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Effect of the Chemical Nature of Fibres on Dynamic Water Vapour and Heat Transport Through Textiles

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An improved mathematical model that takes into account the water vapour sorption mechanisms of wool fibre is developed to describe and predict the coupled heat and moisture transport in wool fabrics. On the basis of the model, the moisture-sorption mechanisms are investigated for fabrics made from fibres 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 fibre and polypropylene fibre. It is concluded that the physical mechanism of moisture diffusion into highly hygroscopic fibres such as wool and cotton can be described by a two stage moisture diffusion process.

Key Words: Chemical nature of fibre, Mathematical model, Moisture diffusion, Hygroscopic fabrics, Humidity transients.

Notations

C_a	Water-vapour concentration in the air filling the inter-fibre void space (kg m^{-3})
C_f	Water-vapour concentration in the fibres of the fabric (kg m^{-3})
C_v	Volumetric heat capacity of the fabric (kJ m^{-3} $°C^{-1}$)
D_a	Diffusion coefficient of water vapour in air (m^2 s^{-1})
D_f	Diffusion coefficient of water vapour in the fibres of the fabric (m^2 s^{-1})
h_c	Convective-mass-transfer coefficient (m s^{-1})
h_t	Convective-heat-transfer coefficient (kJ m^{-2} $°C^{-1}$)
K	Thermal conductivity of the fabric (kJ m^{-1} $°C^{-1}$)
L	Thickness of the fabric (m)
r	Radial coordinate of fibre (m)
t	Real time from change in conditions (s)
T_{ab}	Temperature of the ambient air (°C)
T	Temperature of the fabric (°C)
W_c	Water content of the fibres in the fabric, $W_c = C_f/\rho$

x	Distance (m)
λ	Heat of sorption or desorption of water vapour by the fibres (kJ/kg)
ρ	Density of the fibres (kg/m^3)
τ	Effective porosity of the fabric

INTRODUCTION

Some of the issues of clothing comfort that 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 vapour 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, an individual exercises strenuously, sweats profusely, then rests. During exercise, liquid water accumulates on the skin and starts to wet the clothing layers above 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 vapour 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 to 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 the 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 loss at rest will be reduced.

In cold climates clothing is worn to restrict heat loss from the body. The fabric used in the apparel differs 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 true conduction, because heat transfer takes place by a combination of conduction through fibres and air and infrared radiation. If moisture is present, other mechanisms may be also 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 fibres 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 fibres and show preference for wearing wool garments in cold weather, particularly when light rain or sea spray is involved.

Background

The comfort of a garment is linked to several factors: lightness, heat and vapour transport, sweat absorption and drying. A garment's comfort depends on the properties of each fabric layer and the combination of all the layers worn. The coupled heat and liquid moisture transport of porous material has wide industrial applications in textile engineering and functional design of apparel products. Heat transfer mechanisms in porous textiles include conduction by the solid material of fibres, conduction by intervening air, radiation and convection. Meanwhile, liquid and moisture transfer mechanisms include vapour diffusion in the void space and moisture sorption by the fibre, evaporation and capillary effects. Water vapour moves through textiles as a result of water vapour concentration differences. Fibres absorb water vapour due to their internal chemical compositions and structures. The flow of liquid moisture through the textiles is caused by fibre-liquid molecular attraction at the surface of fibre materials, which is determined mainly by surface tension and effective capillary pore distribution and pathways. Evaporation and/or condensation takes place, depending on the temperature and moisture distribution. The heat transfer process is coupled with the moisture transfer process with phase changes such as moisture sorption/desorption and evaporation/condensation.

The influence of relative humidity on fabric permeability has been previously 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 fibre swelling.

