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MECHANISM OF HEAT AND MASS TRANSFER IN MOIST POROUS MATERIALS

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Abstrak. A mathematical simulation carried out to study the physical mechanisms of moisture diffusion into hygroscopic fabric during humidity transients. On the basis of a mathematical model developed to describe the coupled heat and moisture transfer in wool fabric, the moisture-sorption mechanisms are investigated for fabrics made from fibers with different degrees of hygroscopicity. Theoretical predictions on the moisture uptake and temperature changes under humidity transients are compared with those measured previously in a sorption-cell experiment for fabrics made from wool, cotton, acrylic fiber, and polypropylene fiber. It is concluded that the physical mechanism of moisture diffusion into highly hygroscopic fibers such as wool and cotton can be described by a two stage moisture diffusion process: a fast Fickian diffusion with a concentration-dependent diffusion coefficient and a slow diffusion with a time-dependent diffusion coefficient. For weakly hygroscopic fibers such as polypropylene fiber, the moisture sorption process can be described by a single Fickian diffusion with a constant diffusion coefficient. Heat transfer in moist textiles takes place by conduction, infra-red radiation, and distillation. Until the fiber is saturated, the evaporation process is determined mainly by the fiber's sorption properties. Conductivity increases with water content and also depends on a fiber's sorption properties.

Keywords: Moisture diffusion, hygroscopic fabrics, Humidity transients

Notations

C_a	Water-vapor concentration in the air filling the inter-fiber void space (kgm^{-3})
C_f	Water-vapor concentration in the fibers of the fabric (kgm^{-3})
C_v	Volumetric heat capacity of the fabric $(\mathrm{kJm}^{-3}\,{}^\circ C^{-1})$
D_a	Diffusion coefficient of water vapor in the air $(\mathrm{m}^{-2}\mathrm{s}^{-1})$
D_f	Diffusion coefficient of water vapor in the fibers of the fabric $(\mathrm{m}^{-2}\mathrm{s}^{-1})$
h_c	Convective-mass-transfer coefficient (ms^{-1})
h_t	Convective-heat-transfer coefficient $(\mathrm{kJm}^{-2}\,{}^\circ C^{-1})$
K	Thermal conductivity of the fabric $(\mathrm{kJm}^{-1}\,{}^\circ C^{-1})$
L	Thickness of the fabric (m)
r	Radial co-ordinate of fiber (m)
t	Real time from change in conditions (s)
T_{ab}	Temperature of the ambient air $({}^\circ C)$

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T	Temperature of the fabric (°C)
W_c	Water content of the fibers in the fabric, $W_c = C_f/\rho$
x	Distance (m)
λ	Heat of sorption or desorption of water vapor by the fibers (kJ/kg)
ρ	Density of the fibers (kg/m^3)
τ	Effective tortuosity of the fabric

1.0 INTRODUCTION

Some of the issues of clothing comfort that are most readily involve the mechanisms by which clothing materials influence heat and moisture transfer from skin to the environment. Heat transfer by conduction, convection, and radiation and moisture transfer by vapor diffusion are the most important mechanisms in very cool or warm environments from the skin

It has been recognized that the moisture-transport process in clothing under a humidity transient is one of the most important factors influencing the dynamic comfort of a wearer in practical wear situations. However, the moisture transport process is hardly a single process since it is coupled with the heat-transfer process under dynamic conditions [1 – 9].

Trying to stay warm and dry while active outdoors in winter has always been a challenge. In the worst case, when an individual exercises strenuously, sweats profusely, and then rests. During exercise, liquid water accumulates on the skin and starts to wet the clothing in touch with the skin. Some of the sweat evaporates from both the skin and the clothing. Depending on the temperature and humidity gradient across the clothing, the water vapor either leaves the clothing or condenses and freezes somewhere in its outer layers.

When one stops exercising and begins to rest, active sweating soon ceases, allowing the skin and clothing layers eventually dry. During this time, however, the heat loss from body can be considerable. Heat is taken from the body to evaporate the sweat, both that on the skin and that in the clothing. The heat flow from the skin through the clothing can be considerably greater when the clothing is very wet, since water decreases clothing’s thermal insulation. This post-exercise chill can be exceedingly comfortable and can lead to dangerous hypothermia.

