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Thermophysiological Wear Comfort of Clothing: An Overview

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Abstract

Thermophysiological wear comfort concerns with the heat and moisture transport properties of clothing and the way it helps the clothing to maintain the heat balance of the body during various level of activity. Heat and moisture flow through clothing is a complex phenomenon. So, heat and moisture transfer analysis for clothing is an important issue for researchers. This article delves into the processes which are involved in heat and moisture transmission along with mathematical models of heat, liquid and vapour transport through clothing to understand the exact phenomena of heat and moisture transmission. The reported testing methods and parameters used for determining heat and moisture are also summarized in this article. This article also describes the need of heat and moisture transmission in clothing, desired attributes for heat and moisture management and parameters affecting heat and moisture transmission in clothing.

Keywords: Absorption; Comfort; Conduction; Convection; Diffusion; Condensation; Sorption

Introduction

Comfort may be defined as a pleasant state of psychological, physiological and physical harmony between a human being and the environment. Today humans rely on clothing which protects body from cold and heat throughout full range of human activities, otherwise it leads to discomfort. Discomfort mainly results from the build-up of sweat on the skin and insufficient heat loss during overheating in hot environments and exercise [1-4].

To create a comfortable clothing a designer considers fashion and other technical factors; fiber nature and size (microfibers that have particulars properties), surface modification of fibers (hydrophobic or hydrophilic treatments), hydrophobic (Gortex® e.g.) or hydrophilic membranes fused to the textile layers, weaving or knitting patterns and abrasion of the fabric surface etc. are parameters by which we can enhance comfort of clothing [5].

Extensive research has been published in the literature on the diverse aspects of simultaneous heat and moisture transfer both theoretically and experimentally. Results shows, that the ability of clothing materials to transport moisture vapour is a critical determinant of wear comfort, especially in conditions that involve sweating. So, for satisfactory performance of clothing comfort researchers recognize that clothing comfort has two main aspects. These are thermo physiological and sensorial comfort. The first relates to the way clothing buffers and dissipates metabolic heat and moisture [6-10], whereas the latter relates to the interaction of the clothing with the senses of the wearer, particularly with the tactile response of the skin, which includes moisture sensation on the skin [11-15].

The wear comfort of clothing is affected by physical processes include heat transfer by conduction, convection and radiation, meanwhile, moisture transfer by diffusion, sorption, wicking and evaporation [16-18]. During higher activity level and/or at higher atmospheric temperatures sweat gland get activated which produce liquid as well as perspiration. 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. If moisture transfer rate is not adequate during sweating than it may result in heat stress due to increase in rectal and skin temperature. From last few decades the field of dynamic heat and moisture transport behaviour of clothing and their influences on clothing comfort is main interest of researchers.

Clothing by its nature has an insulating effect and resists transfer of excess heat and moisture from the body. A still layer of air confined between the skin and fabric or between two fabric layers can make the wearer extremely uncomfortable due to its barrier effect. Thus the most important purpose of clothing is to provide a stable microclimate next to skin by maximizing the rate of heat and moisture loss from the body [19].

If ratio of evaporated sweat and produced sweat is very low, moisture will be accumulated in the inner layer of the fabric system, ultimately affect the thermal insulation of clothing [20]. It means there is some correlation between heat and moisture transmission through fabrics, which play a major role in maintaining a wearer's body in comfort zone. Hence a clear understanding of heat and moisture transmission from clothing is required for designing new high performance fabrics for different application.

In this paper attempt has been made to understand the mechanism behind heat and moisture transmission along with postulated models. Details of evaluated properties and equipment used to measure heat and moisture transmission is also explained.

Processes Involved in Heat and Moisture Transmission through Clothing

Process involved in heat and moisture transport is an important factor which influences dynamic comfort of clothing. Heat can be transferred within clothing in the form of conduction, convection,

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radiation and latent heat transfer by moisture transport. Conduction, convection and radiation are dominated by the temperature difference between skin surface and environment and are therefore grouped as dry heat transfer. On the other hand, latent heat transfer is achieved by moisture transmission related to water vapour pressure between the skin surface and the environment.

For an unclothed body seated at rest in mild ambient conditions, the metabolic rate is about 60 W/m^2. If thermal comfort is assumed there is no thermoregulatory sweating and the only source of moisture loss is diffusion through the skin itself. The heat flux associated with this diffusion may be expressed in terms of the condition between skin and the ambient air as follow [21].

$$H=4.0+0.12\ (P_{ssk}-P_a) \tag{2.1}$$

Where H represents evaporative heat flux in W/m^2, P_{ssk} is saturation vapour pressure at temperature of skin (mill bars) and P_a is ambient vapour pressure (mill bars).