King and Cassie[10] conducted an experimental study on the rate of absorption of water vapour by wool fibres. They observed that, if a textile is immersed in a humid atmosphere, the time required for the fibres to come to equilibrium with this atmosphere is negligible compared with the time required for the dissipation of heat generated or absorbed when the regain changes. 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 fibre assembly and the geometry of the constituent fibres. Crank[12] pointed out that the water-vapour-uptake rate of wool is reduced by a rise in temperature that is due to the heat of sorption. The dynamic-water-vapour-sorption behavior of fabrics in the transient state will therefore not be the same as that of single fibres owing to the heat of sorption and the process to dissipate the heat released or absorbed.

Henry[13, 14] was the first man who started a theoretical investigation of this phenomenon. He proposed a system of differential equations to describe the coupled heat and moisture diffusion into bales of cotton. Two of the equations involve the conservation of mass and energy, and the third relates fibre moisture content with the moisture in the adjacent air. Since these equations are non-linear, Henry[13, 14] made a number of simplifying assumptions to derive an analytical solution.

In order to model the two-stage sorption process of wool fibres, Nordon and David[15] proposed three empirical expressions for a description of the dynamic relationship between fibre moisture content and the surrounding relative humidity. By incorporating several features omitted by Henry[13, 14] into the three equations, Nordon and David[15] were able to solve the model numerically. Since their sorption mechanisms (*i.e.*, sorption kinetics) of fibre were neglected, the constants in their sorption-rate equations had to be determined by comparing theoretical predictions with experimental results. Based on conservation equations, this global model consists of two differential coupled equations with variables for temperature and water concentration in air (C_a) and in the fibre of the textile (C_f), which is generally the water adsorbed by hygroscopic fibre. C_f is not in equilibrium with C_a, but an empirical relation between the adjustable parameters is assumed: the rate of sorption is a linear function of the difference between the actual C_f and the equilibrium values. The introduced coefficients are not directly linked to the physical properties of the clothes.

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

Li and Holcombe[18] developed a two-stage model, which takes into account water-vapour-sorption kinetics of wool fibre 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 fibre with two sets of variable diffusion coefficients. These research publications[18, 19] were focused on fabrics made from one type of fibre. The features and differences in the physical mechanisms of coupled moisture and heat diffusion into fabrics made from different fibre have not been systematically investigated.

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

Formulation of the problem

The mathematical model describing the coupled heat and moisture diffusion in textiles was first proposed by Henry[13, 14] and then further developed by Nordon and David[20] and Li and Holcombe[18]. The conservation of heat and moisture can be expressed by the following equations:

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

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

In the equations, both C_v and λ are functions of the concentration of moisture absorbed by the fibre. Most textile fibre 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 fibre and the inter-fibre 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[13, 14] derived a third equation to obtain an analytical solution by assuming that C_f is linearly dependent on T and C_s and that fibre reach moisture equilibrium with the adjacent air instantaneously. Downes and Mackay[21] found experimentally that the sorption of water vapour by wool is a two-stage process; the first stage obeys Ficks law of diffusion with a concentration-dependent diffusion coefficient. The second stage, which involves structural changes within fibre, is much slower than the first. To simulate the two stage-sorption process, Nordon and David[20] proposed an exponential function to describe the rate of change of fibre water content, which needs 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 Cranks truncated solution[12]. 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 a function of the sorption time and the initial regain of the fibre.

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

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

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 fibre, which is dependent on the time of sorption and the location of the fibre. In the first stage, the diffusion coefficient is concentration-dependent and is assumed to be a quadratic function of water content when the sorption is less than 540 s, 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 fibre is attenuated along with the time of sorption when t ≥ 540 s, as shown in equation (4b).

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

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

The second formula for D_f in equation (4b) shows that the rate of moisture diffusion into a wool fibre (when t ≥ 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 fibre, and polypropylene fibre which is reported by Li *et al.*[22] are summarized in the appendix.

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 and humidity (T_{a0}) and humidity (C_{a0} and H_{a0}), the temperature and moisture content being uniform throughout the fabric at known values:

$$T_a(x, 0) = T_{a0} \tag{5}$$

$$C_a(x, 0) = C_{a0} \tag{6}$$

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

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:

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

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

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

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

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.