A dry layer next to the skin is more comfortable than a wet one. If one can wear clothing next to the skin that does not pick up any moisture, but rather passes it through to a layer away from the skin, heat losses at rest will be reduced.

In cold climates, thick clothing save worn to restrict heat losses from the body. The fabric used in apparel differ in moisture sorption and thermal properties, and it is important to consider these properties when choosing garments. One way of expressing the insulating performance of a textile is to quote its “effective thermal conductivity”. Here the term “effective” refers to the fact that conductivity is calculated from the rate of heat flow per unit area of the fabric divided by the temperature gradient between opposite faces. It is not a true conduction, because heat transfer takes place by a combination of conduction through fibers and air and infrared radiation. If moisture is present, other mechanisms may also be involved.

Research on thermal resistance of apparel textiles has established that thermal resistance of dry fabric or one containing very small amounts of water depends on its thickness, and to a lesser extent on fabric construction and fiber conductivity. Indeed, measurements of effective thermal conductivity by standard steady-state methods show that differences between fabrics are mainly attributable to thickness. Despite these findings, consumers continue to regard wool as “warmer” than other fibers, and show preference for wearing wool garments in cold weather, particularly when light rain or sea spray is involved.

2.0 BACKGROUND

The influence of relative humidity on fabric permeability has previously been studied and it was found that there can be a large change in convective gas flow transport properties of woven and nonwoven textile materials due to changes in fabric structure caused by fiber swelling.

King and Cassie [10] conducted an experimental study on the rate of absorption of water vapor by wool fibers. They observed that, if a textile is immersed in a humid atmosphere, the time required for the fibers to come to equilibrium with the atmosphere is negligible compared with the time required for the dissipation of heat generated or absorbed. McMahon and Watt [11] investigated the effects of heat of sorption in the wool-water sorption system. They observed that the equilibrium value of the water content was directly determined by the humidity but that the rate of absorption and desorption decreased as the heat-transfer efficiency decreased. Heat transfer was influenced by the mass of the sample, the packing density of the fiber assembly, and the geometry of the constituent fibers. Crank [12] pointed out that the water-vapor-uptake rate of wool is reduced by a rise in temperature that is due to the heat of sorption. The dynamic-water-vapor-sorption behavior of fabrics in the transient state will therefore not be the same as that of single fibers owing to the heat of sorption and the process to dissipate the heat released or absorbed.

Henry [13,14] was the first to start theoretical investigation of this phenomenon. He proposed a system of differential equations to describe the coupled heat and moisture diffusion into bales of cotton. The equations involved are the conservation of mass and energy, and the relationship between fiber moisture content with the moisture in the adjacent air. Since these equations are non-linear, Henry made a number of simplifying assumptions to derive the analytical solution.

In order to model the two-stage sorption process of wool fibers, Nordon and David [15] proposed three empirical expressions for a description of the dynamic relationship between fiber moisture content and the surrounding relative humidity. By incorporating several features omitted by Henry into the three equations, Nordon and David were able to solve the model numerically. Since their sorption mechanisms (i.e. sorption kinetics) of fibers were neglected, the constants in their sorption-rate equations had to be determined by comparing theoretical predictions with experimental results.

Farnworth [16] reported a numerical model describing the combined heat and water-vapor transport through clothing. The assumptions in the model did not allow for the complexity of the moisture-sorption isotherm and the sorption kinetics of fibers. Wehner et al. [17] presented two mechanical models to simulate the interaction between moisture sorption by fibers and moisture flux through the void spaces of a fabric. In the first model, diffusion within the fiber was considered to be so rapid that the fiber moisture content was always in equilibrium with the adjacent air. In the second model, the sorption kinetics of the fiber were assumed to follow Fickian diffusion. In these models, the effect of heat of sorption and the complicated sorption behavior of the fibers were neglected.

Li and Holcombe [18] developed a two -stage model, which takes into account water-vapor-sorption kinetics of wool fibers and can be used to describe the coupled heat and moisture transfer in wool fabrics. The predictions from the model showed good agreement with experimental observations obtained from a sorption-cell experiment. More recently, Li and Luo [19] further improved the method of mathematical simulation of the coupled diffusion of the moisture and heat in wool fabric by using a direct numerical solution of the moisture-diffusion equation in the fibers with two sets of variable diffusion coefficients. These research publications focused on fabrics made from one type of fiber. The features and differences in the physical mechanisms of coupled moisture and heat diffusion into fabrics made from different fibers have not been systematically investigated.