For a clothed body, comfort refers to the way clothing interacts with the body, with respect to dissipation of heat and moisture generated by metabolic processes [22]. There is production of thermal energy as a by-product of physical activities. For body temperature to be stable heat losses need to balance heat production. This balance is given by following equations.

Store=(Heat production–Heat loss)=(Metabolic rate–External work)–(conduction+convection+radiation+evaporation+respiration)

If heat store is negative, more heat is lost than produced and body starts cooling. If however, heat production by metabolic rate is higher than the sum of all heat losses, heat store will be positive which means that the body heat will increase and body temperature will rise [23,24].

Fundamentals of Heat Transfer through Clothing System

Heat can transfer from textile layers by conduction, convection, radiation and wind penetration mechanisms as shown in Figure 1.

Conduction: Conduction means flow of heat through interaction or collision of adjacent molecules. Dry heat is transferred by conduction through air layers that are found on the surface of the textile layers, as well as through the air within the textile layers and through the textile fibres. Conductivity of textile fibres is much higher than air, indicating the importance of trapped air within garments to the conductive heat loss.

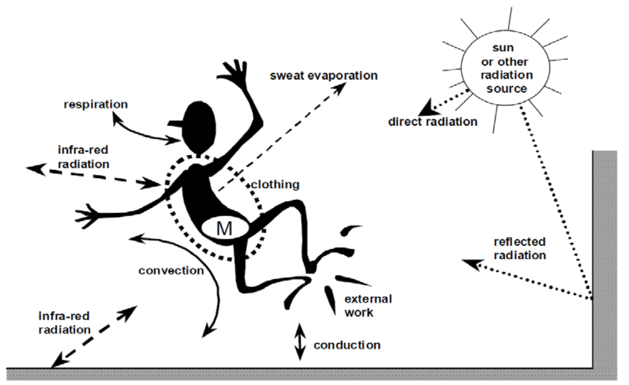

Figure 1: Schematic representation of the pathways for heat loss from the body, M: Metabolic Heat Production.

According to Fourier law, energy conducted can be expressed as [25]:

$$Q_{cond}=-KA\frac{dT}{dx} \tag{2.2}$$

Where k is proportional coefficient called thermal conductivity, A is the cross sectional area from where thermal energy passes through, T is temperature and x is thickness of material.

Convection: Convection means transfer of heat from one place to another within fluid, gas or liquid. The air is not held by textile fibres, and is able to move due to natural convection (rising of warmed air) or is forced to move by forced convection (wind, body movements creating a bellows effect); heat will be transported with the air moved defined by its enthalpy.

Appropriate heat transfer rate equation is given by [25]

$$Q_{conv}=-hA\ (T_s-T_\infty) \tag{2.3}$$

Where Q_{conv} is convective heat flow, T_s and T_∞ represent surface and fluid temperature respectively and h is convective heat transfer coefficient.

Radiation: In radiation heat flow is governed by temperature difference between the heat emitter and the heat absorber. Heat can be transported between the environment and the clothing surface by electro-magnetic radiation. This also occurs between clothing layers, and finally radiant heat transport can take place between the fibres within a textile, through the entrapped air. The more fibres, the less radiant transfer, though an optimum for overall conductivity of a textile is based on the balance between radiation and convection (denser, less radiation but more conduction through the fibre content).

Fanger derived equation for heat loss by radiation from the outer surface of the clothed body [26].

$$Q_{t,rad}=3.97\times10^{-8}[(T_{cl}+273)^4-(T_{mrt}+273)^4]A_{Du}f_{cl} \tag{2.4}$$

Where T_{mrt} is mean radiant temperature (^{0}C), A_{Du} is the DuBois surface area and f_{cl} is the ratio of effective radiating surface to the DuBois surface area.

Wind penetration: Wind penetration is induced by air pressure between inner surface and outer surface of clothing system. Air penetration can induce the air exchange. Kerslake pointed out that the rate of air penetration through the clothing assembly V_{ap} was linearly related to the wind velocity [27].

$$V_{ap}=3600\,A_s f_{op} v \tag{2.5}$$

Where A_s is surface area of the clothing assembly, f_{op} is the apparent portion of the surface area A_s that is open to air flow and v is wind velocity.

Fundamentals of moisture transfer through clothing system

Moisture from clothing may be transferred in vapour and liquid form. In vapour form different mechanism like diffusion, sorption, absorption, convection and condensation are involved whereas in case of liquid form wetting and wicking are two mechanisms which are generally take place as shown in Figure 2.

