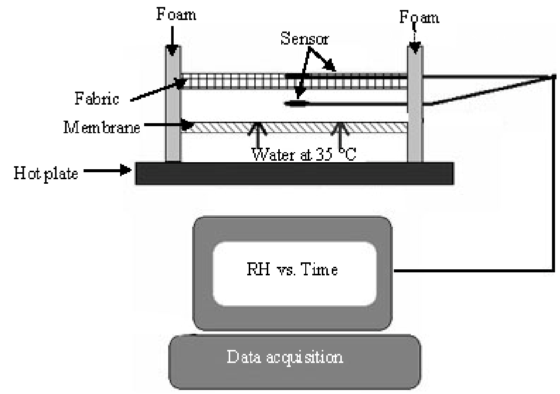

FIGURE 1: Schematic design of the instrument for measurement of moisture transfer

For comparison between different samples, each sample is tested 10 times and for 10 min. All experiments were carried out in a climate chamber conditioned as T=25°C and RH=65%.

EXPERIMENTAL RESULTS

The Influence of Heat Setting

Fabric porosity is defined as pore area per unit fabric area. Results show that spacer fabrics have very porous structures (*Table III*).

Heat setting under drawing of spacer fabrics influences the fabric dimensional properties. Results in Table III indicated that heat setting under drawing of spacer fabrics increases the porosity and air permeability of sample while decreases the thickness and weight per unit area of sample. Comparing the two sample spacer fabrics 1 (raw sample) and 2 (heat setting sample) showed that heat setting sample with higher porosity and air permeability has the higher moisture transfer as shown in *Figure 2*.

Air permeability refers to the rate of passage of air through fabric. Transport property of fabric is strongly dependent on fabric structure. The air permeability of the spacer fabric has a strong effect on the ability of moisture transfer. As expected, the higher air permeability leads to the higher moisture transfer. Fabric thickness serves as an important factor since it determines the distance through which moisture vapor and heat pass in traversing from one side of the fabric to the other.

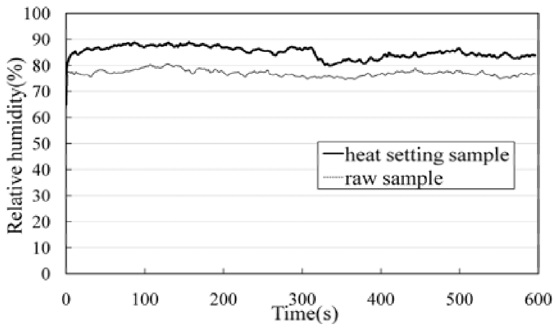

FIGURE 2: Effect of heat setting on the moisture transfer of samples

The Influence of Kind of Spacer Threads

To identify the influence of kind of spacer threads on moisture transfer of spacer fabric, the spacer fabrics with polyester monofilament (sample 3) and nylon monofilament (sample 4) were used. Based on *Figure 3*, the ability of spacer fabric to moisture transfer is very high. Comparing the moisture transfer of two samples, it is obvious that the water vapor concentrations reach steady state very quickly in the spacer fabric with polyester monofilament. Whereas in the spacer fabric with nylon monofilament the steady state is obtained after about 10 minute. The nylon monofilaments are more hygroscopic than the polyester monofilaments. Therefore, the obtained results can be attributed to this different property. Polyester monofilaments are hydrophobic and do not absorb the moisture; so, they transfer the moisture faster than the nylon monofilaments. The results show both samples have same moisture transfer after 10 minute.

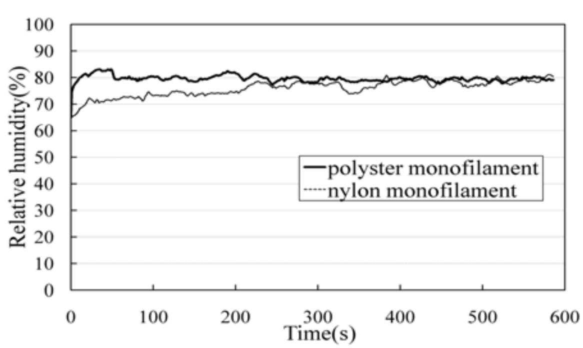

FIGURE 3: Effect of kind of spacer threads on the moisture transfer of samples

COMPUTATIONAL RESULTS

Figure 4 shows the predicted water vapor concentration distribution during moisture diffusion in the air filling of the interfiber void spaces (C_a) in the spacer fabric (sample 1). The results indicate that the diffusion of water vapor into the fabric through these void spaces is very fast.