In this paper, the physical mechanisms of moisture diffusion into fabrics made from different fibers are studied.

3.0 FORMULATION OF THE PROBLEM

The mathematical model describing the coupled heat and moisture diffusion in textiles was first proposed by Henry [20,21] and then further developed by Nordon and David [22] and Li and Holcombe [18]. The conservation of heat and moisture can be expressed by the following equations :

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

$$C_v \frac{\partial T}{\partial t} - \lambda \frac{\partial C_t}{\partial t} = K \frac{\partial^2 T}{\partial x^2} \tag{2}$$

where C_v and λ are functions of the concentration of moisture absorbed by the fibers. Most textile fibers are of very small diameter and have a very large surface/volume ratio. The assumption in the second equation of instantaneous thermal equilibrium between the fibers and the inter-fiber space does not therefore lead to appreciable error. The two equations in the model are not linear and contain the three unknowns, C_p, T, and C_a. A third equation is needed to solve the equations.

Henry [20,21] derived a third equation to obtain an analytical solution by assuming that C_f is linearly dependent on T and C_s and that fibers reach moisture equilibrium with the adjacent air instantaneously. Downes and Mackay [23] found experimentally that the sorption of water vapor by wool is a two-stage process, the first stage obeys Fick's law of diffusion with a concentration-dependent diffusion coefficient. The second stage, which involves structural changes within fibers, is much slower than the first. To simulate the two stage-sorption process, Nordon and David [22] proposed an exponential function to describe the rate of change of fiber water content, which needed to be adjusted according to the measured fabric moisture content. Li and Holcombe [18] developed a two stage sorption-rate equation to describe the moisture sorption of wool. The first stage is represented by a Fickian diffusion with a constant coefficient. The diffusion equation was solved by using Crank's truncated solution [24]. The second stage is described by an exponential relationship, which also needs to be adjusted according to the experimental measurements. The relative contributions of the two stages to the total moisture sorption are function of the sorption time and the initial regain of the fibers.

Li and Luo [19] improved the sorption rate equation by assuming that the moisture sorption of wool fiber can be generally described by a uniform-diffusion equation for both stages of sorption :

$$\frac{\partial C_t}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left\{ r D_t\left(x,t\right)\frac{\partial C_f}{\partial r}\right\} \tag{3}$$

Where $D_f(x,t)$ are the diffusion coefficients that have different values at different stages of moisture sorption. In a wool fabric, $D_f(x,t)$ is a function of water content of the fibers, which is dependent on the time of sorption and the location of the fiber.

In the first stage, the diffusion coefficient is concentration-dependent and is assumed to be quadratic function of water content when the sorption is less than 540 seconds , as given in equation (4a). In the second stage, in which the moisture sorption is much slower than in the first, the diffusion coefficient of moisture in a wool fiber is attenuated along with the time of sorption when $t \geq 540$ s. as shown in equation (4b).

$$D_t\left\{W_c\left(t\right)\right\} = \left\{1.04 + 68.204W_c\left(t\right) - 1342.5924W_c\left(t\right)^2\right\}10^{14}\text{, } t \leq 540 \text{ s} \tag{4a}$$

$$D_t\left\{W_c\left(t\right)\right\} = 1.616405\left[1 - \exp\left\{-18.16323\exp\left(-28.0W_c\left(t\right)\right)\right\}\right]10^{-14}\text{, } t^3 \geq 540\text{ s} \tag{4b}$$

The second formula for D_f in equation (4b) shows that the rate of moisture diffusion into a wool fiber (when $t \geq 540$ s) attenuates in the form of double-exponential function, which may indicate that the attenuating feature of the moisture sorption of wool is due to its microstructural changes and the decreasing number of available polar groups.

Now, we assume that the sorption process for all the fabrics can be described by a uniform diffusion equation from equation (3), with diffusion-coefficient functions to describe the moisture-sorption kinetics. Through a large number of computational experiments in comparison with the measured water-content changes and temperature changes of various fabrics, we try to identify whether the moisture-sorption process needs to be described by a two-stage process or a single Fickian-diffusion process. The diffusion-coefficient functions identified for fabrics made from wool, cotton, porous acrylic fiber, and polypropylene fiber which is reported by Li *et al.* [25] are summarized in the appendix.