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 fibre and fabric properties. Details of the solution method have been reported previously by Li and Luo[19].

EXPERIMENTAL

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. Fibre such as wool are hygroscopic and therefore it is common practice in the textile industry to equilibrate specimens to an atmosphere of 20°C and 65% relative numidity 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 has 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 author has measured the effective thermal conductivities of different knitted fabrics (Table-1) for varying regains. Regain is the mass of water present expressed as a percentage of dry weight of the material. The author believes that the effective thermal conductivity of moist fabrics may be influenced by the fibre sorption properties; so the fibre types we tested had different properties, namely :

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

TABLE-1
PERTINENT PROPERTIES OF FABRICS USED IN WATER ABSORPTION AND DRYING EXPERIMENTS

Fabric	Mass (g/m^2)	Thickness, (mm)	Mass of water in fabric (g)	Time to dry, (h)
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

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. The author obtained the desired regains by drying wetted samples; approximately 10 min 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. As it was noticed that the thickness of a fabric changes slightly with regain, so this approach was chosen for simplicity. After each test, the amount of water condensed on the heat sink by blotting it with a paper tissue was determined and then weighed.

RESULTS AND DISCUSSION

Figs. 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 behaviour of dry or normally conditioned fabrics. At 300% regain, the materials can be considered dripping wet. There are differences in the behaviour 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 fibre 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.

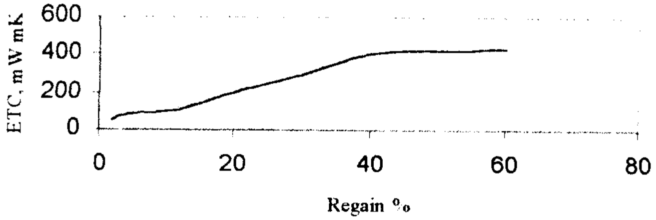

Fig. 1. Effective thermal conductivity (ETC) of a porous acrylic fabric as a function of regain

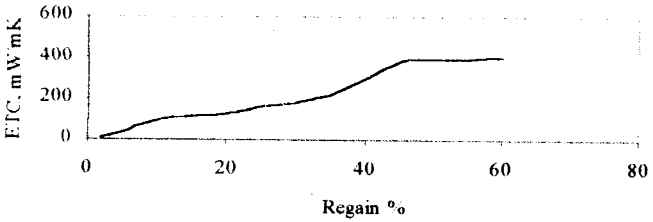

Fig. 2. Effective thermal conductivity (ETC) of a polypropylene fabric as a function of regain

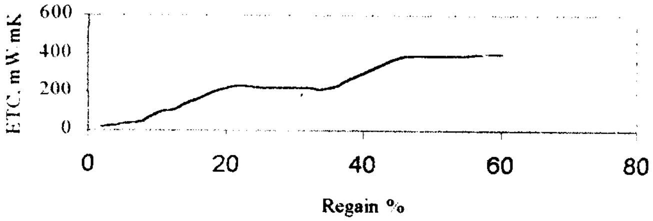

Fig. 3. Effective thermal conductivity (ETC) of a wool fabric as a function of regain

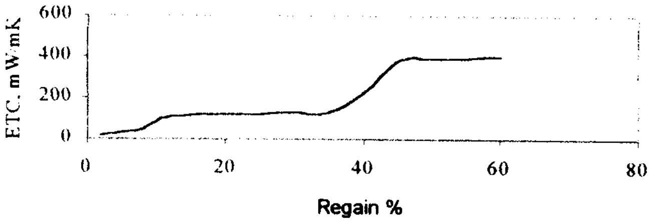

Fig. 4. Effective thermal conductivity (ETC) of a contton fabric as a function of regain

According to Table-1, the author has also found no relationship between regain and the amount of water picked up by the fabric (r = 0.074). Initially, he had plotted the per cent 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, he found the best correlation (r = 0.92) to be between the actual amount of water in the samples and their thickness (Fig. 5).