The distribution of the moisture content in the fibers (C_f) for spacer fabric is shown in *Figure 5*. The process of water vapor diffusion into the fibers takes longer to reach equilibrium. Compared with the process of liquid water diffusion into a porous fabric due to capillary action, the process of moisture diffusion into fiber is relatively slow and takes about 2 minutes to reach equilibrium for polyester.

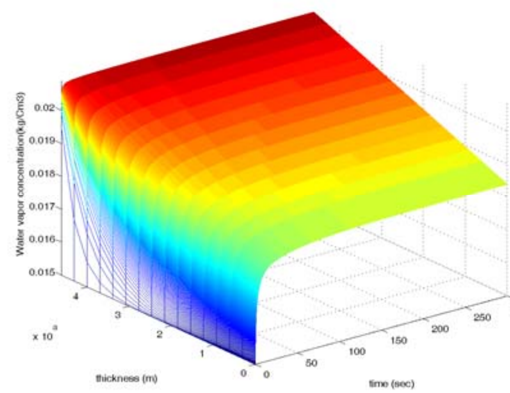

FIGURE 4: Distribution of water vapor concentration in the void spaces of sample 1

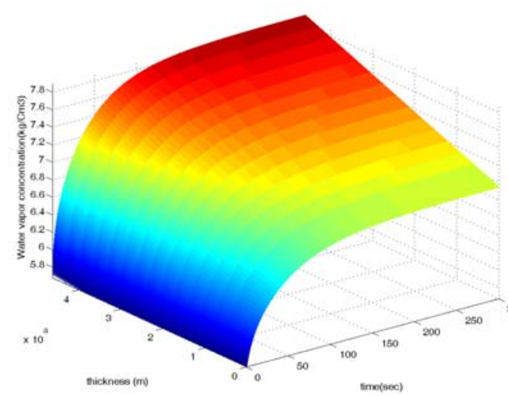

FIGURE 5: Distribution of water vapor concentration in the fibers of sample 1

COMPARISION OF EXPERIMENTAL AND COMPUTATIONAL RESULTS

Figure 6 shows a comparison of the relative humidity in the void spaces (*RH*) at the upper surface of fabric with experimental measurements. The line shows the prediction from model and the individual points are the experimental results. Results showed that there is a good agreement between computational and experimental results. Also, the results showed that the model is able to predict the vapor concentration in the void spaces (C_a) at the upper surface of fabric during the moisture diffusion process.

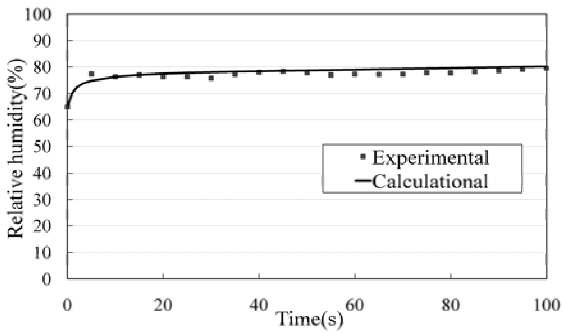

FIGURE 6: Comparison of computational results with experimental observation

CONCLUSION

An important feature for the physiological behavior of the textiles is their ability to act as a buffer to prevent moisture build-up in the microclimate surrounding the skin when the human subject perspires intermittently, and to keep these conditions (moisture and temperature) within levels which will allow the wearer to feel comfortable. Spacer fabrics have two outer textile surfaces with a spacer zone lying in-between. This intermediate zone creates a layer of air, which has an insulating and thermoregulatory effect. Because of the three-dimensional structure and the proper combination of materials used in the spacer fabrics tested, they are able to transport the moisture increase in the microclimate next to the skin during intermittent perspiration of the human subject, and they also guarantee excellent wear comfort.