3.1 Initial and Boundary Conditions

To generate a solution to the above-mentioned equations, we need to specify an initial condition and boundary conditions at the fabric surfaces of the humidity, moisture content, and temperature. Initially, a fabric is equilibrated to a given atmosphere of temperature (T_{ao}) and humidity (C_{ao} and H_{ao}), the temperature and moisture content being uniform throughout the fabric at known values:

$$T_a(x,0) = T_{ao} \tag{5}$$

$$C_a(x,0) = C_{ao} \tag{6}$$

$$C_f(x,r,0) = f(H_{a0}, T_0) \tag{7}$$

The fabric then undergoes a step change to a different atmosphere. Its boundaries are exposed to an air stream of a new moisture concentration C_{ab} and temperature T_{ab}. Considering the convective nature of the boundary air layers, the boundary conditions can be described by the following equations:

$$D_a \varepsilon \left.\frac{\partial C_a}{\partial x}\right|_{x=0} = h_c(C_a - C_{ab}) \tag{8}$$

$$D_a \varepsilon \left.\frac{\partial C_a}{\partial x}\right|_{x=L} = -h_c(C_a - C_{ab}) \tag{9}$$

$$K \varepsilon \left.\frac{\partial T}{\partial x}\right|_{x=0} = h_t(T - T_{ab}) \tag{10}$$

$$K\varepsilon \left.\frac{\partial T}{\partial x}\right|_{x=L} = -h_t\left(T - T_{ab}\right) \tag{11}$$

These conditions show that the thermal and moisture fluxes across the boundaries are proportional to the differences in the temperature and moisture concentration between the surrounding medium and the fabric surface respectively.

3.2 Numerical Solution

Equations (1) and (2) are solved by a finite-difference method by using the Crank-Nicolson scheme, and equation (3) is solved by using an implicit-difference scheme, together with specification of the initial condition of equations (5)–(7), the boundary conditions of equations (8)–(11), and the fiber and fabric properties. Details of the solution method have been reported previously by Li and Luo [19].

4.0 EXPERIMENTAL PROCEDURE

The discrepancy between laboratory tests and consumer preferences may be partly due to the fact that existing methods for measuring conductivity normally involve fabrics pre-conditioned to standard atmosphere. Fibers such as wool are hygroscopic, and therefore it is a common practice in the textile industry to equilibrate specimens to an atmosphere of 20°C and 65% relative humidity before testing. The state of a specimen obtained by such method does not necessarily represent typical wear conditions. Clothing may contain moisture levels in excess of those present during these tests as a result of perspiration, or as mentioned above from rain or spray.

Current methods cannot be used to measure the thermal properties of fabrics containing water. Typical methods such as the guarded hot plate and ratio-metric devices use a temperature gradient across the specimen, and measurements are made when equilibrium heat flow is reached. This can take a long time, especially with specimens of large heat capacity such as those containing higher amounts of water, and is of questionable accuracy owing to the possibility of moisture in the fabric redistributing itself. Measuring the thermal properties of moist fabrics requires a rapid technique. In this study, a transient technique have been applied to textiles containing moisture. The apparatus consists of a heat source of constant temperature higher than ambient and passive guarded heat sink that is initially at ambient temperature. The distance between the sink and source plates is adjusted to suit the specimen thickness, and the fabric is placed between the two plates. From that moment the temperature of the heat sink rises, and the effective thermal conductivity of the fabric can be determined from this rise during the first 100 seconds of heat flow.

The effective thermal conductivities of different knitted fabrics (Table 1) were measured for varying regains. Regain is the mass of water present expressed as a percent-

Table 1 Pertinent properties of and results for fabrics used in water absorption and drying experiments.

