MOISTURE TRANSMISSION THROUGH TEXTILES

Part I: Processes involved in moisture transmission and the factors at play

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Abstract:

Moisture transmission through textiles has a great influence on the thermo-physiological comfort of the human body which is maintained by perspiring both in vapour and liquid form. The clothing to be worn should allow this perspiration to be transferred to the atmosphere in order to maintaining the thermal balance of the body. Diffusion, absorption-desorption and convection of vapour perspiration along with wetting and wicking of liquid perspiration play a significant role in maintaining thermo-physiological comfort. The scientific understanding of the processes involved in moisture transmission through textiles and the factors affecting these processes are important to designing fabrics and clothing assemblies with efficient moisture transfer in different environment and workload conditions.
This paper is in two parts.
Part I focuses on the moisture transmission through textile materials and it discusses the processes involved in moisture transmission and the key influencing factors at play to maintaining comfort. It is underlined that the processes which play the major role in moisture transmission in a particular situation are dependant on the moisture content of the fabric, the type of material used, the perspiration rate and the atmospheric conditions, such as humidity, temperature and wind speed.
Part II is concerned with the selection of the measurement techniques which are of great importance in determining fabric factors that influence comfort. The instruments and methods used for testing purposes should adequately simulate the exact conditions for which the fabric will be used, in order to determine the effectiveness of that fabric for a particular wearing situation and environmental condition. The testing methods used and the apparatus developed by different researchers for determining moisture transmission through textiles by different mechanisms are discussed in this paper. Moreover, this part of the paper deals with the mathematical models of liquid and vapour transport through textile materials developed by several scientists in order to understand the exact phenomena involved and to predict the factors affecting the transmission under a particular condition.
When designing the comfort of a clothing product for a particular application, the requirements may result from needs concerning the application, the individual wearer and the environmental conditions.

Key words:

Thermophysiological comfort, diffusion, absorption, condensation, wicking, heat transfer

Introduction

Comfort is a pleasant state of psychological, physiological and physical harmony between the human being and the environment [1]. The processes involved in human comfort are physical, thermo-physiological, neuro-physiological and psychological [2]. Thermo-physiological comfort is associated with the thermal balance of the human body, which strives to maintain a constant body core temperature of about 37^0C and a rise or fall of ~ $\pm 5^0$C can be fatal [3]. Hypothermia and hyperthermia may result, respectively, due to the deficiency or excess of heat in the body, which is considered to be a significant factor in limiting work performance [4].

In a regular atmospheric condition and during normal activity levels, the heat produced by the metabolism is liberated to the atmosphere by conduction, convection and radiation and the body perspires in vapour form to maintain the body temperature. However, at higher activity levels and/ or at higher atmospheric temperatures, the production of heat is very high and for the heat transmission from the skin to the atmosphere to decrease, the sweat glands are activated to produce liquid perspiration as well. The vapour form of perspiration is known as insensible perspiration and the liquid form as sensible perspiration [5]. When the perspiration is transferred to the atmosphere, it carries heat (latent as well as sensible) thus reducing the body temperature. The fabric being worn should allow the perspiration to pass through, otherwise it will result in discomfort. The perception of discomfort in the active case depends on the degree of skin wetness. During sweating, if the clothing moisture transfer rate is slow, the relative and absolute humidity levels of the clothing microclimate will increase suppressing the evaporation of sweat. This will increase rectal and skin temperatures, resulting in heat stress [6].

It is also important to reduce the degradation of thermal insulation caused by moisture build-up. If the ratio of evaporated sweat and produced sweat is very low, moisture will be accumulated in the inner layer of the fabric system, thus reducing the thermal insulation of clothing [6] and causing unwanted loss in body heat. Therefore, both in hot and cold weather and during normal and high activity levels, moisture transmission through fabrics plays a major role in maintaining the wearer's body at comfort. Hence, a clear understanding of the role of moisture transmission through clothing in relation to body comfort is essential for designing high performance fabrics for particular applications.