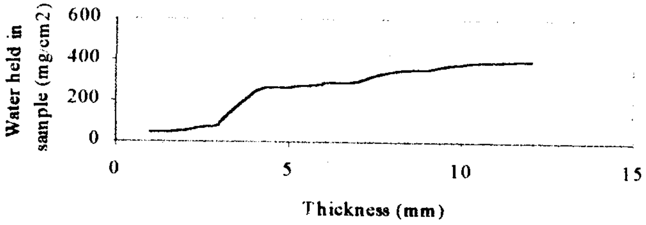

Fig. 5. A plot of Fourt *et al.* results for thickness versus the amount of water held

When he converted the results of others (Maejima[23], Dolhan[24], Fourt *et al.*[25], Bertioniere[26]) from liquid content to actual liquid content and plotted these values against thickness, he again found a very good correlation. The results of Fourt *et al.*[24], whose experiment included a very wide range of materials, are given in Fig. 6. It was concluded that expressing the amount of water in a fabric as a per cent of its mass is simply an extension of the per cent regain calculation for water vapour to that for liquid water. The amount of water vapour a fibre picks up, expressed as a per cent of its mass, is valid because it is directly related to the number of hydrophilic sites the fibre has to which water vapor can bond: this is proportional to fiber mass. Like Fourt *et al.*[24], 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 fibre type. Note that Fourt *et al.*[24] found that this relationship 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. After an initial equilibrium period at 0% r.h., 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 fabrics. Fig. 6 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 fibre fabrics.

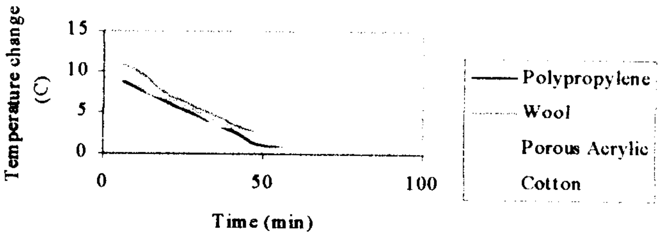

Fig. 6. Temperature changes at surface of fabrics during humidity transient

Finally, the question arises Can these results be applied to the person exercising strenuously and sweating? Several researchers have examined the effect of clothing made from various fibre of constructions on the physiological responses of subjects during work followed by rest.

Holmer[27] compared the heat exchange and thermal insulation of two ensembles, one made from wool, the other from nylon, worn by subjects who exercised either lightly (dry condition) or strenuously (wet condition) for 60 min, then rested 60 min. He found that there was a significant difference in physiological and subjective responses between dry and wet conditions, but not between the two fibre types. Further, there was no significant difference between the ratings of temperature and humidity sensations for the wool and nylon garments. The wool garment picked up more water than the nylon garment (245 g *vs.* 198 g) for the wet condition. However, the wool fabric may have been slightly thicker than the nylon fabric, since it was reported to have a slightly greater thermal resistance and therefore hold more water.

Nielsen and Edrusick[28] evaluated the effect of five kinds of knit structures, all made from 100% polypropylene on subjects exercising for 40 min at 5°C followed by 20 min at rest, and then repeated. The thickest knit, a fleece, caused the greatest total sweat production, retained the most moisture, and wetted skin the most. They stated that the hydrophobic polypropylene prevented extensive sweat accumulation in the underwear (10 to 22%) causing the sweat to accumulate in the outer garments.

Bakkevig and Nielsen[29] repeated the protocol above, but used low and high work rates with three kinds of underwear (a polypropylene 1 × 1 knit, a wool 1 × 1 knit and a fishnet polypropylene) worn under wool fleece covered by polyester/cotton outer garments. Total sweat production and evaporated sweat were the same for all three underwear fabrics, but where the sweat accumulated differed significantly. More sweat accumulated in the wool underwear than either polypropylene at both work rates. At the higher work rate, more sweat moved into the fleece layer from both kinds of polypropylene underwear than for the wool. Most likely for the 1 × 1 knits, the thicker wool underwear (1.95 mm) simply holds more water than the polypropylene underwear (1.41 mm) and based on outer layer-to layer wicking results, needs a greater volume of sweat to fill its pores before it starts to donate the excess to the layer above it.