Fabric,	**Mass, g/m^2**	**Thickness, s, mm**	**Mass of water in fabric, g**	**Time to dry, hours**
Wool plain weave	122	0.48	0.60	3
Wool single knit	214	0.83	1.66	7
Polypropylene plain weave	168	0.66	0.82	3
Polypropylene knit	223	1.26	2.28	9
Cotton duck	364	0.68	1.27	5
Cotton sheeting	157	0.43	0.98	5
Acrylic plain weave	143	0.40	0.52	2
Acrylic knit	123	0.73	1.47	5

age of dry weight of the material. We believe that the effective thermal conductivity of moist fabrics may be influenced by the fiber sorption properties, so the fiber types tested had different properties namely:

- Wool (nonwicking and absorbent).
- Polypropylene (nonwicking and almost nonabsorbent).
- Cotton (wicking and absorbent).
- Porous acrylic (wicking and almost nonabsorbent).

To measure the absorption of liquid water in fabrics, circular samples were uniformly wetted in water and left overnight sandwiched between two wet sponges. The next day, the mass of water freely absorbed by each sample was recorded. We obtained the desired regains by drying wetted samples; approximately 10 minutes was allowed after drying for the specimen to reach uniform moisture distribution. Regain was determined shortly before the test by weighting the sample. Fabric thickness was measured after conditioning to standard textile test conditions (65% RH, temperature 20°C), and the distance between the heat source and the sink was adjusted to this figure. While it was noticed that the thickness of a fabric changes slightly with regain, we chose this approach for simplicity. After each test, we determined the amount of water condensed on the heat sink by blotting it with a paper tissue, which we then weighed.

5.0 Results

Figures 1–4 present the results of conductivity measured using transient technique as a function of regain over the range of 0 to 300% on porous acrylic, polypropylene, wool, and cotton fabrics. The conductivity of four fabrics is approximately the same at the zero regain, which is consistent with known thermal behavior of dry or normally conditioned fabrics. At 300% regain, the materials can be considered *dripping wet*. There are differences in the behavior of each fabric between dry and wet, which can be explained in terms of the amount of water present in the material and the way it is held, e.g., absorbed into the fiber in the case of absorbent material, retained in pores within the fiber structure within the porous acrylic, or as free water between fibers and yarns.

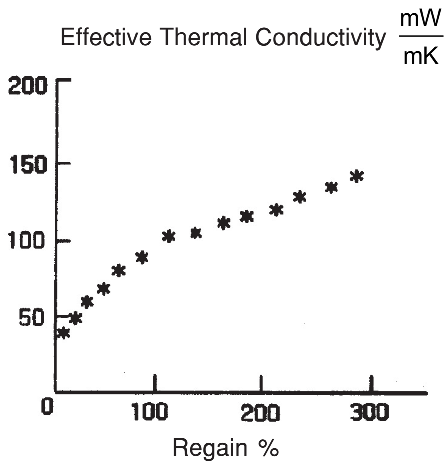

Figure 1 Effective thermal conductivity of a porous acrylic fabric as a function of regain

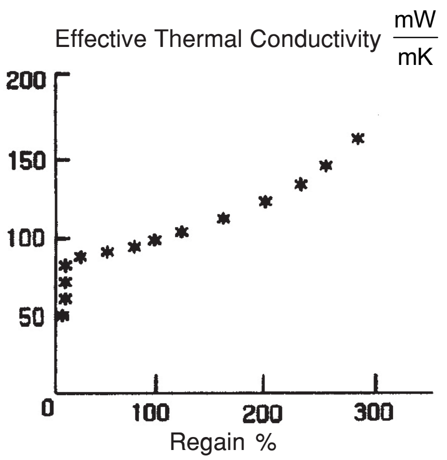

Figure 2 Effective thermal conductivity of a polypropylene fabric as a function of regain