Processes involved in moisture transmission through textiles

The process of moisture transport through clothing under transient humidity conditions is an important factor which influences the dynamic comfort of the wearer in practical use. Moisture may transfer through textile materials in vapour and in liquid form, as outlined bellow.

<u>Water vapour transmission</u>

Water vapour can pass through textile layers by the following mechanisms:

- Diffusion of the water vapour through the layers.
- Absorption, transmission and desorption of the water vapour by the fibres.
- Adsorption and migration of the water vapour along the fibre surface.
- Transmission of water vapour by forced convection.

The diffusion process

In the diffusion process, the vapour pressure gradient acts as a driving force in the transmission of moisture from one side of a textile layer to the other. The relation between the flux of the diffusing substance and the concentration gradient was first postulated by Fick [8].

$$J_{Ax} = D_{AB}\frac{dC_A}{dx} \quad (1)$$

Where, J_{Ax} is the rate of moisture flux; $\frac{dC_A}{dx}$ is the concentration gradient; and D_{AB} is the diffusion coefficient or mass diffusivity of one component, diffusing through another media.

Water vapour can diffuse through a textile structure in two ways, simple diffusion through the air spaces between the fibres and yarns and along the fibre itself [9,10]. In the case of diffusion along the fibre, water vapour diffuses from the inner surface of the fabric to the fibres' surface and then travels along the interior of the fibres and its surface, reaching the outer fabric surface. At a specific concentration gradient the diffusion rate along the textile material depends on the porosity of the material and also on the water vapour diffusivity of the fibre. The diffusion co-efficient of water vapour through air is 0.239 cm^2/sec and through a cotton fabric is around $10^{-7}cm^2$/sec. The moisture diffusion through the air portion of the fabric is almost instantaneous whereas through a fabric system is limited by the rate at which moisture can diffuse into and out of the fibres, due to the lower moisture diffusivity of the textile material [2].

In the case of hydrophilic fibre assemblies, vapour diffusion does not obey Fick's law. It is governed by a non-Fickian, anomalous diffusion [12,13]. This is a two stage diffusion process. The first stage corresponds to a Fickian diffusion but the second stage is much slower than the first, following an exponential relationship between the concentration gradient and the vapour flux [14-17].

This diffusion process can be explained by swelling of the fibres. Due to the affinity of the hydrophilic fibre molecules to water vapour, as it diffuses through the fibrous system, it is absorbed by the fibres causing fibre swelling and reducing the size of the air spaces, thus delaying the diffusion process [18,19]. Newns [20] has explained this reduction in the diffusion rate, as caused by the stress relaxation of the fibre after swelling. Li et. al. [21] have given an account to this phenomenon; the heat of sorption produced increases the temperature of the fibrous assemblies, which in turn affects the rate of moisture transmission.

The moisture diffusivity of a textile material is influenced by a number of factors. It decreases with an increase in the fibre volume fraction of the material. As the fibre volume fraction increases, the proportion of air in the fibrous assembly decreases, reducing the total diffusivity. The moisture diffusivity through the fabric decreases with an increase in the flatness of the fibre cross section [22]. With an increase in fabric thickness, the porosity of the material is reduced, thus reducing the diffusion rate [23]. Water vapour diffusion is highly dependent on the air permeability of the fabric [24]. Air permeability increases as the porosity of the fabric increases; which also results in higher moisture through the air spaces within the fabric. The type of finish applied (i.e. hydrophilic or hydrophobic) to a fabric has no great effect on the diffusion process [25]. The diffusion co-efficient of water vapour in air can be given as a function of temperature and pressure by the following equation [26]:

$$D = 2.20 \times 10^{-5} \left[\frac{\theta}{\theta_0} \right]^2 \left[\frac{P_0}{P} \right] \quad \text{(1a)}$$

Where D is the diffusion co-efficient of water vapour in air (m^2/sec), θ is the absolute temperature (K), θ_0 is the standard temperature of 273.15 K, P is the atmospheric pressure and P_0 is the standard pressure (Bar).