Diffusion: The transfer of water vapour molecules as a result of kinetic energy due to their random movement, which occurs through the air spaces between the fibers and yarns and along the fibers itself to keep microclimate dry enough to allow more sweat evaporation.

According to Fickian law, the moisture transmitted through the

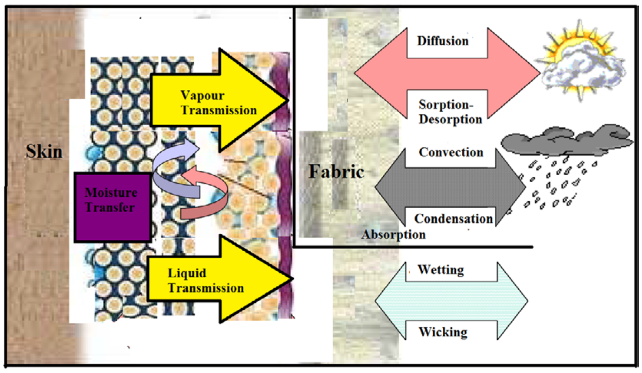

Figure 2: Schematic representation of the pathways for moisture loss from the body.

void space of the fabric through diffusion can be expressed as following [28].

$$m_{diff} = -D_{eff} A \frac{dC}{dx} \quad (2.6)$$

Where D_{eff} is effective diffusion coefficient of water vapour in fabric, A is the cross sectional area that the water vapour passes through, dC/dx is the gradient of water vapour concentration in void space.

D_{eff} is dependent on the volume fraction of water vapour (f_a) and defined as:

$$D_{eff} = \frac{D_a f_a}{\tau} \quad (2.7)$$

Where τ is effective tortuosity of the fabric for water vapour diffusion, D_a is the diffusion coefficient of water vapour in air.

Sorption-desorption: Any water bound to the textile fibres may be released as vapour again and take with it the heat of swelling plus the heat of evaporation, i.e. the reversal of absorption. This will reduce the local temperature. Sorption-desorption are 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 [29,30].

Absorption (adsorption): Water vapour travelling through textiles may be absorbed by the textile fibre. All materials, when allowed to absorb vapour until an equilibrium is reached, have characteristic absorption levels (expressed as regain), which increase with relative humidity and are typically higher for natural versus man-made fibres [31]. With this absorption heat is released in the textile, composed of the heat of condensation and the heat of swelling, raising the local temperature.

Convection: Similar to dry heat loss by convection, moving air will take with it the moisture contained in the microclimate, which can then be replaced by fresh air if the convective stream actually leaves the garment (ventilation). If not, it will have an equilibrating effect on local microclimate conditions.

The rate of moisture convection (m_{conv}) can be expressed as the form of Newton's law of cooling [32]

$$m_{conv} = h_m A (C_s - C_\infty) \quad (2.8)$$

Where h_m is the moisture convective transfer coefficient, C_s and C_∞ are moisture concentration at surface and liquid.

Condensation: Condensation is a direct result of a fabric being saturated by liquid perspiration**.** It occurs within the fabric whenever the local vapour pressure rises to saturation vapour pressure at the local temperature [33]. 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. Condensation in dry porous material takes place in three stages [34]. 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 below saturation for the local temperature, condensation occurs only over a region within the fabric.

Wetting: Wetting is the initial process involved in fluid spreading. In this process the fibre-air interface is replaced with a fibre-liquid interface. The forces in equilibrium at a solid-liquid boundary are commonly described by the Young-Dupre equation, given below [35]:

$$\Upsilon_{SV} - \Upsilon_{SL} = \Upsilon_{LV} \, Cos\,\theta \quad (2.9)$$

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 solid to be wetted.

Wicking: 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. The magnitude of the capillary pressure is given by the Laplace equation [31]:

$$P = \frac{2\Upsilon_{LV} \, Cos\,\theta}{R_C} \quad (2.10)$$

Where P is the capillary pressure developed in a capillary tube of radius *Rc*. 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 [36]. The ability to sustain the capillary flow is known as wickability [37]. The distance travelled by a liquid flowing under capillary pressure, in horizontal capillaries, is approximately given by the Washburn-Lukas equation [38]:

$$L = \sqrt{\frac{R_C \Upsilon Cos\theta}{2\eta}} t^{1/2} \quad (2.11)$$

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.

Evaluated Properties and Equipment used to Measure Heat Transfer through Clothing

Thermal conductivity, thermal resistivity and thermal absorptivity are some of properties which are measured for heat transfer through clothing.