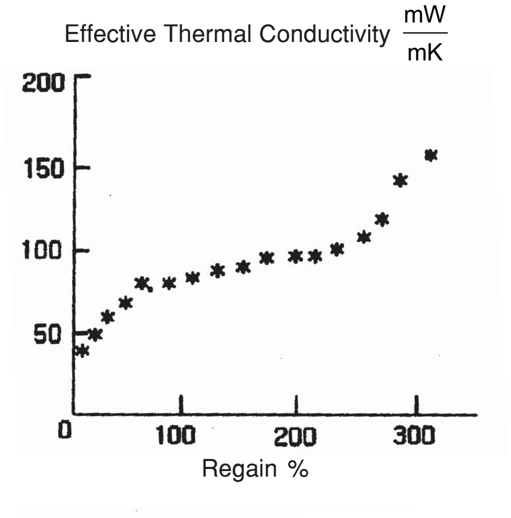

Figure 3 Effective thermal conductivity of a wool fabric as a function of regain

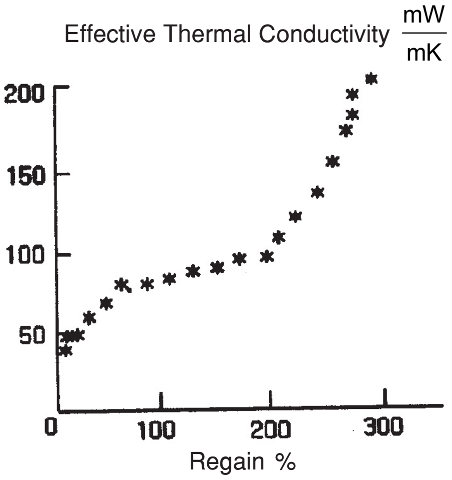

Figure 4 Effective thermal conductivity of a cotton fabric as a function of regain

According to Table 1, no relationship can be established between regain and the amount of water picked up by the fabric (*r* =0.074). Initially, we plotted the percent water in the sample, based on its mass, against thickness and found poor correlation (*r* = 0.48). However, after plotting actual water content against various properties, we found the best correlation (*r* = 0.92) to be between the actual amount of water in the samples and their thickness (Figure 5).

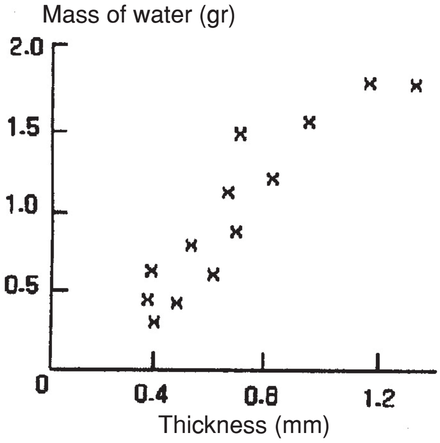

Figure 5 There is a good correlation between the mass of water held by the fabric and its thickness

When we converted the results of others (Maejima [26], Dolhan [27], Fourt *et al.* [28], Bertioniere [29]) from liquid content to actual liquid content and plotted these values against thickness, we again found a very good correlation. The results of Fourt *et al.*, whose experiment included a very wide range of materials, are given in figure 6. It was concluded that expressing the amount of water in a fabric as a percentage of its mass is simply an extension of the percent regain calculation for water vapor to that for liquid water. The amount of water vapor a fiber pick up, expressed as a percentage of its mass, is valid because it is directly related to the number of hydrophilic sites the fiber has to which water vapor can bond: this is proportional to the fiber mass. Like Fourt *et al.* [28], we found a very good correlation (*r* = 0.98) between the amount of water initially in these fabrics and the time for them to dry; this correlation was independent of fiber type (Figure 7). Note that Fourt *et al.* found this relationshi p did not hold for some of their napped fabrics, explaining that the napped surface retarded heat flow to the water in the fabric and thus limited the evaporation rate.

Figure 8 shows the mean moisture uptake of the fabrics during humidity transients. After an initial equilibrium period at 0% RH, the humidity in the cell was raised to 99% in a single step, the mean air velocity at the fabric surface being 1.7 m/s. This figure shows that wool fabric has a significantly greater total moisture uptake than other

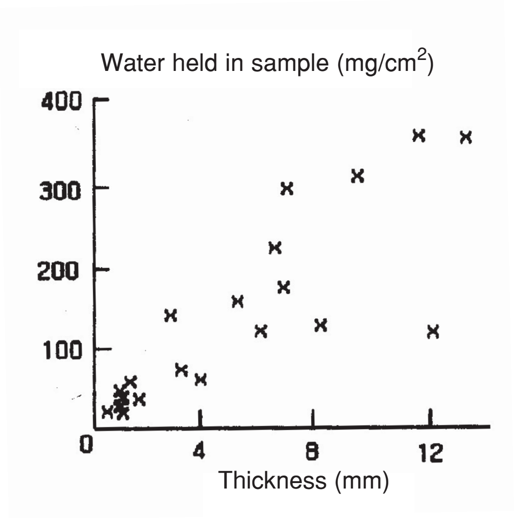

Figure 6 Effective thermal conductivity of a porous acrylic fabric as a function of regain