In general, the diffusion co-efficient of fibres increases with an increase in the concentration of water in the fibres; an exception to this behaviour is shown by polypropylene [12], due to its high hydrophobicity. The water vapour transmission through fabrics increases with an increase in the moisture content and in the condensation of water in the fabric [11].

The sorption-desorption process

Sorption-desorption is an important process to maintain the microclimate during transient conditions. A hygroscopic fabric absorbs water vapour from the humid air close to the sweating skin and releases it in dry air. This enhances the flow of water vapour from the skin to the environment comparatively to a fabric which does not absorb and reduces the moisture built up in the microclimate [27-30]. In the absorption-desorption process an absorbing fabric works as a moisture source to the atmosphere [31]. It also works as a buffer by maintaining a constant vapour concentration in the air immediately surrounding it, i.e. a constant humidity is maintained in the adjoining air, though temperature changes due to the heat of sorption. Barnes and Holcombe [27] examined the magnitude of the differences in moisture transport caused by fabric sorption, and the perception of these differences. Adsorption of water molecules takes place below a critical temperature, due to the Van der Waal's forces between the vapour molecules and the solid surface of the structure. The higher the vapour pressure and the lower the temperature, the higher is the amount absorbed. In a thermodynamic equilibrium the chemical potential of the vapour is equal to that of the absorbed film. An increase in vapour pressure causes an imbalance in chemical potential, and more vapour transfers to the absorbed layer to restore the equilibrium [19]. The amount of water vapour which can be absorbed by the materials is dependent on the fibre regain and the humidity of the atmosphere (%). In the case of absorbent fibres, e.g. cotton, rayon, the moisture sorption is not only dependent on regain and humidity, but also on the phenomena associated with sorption hysteresis, the effect of heat, dimensional changes and elastic recovery effects, due to the reduced swelling of the fibres. During swelling, the fibre macro-molecules or micro-fibrils are pushed apart by the absorbed water molecules, reducing the pore size between the fibres as well as the yarns, thus reducing the water vapour transmission through the fabric. As swelling increases the capillaries between the fibres get blocked, resulting in lower wicking. Also, the distortion caused by swelling sets up internal stresses which influence the moisture sorption process. The mechanical hysteresis of the fibres accentuates the adsorption hysteresis [19]. The adsorption hysteresis increases with an increase of the fibre hydrophilicity.

Convection process

Convection is a mode of moisture transfer that takes place while air is flowing over a moisture layer. This is known as the forced convection method. The mass transfer in this process is controlled by the difference in moisture concentration between the surrounding atmosphere and the moisture source. The process is governed by equation (2) [32].

$$Q_m = - A\, h_m\, (C_a - C_\alpha) \qquad (2)$$

Where Q_m is the mass flow by convection through area A of the fabric along the direction of the flow, C_a is the vapour concentration on the fabric surface and C_α is the vapour concentration in the air. The flow is controlled by the concentration difference ($C_a - C_\alpha$) and the convective mass transfer coefficient h_m, which depends on the fluid properties as well as on its velocity. In a windy atmosphere the convection method plays a very important role in transmitting moisture from the skin to the atmosphere [33, 34].

Evaporation and condensation also have a noteworthy effect on moisture transmission. Evaporation and condensation depend on the temperature and moisture distribution in porous textiles at the time of moisture transfer [35]. During the evaporation of liquid perspiration, latent heat is taken from the body, cooling it down. The role of evaporative heat transfer in maintaining thermal balance becomes more crucial with an increase in the surrounding atmospheric temperature. In this case, due to the low temperature gradient between the skin and the environment, conduction and convection heat transfer are reduced [36]. When a negative temperature gradient exists between the skin and the environment, evaporative heat transfer becomes the only way to cool down the body temperature. Since the latent heat of water is quite large (2500 kJ/kg), even a small amount of evaporation adds significantly to the total heat flow [37]. Wind enhances the evaporative heat transfer and results in additional cooling that is desirable in periods of peak performance. In the steady state, the latent heat lost by water due to evaporation is equal to the heat that comes to the water from the surrounding air, making it cooler. In that case the energy balance equation at the air-water interface [8] is as follows:

$$q_{conv} = q_{evap} \qquad (3)$$

Where q_{conv} is the convective heat transfer from the surrounding air to the water and q_{evap} is the heat taken from the water due to evaporation.