The Results show that water vapor produced by sweating can be easily and quickly transferred from close to the skin to the outer surface of spacer fabrics to keep the skin dry. Heat setting under drawing of spacer fabrics decreases thickness and weight per unit area and increases the porosity and air permeability of samples. Therefore, heat setting spacer fabrics tends to increase the moisture transfer. These results indicate the importance of parameters such as porosity and air permeability in moisture transfer process. Also, the kind of inter monofilaments as spacer threads was effective. The moisture transfer of spacer fabric with polyester monofilament is faster than spacer fabric with nylon monofilament. The nylon monofilaments are more hygroscopic than the polyester monofilaments, thus the results can be attributed to this different property.

Based on computational results, the diffusion of water vapor into the fabric through these void spaces is very fast. The process of water diffusion into the fibers takes longer to reach equilibrium. Finally, results showed that there is a good agreement between computational and experimental results.

REFRENCES

[1] http://www.karger.com/gazette/67Elsner/ art_1.htm.

[2] Yoo,SH.; Barker,R.L.; "Moisture Management Properties of Heat-Resistant Work wear Fabrics-Effects of Hydrophilic Finishes and Hygroscopic Fiber Blends" , *Textile Research J*, 2004., 74(11), 995-1000.

[3] Weder,M.; et al.; "Neutron Radiography Measurements of Moisture Distribution in Multilayer Clothing Systems" , *Textile Research J.* , 2004, 74(8), 695-700.

[4] Li,Y.;"The Science of Clothing Comfort ",*Textile Progress*,1999, 31, 1/2.

[5] Wehner,J.A.; Miller,B.; Rebenfeld.L.,"Dynamic of Water Vapor Transmission Through Fabric Barriers", *Textile Research J.* ,1988,58(10), 581-592.

[6] Scheurell,D.M.; Spivak,S.M.; Hollies.N.R.S.; "Dynamic Surface Wetness of Fabrics in Relation to Clothing Comfort",*Textile Research J.* ,1985, 55(7), 394-399.

[7] Li,Y.; Zue,Q.; "Simulation Heat And Moisture Transfer with Moisture Sorption, Condensation and Capillary Liquid Diffusion in Porous Textiles" , *Textile Research J.* , 2003, 73(6), 515-524.

[8] Kunde K.; Spacer fabrics-their Application and future opportunities, *Melliand Int*, 2004, 10.

[9] Bruer,SH.M.; Powel,N.; Smith,G.; "Three-dimensionally Knit Spacer Fabrics: A Review of Production Techniques and Applications ", *J . of textile and apparel,technology and management*, 2005 , 4.

[10] Prahsarn,C.; Barker,R.L.;Gupta,B.S.; "Moisture Vapor Transport Behavior of Polyester Knit Fabrics" , *Textile* Research *J*, 2005, 75 , 346-351.

[11] Li,Y.; Holcombe,B.V.; "Mathematical Simulation of Heat and Moisture Transfer in a Human – Clothing – Environment System", *Textile Research J.* ,1998,68 , 389-397.

[12] Wang Z., Li.Y. Zhu Q.Y., Lue Z.X., Radiation and Conduction Heat Transfer Coupled with Liquid Water Transfer, Moisture Sorption, and Condensation in Porous Polymer Materials, J. of Applied. Polymer Science, 2003, 89, 2780-2790.

[13] Li,Y.; Zue,Q. and Yeung K.W.; "Influence of Thickness and Porosity on Coupled Heat And Liquid Moisture Transfer in Porous Textiles" , Textile Research J. , 2002, 72(5), 435-446.

[14] Li,Y.; Luo,Z.X.; "An Improved Mathematical Simulation of the Coupled Diffusion of Moisture and Heat in Wool Fabric" , Textile Research J,1999, 69(10), 760-768.

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