Thermal conductivity

Thermal conductivity is fundamental to determine the heat transfer through fabrics. For textile materials, still air in the fabric structure is the most important factor for conductivity value, as still air has the lowest thermal conductivity value when compared to all fibers ($\lambda air=0.025$). Therefore, air transports a low quantity of energy by conduction and thermal conductivity decreases as well [39].

Thermal resistance

Thermal resistance expresses the thermal insulation of fabrics and is inversely proportional to thermal conductivity. In a dry fabric or containing very small amounts of water it depends essentially on fabric thickness and, to a lesser extent, on fabric construction and fiber conductivity [40].

Thermal absorptivity

Thermal absorptivity is the objective measurement of the warm-cool feeling of fabrics and is a surface related characteristic. If the thermal absorptivity is high, it gives a cooler feeling at first contact with the skin. The surface character of the fabric greatly influences this sensation [41].

Also various type of instrument has been used for measuring thermal properties of fabrics. The methods used for this purpose are discussed below.

Cooling method

In this method, a hot body is surrounded by fabric whose outer surface is exposed to air and the rate for the cooling of the body is determined. This method was used by Black and Mathew with a "kata-thermometer" [42].

Disc method

The fabric is held between a heat source and a heat sink at different temperatures and the flow of heat is measured by a thin disc. This gives the value of thermal transmissivity under particular conditions in the experiment. Since the fabric is compressed, it contains less air than under normal conditions during wear. Hence, the results that are obtained would only pertain to the particular apparatus and the pressure applied.

Measurement of propagation of waves (heat pulses)

This is a relatively new technique. It is an extension of the rate of the cooling method. In this technique, multiple waves of temperature gradients are passed through the sample and the damping of the wave is used to calculate the heat flux through the sample [43].

Constant temperature method

This method is used to get the most accurate determination of the thermal resistance. The fabric is placed on one side of an isothermal hot body that is insulated on all sides and energy required to maintain the hot body at a constant temperature is measured. The guarded hot plate is the most common form in this method which gives the most accurate determination of the thermal insulating properties of fabric. Three basic types of instruments have been tried by various workers to measure the thermal resistance of fabrics by the constant temperature method. They include

Hot cylinder type: There are many variations of the instruments that use this principle. Some useful descriptions are given by Morris [44]. Materials were wrapped around a constant temperature cylinder that was contained within another coaxial cylinder immersed in water. These instruments have the disadvantage of introducing a seam into the material, which is not recommended.

Hot semi-cylinder type (guarded): In view of the previously mentioned disadvantage, Baxter and Cassie [45] developed this instrument and provided a theory for measurements of thermal behaviour, which was based on Newton's law of cooling.

(Guarded) Hot plate type: Many workers have used this type of instrument based on the constant temperature method. The Shirley Togmeter is also based on the hot plate principle [46]. The guarded hot plate measurement technique has been employed in two modern internationally accepted standards viz. ASTM standard D1518 (2000) and BS 4745 (1974).

Evaluated Properties and Equipment Used to Measure Moisture Transfer through Clothing

As earlier, explained moisture can be transferred through clothing in two ways i.e either in vapour form or in liquid form.

Methods of measuring vapour transmission

Water vapour permeability is one major property which is measure for vapour transmission behaviour of clothing. For determination of water vapour permeability three methods are used viz. Permetest method, Cup method and MVTR cell method.

In different methods, different terms are used to express the water vapour permeability of a material [47]. Results obtained from the different available methods are not always comparable due to the different testing condition and the units used in the measurements. The most common units used for the measurement of the water vapour permeability of fabrics are [48-50] listed below:

- ***The percentage water vapour permeability index:*** WVP (% of turl reference fabric) is used in the evaporative disc method (BS 7209); this method uses water at 20°C and an atmospheric condition of 20°C and 65% relative humidity; this standard is based on the control dish method (CAN2-4.2-M77).

- ***The moisture vapour transmission rate:*** (in g m^{-2} day^{-1}) is used in the cup method (ASTM E 96-66); it uses air at relative humidity of 50% and a recommended water temperature of 32.2°C or a desiccant.

- ***The resistance to evaporative heat transfer:*** R_{et} (in m^2Pa/W) is used in the sweating guarded hot plate (ISO 11092:1993, EN 31092); it is an indirect method of measuring the vapour transmission property of a fabric. In this test method, the experiment is carried out at isothermal condition at standard atmospheric condition.

- ***The Resistance****:* in cm, of equivalent standard still air (in cm ESSA) is used in the holographic visualization method; in this method it is possible to measure the resistance offered by the fabric layer and the air layer separately. The resistance of the fabric (cm) can be expressed in terms of the standard still air providing the same vapour resistance.