Condensation is a direct result of a fabric being saturated by liquid perspiration [12]. It occurs within the fabric whenever the local vapour pressure rises to saturation vapour pressure at the local temperature [38]. Condensation normally occurs when the atmospheric temperature is very low. When the warm and moist air from the body meets the fabric, it works as a cold wall, and condensation occurs. The results presented from laboratory testing and field trials have confirmed that condensation occurs at atmospheric temperatures below 10^0C [39]. In the case of fabrics where the water vapour can diffuse from the skin to a part of the fabric layer more easily than from the fabric layer to the atmosphere, such as in the case of water proof fabrics, the probability of occurrence of condensation is very high.

Condensation in an initially dry porous material takes place in three stages [40]. First of all, velocity, temperature and vapour concentration fields are developed within the material and condensation begins. In the second stage, the liquid content increases gradually, but it is still too low to move and finally, as the liquid content increases further and goes beyond a critical value, the pendulum like drops of condensate coalesce and begin to move under surface tension and gravity. When the vapour concentration at the two faces of the fabric, are at the saturation level, condensation occurs throughout the entire thickness of the fabric. If the vapour concentration at the two faces is bellow saturation for the local temperature, condensation occurs only over a region within the fabric. In this case, condensation occurring in the fabric forms a wet zone, separated by two dry zones [39, 40]. The extent of the wet region increases with the increase in condensation. The extension of condensation develops mainly in the direction of the hot side rather than that of the cold side. In the case of a waterproof breathable fabric, the extent of condensation is very high. The temperature and vapour concentration profiles during condensation along a normal fabric (a) and a three layer water proof breathable fabric (b) are shown in the Figure 1 [41].

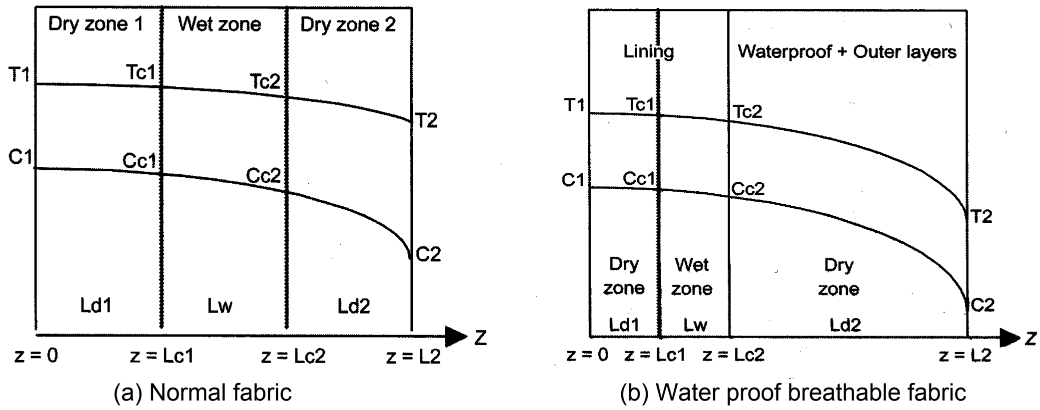


Figure 1. Temperature and vapour concentration in fabrics during condensation (thickness view)

Where T and C are the temperature and vapour concentration in the different layers of the fabric. z=0 and z=L2 consecutively stand for the inner and outer layers of the fabric. The rate of condensation is reduced, both with an increase in the hygroscopicity of the layer and with a decrease in the water vapour resistance of the fabric [42]. The water vapour transfer rate increases with an increase in the moisture content and condensation in the inner layer of the fabric [43]. With an increase in the amount of condensation in the fabric layer, its thermal insulation properties are reduced, as the thermal conductivity of water is 23 times larger than that of air [37].