Galbraith *et al.*[30] compared cotton, water repellent cotton and acrylic garments through wearing tests and concluded that the major factor causing discomfort was the excess amount of sweat remaining on the skin surface. Niwa[31] stated that the ability of fabrics to absorb liquid water (sweat) is more important than water vapour permeability in determining the comfort factor of fabrics.

Morooka and Niwa[32] postulated physiological factors related to the wearing comfort of fabrics as follows: sweating occurs whenever there is tendency for the body temperature to rise, such as high temperature in the surrounding air and physical exercise, etc. If liquid water (sweat) cannot be dissipated quickly, the humidity of the air in the space in between the skin and the fabric that contacts with the skin rises. This increased humidity prevents rapid evaporation of liquid water on the skin and gives the body the sensation of "heat" that triggered the sweating in the first place. Consequently, the body responds with increased sweating to dissipate excess thermal energy. Thus a fabric's inability to remove liquid water seems to be the major factor causing uncomfortable feeling for the wearer.

Hollies *et al.*[33] conducted wear trails for shirts made of various fibre. They concluded that the largest factor that influenced wearing comfort was the ability of fibre to absorb water, regardless of whether fibers were synthetic or natural.

All of these studies indicates that the transient state phenomenon responding to the physiological demand to cause sweating is most relevant to comfort or discomfort associated with this general principle. It is important to point out that a highly water absorbing fabric placed in the first layer keeps the partial pressure of water vapour near the skin low, which helps dissipate water at the skin surface, although the water vapour transport rate is smaller than for non-absorbing fabrics.

In other words, the dissipation of water by means of absorption by fabrics appears to be a much more efficient way to keep the water vapour pressure near the skin low than dissipation by permeation through fabrics. Highly water absorbing fabrics raise the temperature of the air space near the skin. The temperature rise will further decrease relative humidity; however, the higher temperature may or may not desirable depending on environmental conditions.

In the literature, the emphasis has been placed on the correlation between sweating and discomfort associated with wearing fabrics. However, there is relatively less emphasis placed on the influence of changes in the surrounding conditions, that is, the influence of the seasons. Many comfort studies are conducted with a single layer of fabric in relatively warm and moderately humid conditions. Severe winter conditions, which mandate the use of layered fabrics, would necessitate totally different kinds of testing procedures. Consequently, it is necessary to distinguish the comfort factor and the survival factor, and to investigate these factors with different perspectives.

The evaporation process is also influenced by the liquid transport process. When liquid water cannot diffuse into the fabric, it can only evaporates at the lower surface of the fabric. As the liquid diffuses into the fabric due to capillary action, evaporation can take place throughout the fabric.

Moreover, the heat transfer process has significant impact on the evaporation process in cotton fabrics but not in polyester fabrics. The process of moisture sorption is largely affected by water vapour diffusion and liquid water diffusion, but not by heat transfer. When there is liquid diffusion in the fabric, the moisture sorption of fibre is mainly determined by the liquid transport process, because the fibre surfaces are covered by liquid water quickly. Meanwhile, the water content distributions in the fibre are not significantly related to temperature distributions.

All moisture transport processes, on the other hand, affect heat transfer significantly. Evaporation and moisture sorption have a direct impact on heat transfer, which in turn is influenced by water vapour diffusion and liquid diffusion. The temperature rise during the transient period is caused by the balance of heat released during fibre moisture sorption and the heat absorbed during the evaporation process.