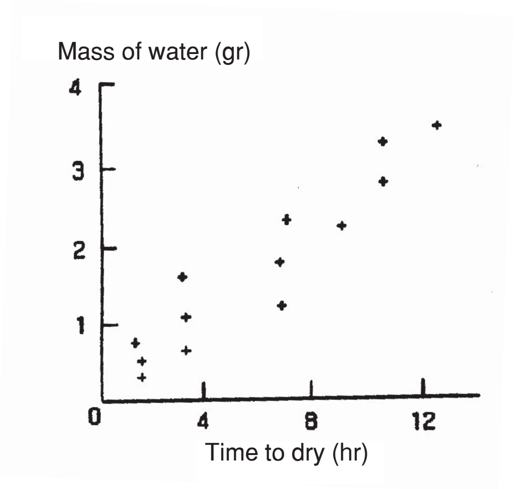

Figure 7 Effective thermal conductivity of a porous acrylic fabric as a function of regain

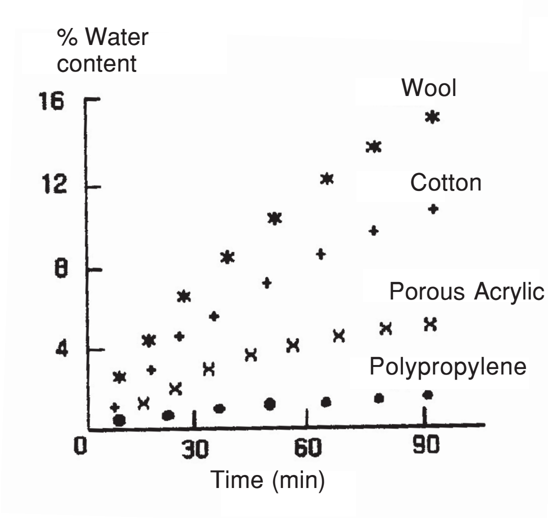

Figure 8 Effective thermal conductivity of a porous acrylic fabric as a function of regain

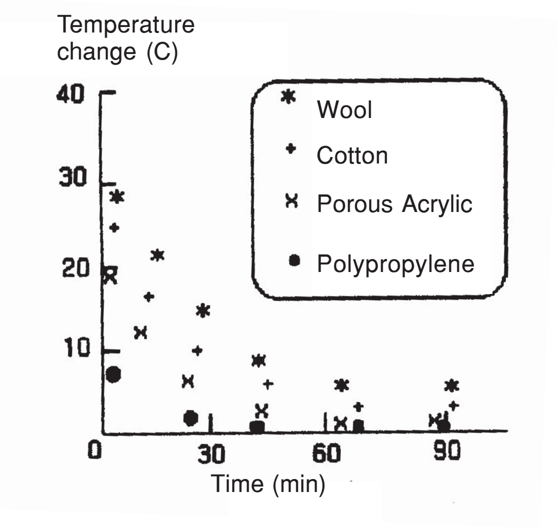

Figure 9 Effective thermal conductivity of a porous acrylic fabric as a function of regain

fabrics. Figure 9 shows temperature changes at the surface of fabric during the dynamic-moisture-diffusion process. Obviously, the wool fabric had the highest temperature rise during the humidity transients and was closely followed by the cotton, acrylic and polypropylene fiber fabrics.

6.0 CONCLUSIONS

In summary, the physical mechanisms of moisture diffusion into fabrics vary with fabrics made from different degree of hygroscopicity. For highly hygroscopic fibers such as wool and cotton, the moisture diffusion can be described by two-stage process: a fast Fickian diffusion with a concentration-dependent diffusion coefficient and a slow diffusion with a time-dependent diffusion coefficient. For weakly hygroscopic fibers such as polypropylene fiber, the moisture-sorption process can be described by a single Fickian diffusion with a constant diffusion coefficient.