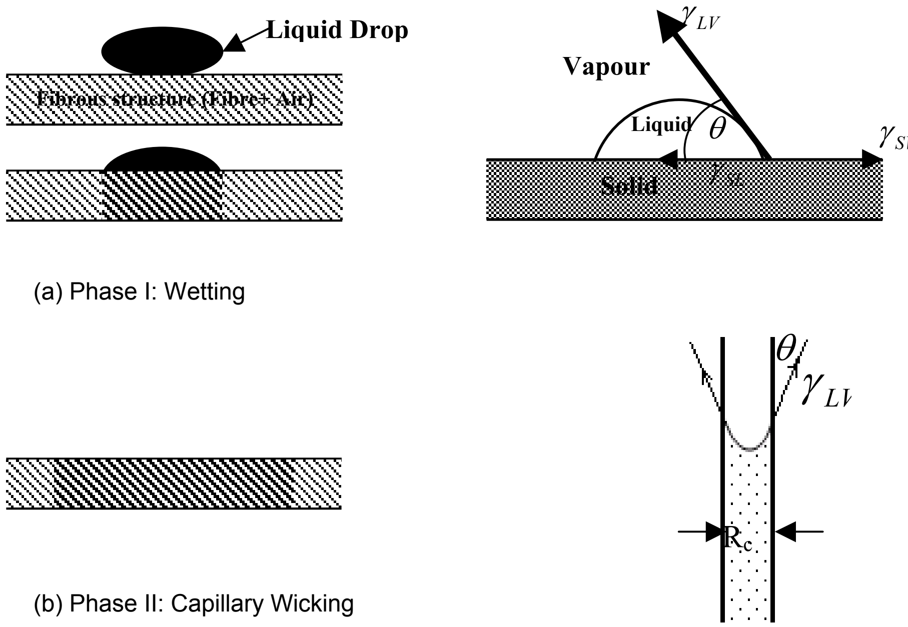
Liquid water transmission: Steady state flow

The flow of liquid moisture through textiles is caused by fibre-liquid molecular attraction at the surface of the fibre materials, which is mainly determined by the surface tension and the effective capillary pore distribution and pathways [35]. Liquid transfer through a porous structure involves two sequential processes – wetting and wicking. Wetting is the initial process involved in fluid spreading. In this process the fibre-air interface is replaced with a fibre-liquid interface as shown in Figure 2(a). The forces in equilibrium at a solid-liquid boundary are commonly described by the Young-Dupre equation, given below [44]:

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta \qquad (4)$$

Where, γ represents the tension at the interface between the various combinations of solid (*S*), liquid (*L*) and vapour (*V*), and θ is the contact angle between the liquid drop and the surface of the solid to be wetted. In the case of a textile material, the fibre represents the solid portion.

There are several factors influencing the wettability of the material. The contact angle is a direct measurement of the fabric wettability. A low contact angle between the fibre and the liquid means high wettability [45]. The wettability also increases, as the surface tension between the solid and the liquid interface diminishes. With an increase in the temperature of the liquid, its surface tension is reduced, resulting in higher wetting [19]. Also, with an increase in the liquid's density and viscosity, the surface tension of the material increases, thus reduces wettability. With an increase in surface roughness, the spreading of water along the surface becomes faster due to the troughs offered by rough surfaces as the apparent wetting angle is decreased. The wettability of the material also changes with the chemical nature of the surface and so with an increase in hydrophilicity, the contact angle is reduced, thus increasing the surface wettability [46]. As the roundness and the diameter of the fibres are reduced, the cosine values of the advancing angle increase, thus increasing the surface wettability.