As a whole, a dry fabric exhibits three stages of transport behaviour in responding to external humidity transients. The first stage is dominated by two fast processes: water vapour diffusion and liquid water diffusion in the air filling the interfibre void spaces, which can reach new steady states within fractions of seconds. During this period, water vapour diffuses into the fabric due to the concentration gradient across the two surfaces. Meanwhile, liquid water starts to flow out of the regions of higher liquid content to the dryer regions due to surface tension force.

The second stage features the moisture sorption of fibre, which is relatively slow and takes a few minutes to a few hours to complete. In this period, water sorption into the fibre takes place as the water vapour diffuses into the fabric, which increases the relative humidity at the surfaces of fibre. After liquid water diffuses into the fabric, the surfaces of the fibre are saturated due to the film of water on them, which again will enhance the sorption process. During these two transient stages, heat transfer is coupled with the four different forms of liquid transfer due to the heat released or absorbed during sorption/desorption and evaporation/condensation. Sorption/desorption and evaporation/condensation, in turn, are affected by the efficiency of the heat transfer. For instance, sorption and evaporation in thick cotton fabric take a longer time to reach steady states than in thin cotton fabrics.

Finally, the third stage is reached as a steady state, in which all four forms of moisture transport and the heat transfer process becomes steady, and the coupling effects among them become less significant. The distributions of temperature, water vapour concentration, fibre water content, and liquid volume fraction and evaporation rate become invariant in time. With the evaporation of liquid water at the upper surface of the fabrics, liquid water is drawn from capillaries to the upper surface.

Conclusions

In summery, the physical mechanisms of moisture diffusion into fabrics vary with fabrics made from different degree of hygroscopicity. For highly hygroscopic fibre such as wool and cotton, the moisture diffusion can be described by a 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 fibre such as polypropylene fibre, 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 fibre 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. Fibre sorption properties mainly determine the evaporation process and therefore the heat and mass transfer by evaporation of water, diffusion of water vapour, and condensation. Fibre 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 fibre 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 fibre 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.

The overall dissipation rate of water vapour depends on both the vapour transport rate and the vapour absorption by fibre, which are mutually interrelated. Water vapour transport is governed by the vapour pressure gradient that develops across a fabric layer. When a fabric is subjected to given environmental conditions, the actual water vapour transport rate greatly differs depending on the nature of the fibre, even when other parameters are nearly identical, such as density, porosity, and thickness.

Appendix (Physical Characteristics)

Wool

Diffusion coefficient of water vapor—1st stage:

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

Diffusion coefficient of water vapor—2nd stage:

$$D_f = 1.6164\{1 - \exp[-18.163 \exp(-28.0W_c)]\}10^{-14}, \quad t \geq 540\ \mathrm{s} \tag{A2}$$

Diffusion coefficient in the air:

$$D_a = 2.5e^{-5} \tag{A3}$$

Volumetric heat capacity of fabric:

$$C_v = 373.3 + 4661.0W_c + 4.221T \tag{A4}$$

Thermal conductivity of fabric:

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

Heat of sorption:

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

Cotton

Diffusion coefficient of water vapor—1st stage:

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

Diffusion coefficient of water vapor—2nd stage:

$$D_f = 2.5\{1 - \exp[-3.5385 \exp(-45W_c)]\}10^{-14}, \quad t \geq 540\ \mathrm{s} \tag{A8}$$

Diffusion coefficient in the air:

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

Volumetric heat capacity of fabric:

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

Thermal conductivity of fabric:

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

Heat of sorption:

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

Porous Acrylic Fibre

Diffusion coefficient of water vapor—1st stage:

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

Diffusion coefficient of water vapor—2nd stage:

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

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 fibre:

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

Heat of sorption:

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

Polypropylene Fibre

Diffusion coefficient of water vapour—1st stage:

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

Diffusion coefficient of water vapor—2nd stage:

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

Diffusion coefficient in the air:

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

Volumetric heat capacity of fibre:

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

Thermal conductivity of fibre:

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

Heat of sorption:

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

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