For the range of fabrics studied, we found no correlation whatsoever between fiber regain and the amount of liquid water a fabric absorbed or freely picked up. We have shown that the effective thermal conductivity of moist materials is substantially higher than that for dry materials. Fiber sorption properties mainly determine the evaporation process and therefore the heat and mass transfer by evaporation of water, diffusion of water vapor, and condensation. Fiber sorption properties influence the heat and mass transfer up to the point when the rate of increased conductivity with regain is low in the curves, and then all fiber types behave similarly. Generally heat transfer increases with increasing regain, but in this initial region the rise is most pronounced for the nonabsorbent polypropylene. The fiber with the lowest effective conductivity over the region 0–200% regain is wool, an effect that is especially pronounced in the region of low regains from zero to saturation. Cotton fabric had the highest effective thermal conductivity for almost the whole region of regains tested.

APPENDIX (PHYSICAL CHARACTERISTICS)

Wool:

Diffusion coefficient of water vapor – 1st stage:

$$D_f = (1.04 + 68.20W_c - 1342.59W_c^2)10^{-14}, \ \text{t} < 540 \text{ s} \qquad \text{(A1)}$$

Diffusion coefficient of water vapor – 2nd stage:

$$D_f = 1.6164\{1 - \exp[-18.163\exp(-28.0W_c)]\}10^{-14}, \ \text{t} \ {}^3\ 540\text{s} \qquad \text{(A2)}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \qquad \text{(A3)}$$

Volumetric heat capacity of fabric:

$$C_v = 373.3 + 4661.0W_c + 4.221T \qquad \text{(A4)}$$

Thermal conductivity of fabric:

$$K = (38.49 - 0.720W_c + 0.113W_c^2 - 0.002W_c^3)10^{-3} \qquad \text{(A5)}$$

Heat of sorption:

$$\lambda = 1602.5\exp\left(-11.72W_c\right) + 2522.0 \tag{A6}$$

Cotton:

Diffusion coefficient of water vapor – 1st stage:

$$D_f = \left(0.8481 + 50.6W_c - 1100W_c^2\right)10^{-14}, \quad t < 540 \text{ s} \tag{A7}$$

Diffusion coefficient of water vapor – 2nd stage:

$$D_f = 2.5\left\{1 - \exp\left[-3.5385\exp\left(-45W_c\right)\right]\right\}10^{-14}, \, t\ ^{3}\ 540 \text{ s} \tag{A8}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \tag{A9}$$

Volumetric heat capacity of fabric:

$$C_v = \frac{\left(1663.0 + 4184.0W_c\right)}{\left(1 + W_c\right)1610.9} \tag{A10}$$

Thermal conductivity of fabric:

$$K = \left(44.1 + 63.0W\right)10^{-3} \tag{A11}$$

Heat of sorption:

$$\lambda = 1030.9\exp\left(-22.39W_c\right) + 2522.0 \tag{A12}$$

Porous Acrylic Fiber:

Diffusion coefficient of water vapor – 1st stage:

$$D_f = \left(1.12 - 410W_c - 8200W_c^2\right)10^{-13}, \quad \text{t} < 540 \text{ s} \tag{A13}$$

Diffusion coefficient of water vapor – 2nd stage:

$$D_f = (6.23)10^{-13}, \, \text{t}\ ^{3}\ 540 \text{ s} \tag{A14}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \tag{A15}$$

Volumetric heat capacity of fiber:

$$C_v = 1610.9 \tag{A16}$$

Thermal conductivity of fiber:

$$K = (28.8)10^{-3} \tag{A17}$$

Heat of sorption:

$$\lambda = 2522 \text{ kj/kg} \tag{A18}$$

Polypropylene Fiber:

Diffusion coefficient of water vapor – 1st stage:

$$D_f = 1.3e^{-13}, \quad t < 540 \text{ s} \tag{A19}$$

Diffusion coefficient of water vapor – 2nd stage:

$$D_f = 1.3e^{-13}, \quad t\ ^3\ 540 \text{ s} \tag{A20}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \tag{A21}$$

Volumetric heat capacity of fiber:

$$C_v = 1715.0 \tag{A22}$$

Thermal conductivity of fiber:

$$K = (51.80)10^{-3} \tag{A23}$$

Heat of sorption:

$$\lambda = 2522 \text{ kj/kg} \tag{A24}$$

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