(a) Phase I: Wetting

(b) Phase II: Capillary Wicking

Figure 2. The liquid transfer processes through a porous media

In sweating conditions, wicking is the most effective process to maintain a feel of comfort. In the case of clothing with high wicking properties, moisture coming from the skin is spread throughout the fabric offering a dry feeling and the spreading of the liquid enables moisture to evaporate easily.
When the liquid wets the fibres, it reaches the spaces between the fibres and produces a capillary pressure. The liquid is forced by this pressure and is dragged along the capillary due to the curvature of the meniscus in the narrow confines of the pores as shown in the Figure 2(b). The magnitude of the capillary pressure [19] is given by the Laplace equation:

$$P = \frac{2\gamma_{LV}\cos\theta}{R_c} \tag{5}$$

Where P is the capillary pressure developed in a capillary tube of radius R_c. A difference in the capillary pressure in the pores causes the fluid to spread in the media. Hence, a liquid that does not wet the fibres cannot wick into the fabric [47]. The ability to sustain the capillary flow is known as wickability [48]. The distance travelled by a liquid flowing under capillary pressure, in horizontal capillaries, is approximately given by the Washburn-Lukas equation [45]:

$$L = \sqrt{\frac{R_c \gamma \cos\theta}{2\eta}}\, t^{1/2} \tag{6}$$

Where, L is the capillary rise of the liquid in time t and η is the viscosity of the liquid. The amount of water that wicks through the channel is directly proportional to the pressure gradient. The capillary pressure increases as both the surface tension in the solid-liquid interface and the capillary radius decrease. A textile material consists of open capillaries, formed by the fibres walls [49]. From the Lukas-Washburn equation, it is expected that capillary rise at a specific time will be faster in a medium with larger pore size. However, Miller [50], using a comparative wicking study, showed that this is not always the case. He found that higher initial wicking through the capillaries with bigger diameter has been overtaken with time by the capillaries with smaller diameter. A larger amount of liquid mass can be retained in larger pores but the distance of liquid advancement is limited. This may be explained by the Laplace equation, as the radius of the capillary decreases, the pressure generated in the capillary will be higher, causing faster flow through the capillary. The model developed by Rajagopalan and Aneja [51] also predicts that at a constant void area, increasing the perimeter of the filaments increases the maximum height attained by the liquid. Conversely, increasing the void area at a constant perimeter decreases the final height attained, but increases the initial rate of liquid penetration. With the increase in the packing coefficient of the yarn, the fibres come closer to each other introducing a greater number of capillaries with smaller diameter likely to promote liquid flow. In any system where capillarity causes relative motion between a solid and a liquid, the shape of the solid surfaces is an important factor, which governs the rate and direction of liquid flow [52]. The shape of the fibres in an assembly changes the size and geometry of the capillary spaces between the fibres and consequently the wicking rate. With an increase in the non-roundness of a fibre, the specific area increases, thus increasing the proportion of capillary wall that drags the liquid.

The tortuosity [53] of the pores has a great influence on the wicking process. It depends on the alignment of the fibres as well as on irregularities in the fibre diameter or shape along the pores. With an increase in the tortuosity of the pores, its wicking potential is reduced [54, 55, 56]. For instance, yarns spun with natural fibres have very irregular capillaries due to various factors such as fibre roughness, cross-sectional shape and limited length, which interrupt the flow along the length of the yarn [56]. In the case of textured filament yarns, as the number of loops in the yarn increases, the continuity of the capillaries formed by the filaments decreases as the filament arrangement becomes more random. Under these conditions wicking is reduced. The same explanation is also applicable to the slower wicking found in twisted yarns. During the spinning process, at higher twist levels, slow migration of fibres takes place along the yam structure, changing the packing density and resulting in disruption of the continuity, length and orientation of the capillaries. The twist direction has no significant effect on the yarn wicking performance. The presence of a wrapper filament also retards wicking as the volume of liquid in the capillaries is reduced [57].
The density and geometry of fabric pores, which can be varied according to woven fabric structure, has a significant influence on the liquid flow pattern, both in the interstices and downstream [53, 58].

Darcy's law [19] is used to describe a linear and slow steady state flow through a porous media, and is given by equation (7). The rate of flow (Q) changes directly with the pressure head (ΔP) and is inversely proportional to the length of the sample (L_0) in the direction of flow:

$$Q = -K\frac{\Delta P}{L_0} \tag{7}$$

K is the proportionality constant, known as the flow conductivity of the porous medium with respect to the fluid. K is dependent on the properties of the fluid and on the pore structure of the medium [59]. Hydraulic conductivity can be written more specifically in terms of permeability and the properties of the fluids:

$$K = \frac{\mathrm{k}}{\eta} \tag{8}$$

where *k* is the permeability of the porous medium and is normally a function of the pore structure [49, 59] and η is the viscosity of the liquid. Capillary pressure and permeability are the two fundamental properties used to predict the overall wicking performance of a fabric [50]. The capillary pressure decreases with an increase in the saturation as the pores fill with liquid and decreases to zero for a completely saturated media. The permeability of the media increases with an increase in the saturation, due to the higher cross sectional area of the absorbed water film to flow [46]. At low saturation level, smaller pores in the media fill up first than larger pores. According to Adler [11] wicking can not begin until the moisture content is very high. Fast liquid spreading in a fibrous material is facilitated by small, uniformly distributed and interconnected pores. On the other hand, high liquid retention can be achieved by having a large number of pores or a high total pore volume [48, 60].

The dynamic surface wetness of fabrics, as described by Scheurell et al. [61], is an important parameter influencing the skin contact comfort in actual wear, as it is influenced by both the collection and the passage of moisture along the fabric. The dynamic surface wetness of fabrics has been found to correlate with the skin contact comfort in wear for a variety of types of fabrics, suggesting that the mobility of thin films of condensed moisture is an important element of wearing comfort.

Under normal condition unstressed perspiration of a resting person amounts to about 15 g/m^2.h and under conditions of exertion or in a hot environment, the perspiration increases to a value that may exceed 100 g/m^2.h. Perspiration rate increases with the level of activity [62]. Moisture collection by clothing, after exercise, in cold weather, may exceed 10% of the weight of the added water. It creates a surprisingly discomfort sensation due to the presence of a certain amount of water in the skin-clothing interface. Even as little as 3-5% moisture content in the garment creates ample discomfort

[61]. Clothing thermal insulation also decreases due to the moisture accumulation, and the amount of reduction varies from 2 to 8%, as related to moisture collection within the clothing assemblies [7]. Thus, in case of those activities where production of sensible perspiration is very high, dynamic surface wetness is a very important factor.

In the case of a cotton fabric, even though the moisture uptake from the skin is high due to high wettability, the dynamic surface wetness is not very good, as due to low capillarity, the passage of moisture is not spontaneous. It collects moisture in spite of flowing it out. As a result, it creates a clammy feeling in high sweating condition.

In the case of normal polyester fibre fabrics, even though capillarity is good, due to poor wettability they are not comfortable to wear. In the case of polyester microdenier fibre fabrics, the water up take is high and due to the high number of capillaries a large amount of moisture can pass very quickly through them to the atmosphere, thus providing a dry and comfortable feeling to the wearer.

Combined vapour and liquid transmission

In a humid transient condition, moisture is transported through textiles both in liquid and vapour form. Y.Li et al. [35] have identified that the transportation of moisture in humid transient conditions happens in three different stages. The first stage is dominated by two fast processes - water vapour diffusion and liquid water diffusion in the air filling the inter fibre voids, which can reach a new steady state condition in a fraction of a second. During this period, water vapour diffuses into the fabric due to the concentration gradient across the two surfaces. Meanwhile, the liquid water starts to flow out of the regions of higher liquid content to the drier regions, driven by surface tension. During the second stage, the moisture sorption of the fibres is much slower than during the first stage, and takes a few minutes to a few hours to complete, depending on the heat transfer processes. In this period, sorption of water into the fibres takes place as the water vapour diffuses into the fabric, which increases the relative humidity at the fibre surfaces. After liquid water diffuses into the fabric, the surfaces of the fibres are saturated due to the film of water on them, which enhances the sorption process. Finally, the third stage is reached as a steady state, in which all forms of moisture transport and heat transfer become steady and the coupling effect between them becomes less significant. In this condition, distributions of temperature, water vapour concentration, fibre water content, liquid fraction volume and evaporation rate become independent of time. With liquid water evaporation, liquid water is drawn from the capillaries to the upper surface. Combined liquid water and water vapour transmission along the fabric is very important in the case of sweat. The liquid transport (i.e. liquid diffusion or capillary wicking) is very small compared with the vapour diffusion at low moisture content, whereas at saturation, capillary wicking is the major mechanism of moisture transport [63, 11].

Combined heat and mass transmission

Moisture transmission through a textile material is not only associated with the mass transfer processes, but heat transfer must also be taken into account. Heat and moisture absorption in hygroscopic materials are inseparably interrelated.

During the transmission of water molecules through textile materials, they are absorbed by fibre molecules due to their chemical nature and structure. Absorption of water is followed by the liberation of heat, known as heat of absorption. The amount of heat produced is dependant on the absorption capacity of the material. Due to the production of heat, as the temperature is increased on the surface of the material, the rate of moisture vapour transmission is reduced [14,15,16]. During the investigation of the wool-water system, King and Cassie [4] observed that in a textile material, immersed in a humid atmosphere, the time required for the fibres to come to equilibrium with the atmosphere is negligible compared with the time required for the dissipation of heat generated and absorbed by the fibres when regain changes. With an increase in humidity, the heat transfer efficiency of the material increases. The heat transfer process also comes into play during the moisture transportation, under dynamic conditions, due to phase change of the water molecules. Thus, during the transient stages of moisture sorption and diffusion, the heat transfer process is coupled with four different forms of moisture transfer due to the heat released or absorbed during sorption/ desorption and evaporation/ condensation which in turn are affected by the efficiency of heat transfer and the length of the transient stage is dependent on the heat transfer process [7].

The coupling effect, between moisture diffusion and heat transfer depends on a number of properties, such as the moisture of sorption capacities (isotherm), the fibre diameter, the water vapour diffusion coefficient, the density and the heat of sorption [65]. The heat of wetting of cellulosic fibres depends to some extent on the moisture regain and the crystalline structure, and it decreases proportionally with an increase in the degree of crystallinity of the fibres [66].

Two transient phenomena, buffering and chilling, are associated with the simultaneous heat and moisture vapour transport through fibre assemblies [7]. The cooling effect or buffering effect is experienced due to perspiration in hot climates and the chilling effect is associated with the after exercise sweating in cool climates. At a sudden increase in relative humidity in the climate, fabrics absorb moisture maintaining a microclimatic condition and generating heat. This gives rise to a thermostatic or buffering action for the person wearing the fabric in clothing [29]. The cooling effect was first postulated by Spencer-Smith [68], who postulated that there would be a cooling effect at the onset of perspiration in hot climates, whereas in the case of cold climates it would result in a 'post exercise chilling effect' [69]. It reduces the working performance, even causing hypothermia. When water vapour (vapour perspiration) comes into contact with a cold wall (clothing), it condensates, thus reducing the thermal insulation of clothing. Both these phenomena are extremely dependent on atmospheric temperature and humidity conditions.

Conclusions

Diffusion is the main mechanism for transferring moisture in low moisture content conditions. Water vapour diffusion is mainly dependent on the porosity of the fabrics. The convection method is important in transferring perspiration from the skin to the atmosphere in windy conditions. With an increase in air velocity, the moisture transfer by convection increases. Wicking plays an important role in moisture transmission, when the moisture content of clothing is very high, and the body is producing large quantities of liquid perspiration. Fabrics to be worn as work wear in tropical climates, or as sports wear, should possess very high wicking properties. Therefore a fabric should be designed according to the area of application, e.g. best comfort for the level of perspiration generated.

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