Permetest method: This instrument works on principle of heat flux sensing [51]. The temperature of measuring head was maintained at room temperature for isothermal conditions. When water evaporates from measuring head, the heat lost from it is indirectly sensed by heat sensor. This instrument measures the heat loss from measuring head due to the evaporation of water in bare condition and with being covered by the fabric. Samples can be measured according to ISO 9920 and BS 7209 testing standard. The results of measurement are expressed by the instrument in terms of relative water vapour permeability (%) and water vapour resistance R_{et} (in m^2Pa/W). The relative water vapour permeability (p_{wv}) of the fabric sample has been calculated by the ratio of heat loss from the measuring head with fabric sample (μ_s) and without fabric (μ_o), and is determined using the following equation.

$$p_{wv}\ (\%)=100\frac{\mu_s}{\mu_0} \quad (4.1)$$

Cup method: This method directly determines the weight loss, with evaporation time (24 h) of water contained in a cup, the top of which is covered by the cover ring. In this method, test fabric is placed in an airtight manner over the top of the cup. Another cup contains the reference fabric secured in the same airtight manner and the experiment is performed in triplicate, so that three cups with sample fabric and three with reference fabric are tested. In this type of instrument samples can be tested according to ASTM E 96 (Procedure B) testing standard [52]. The results of measurement are expressed in terms of water vapour permeability index. Water vapour permeability index can be calculated by expressing the water vapour permeability (WVP) of the fabric as a percentage of the WVP of reference fabric, as shown below:

$$WVP=\frac{24\,X\,M}{A\,X\,T}\,g\,/\,m^2\,/\,24h \quad (4.2)$$

Where M is the loss in mass (g); T, the time interval (h); and A, the internal area of the cup (m^2). A was calculated using the following relationship:

$$A=\frac{\Pi d^2}{4}X\,10^{-6} \quad (4.3)$$

Where d is the internal diameter of cup (mm). Water vapour permeability index (I) in % was calculated using the following equation.

$$I=\left[\frac{(WVP)_f}{(WVP)_r}\right]X\,100 \quad (4.4)$$

MVTR cell method

The Grace, Cryovac Division has developed a moisture vapour transmission cell (MVTR cell), which offers a faster and more simplified method for measuring the water vapour transmission behaviour of a fabric. In principle, the cell measure the humidity generated under controlled conditions as a function of time. The change in humidity at a time interval gives the moisture transmission rate (T) of the fabric, as shown below.

$$T=(269\,X\,10^{-7})\,X\left(\Delta RH\%\,X\frac{1440}{t}\right)X\,H\,g\,/\,m^2\,/\,24h \quad (4.5)$$

Where ΔRH% is the average difference in successive %RH values; t, the time interval in min; H, the gram water per m^3 of air at cell temperature.

Methods of measuring liquid moisture transmission

Liquid moisture transfer through clothing consists of two processes–wetting and wicking.

Methods used to determine the wettability of a textile material: Tensiometry and Goniometry are used to measure the wettability of the textile material.

Tensiometry: The Processor Tensiometer has been developed to measure the wettability of the fabric by measuring the wetting force by the Wilhelmy method. In this method the wetting force (force applied by the surface, when the liquid comes in contact with it) is measured. The contact angles are calculated indirectly from the wetting force when a solid is brought in contact with the test liquid using the Wilhelmy principle [53].

Goniometry: In this method the wettability of a material is measured by measuring the contact angle between the liquid and the fabric by a image processing method [54]. The developments of Automated Contact Angle Tester (ASTM D 5725-99), HTHP contact angle tester and drop analyser tester have been based on this principle. In the case of the drop analyser tester two processes are used, namely the static wetting angle measurement and the dynamic wetting angle measurement [55]. The dynamic contact angle is used as a boundary condition for modelling problems in capillary hydrodynamics, including certain stages of the droplet impact problem. The dynamic contact angle differs appreciably from the static advancing or receding values, even at low velocities.

Methods used to determine wicking through a textile material: After wetting the fibre, the liquid reaches the capillary, and a pressure is developed which forces the liquid to wick or move along the capillary. This capillary penetration of a liquid may occur from an infinite (unlimited) or a finite (limited) reservoir [56]. The different forms of wicking from an infinite reservoir are transplanar or transverse wicking, in-plane wicking and vertical or longitudinal wicking. A spot test is a form of wicking from a limited reservoir. In the case of a vertical capillary rise, the effect of gravity slows down the flow rate before equilibrium is reached.

There are different standards to determine the wickability (vertical wicking) of fabrics [57]:

BS 3424:1996, Method 21 - specifies a very long time period (24 hours) and is intended for coated fabrics with very slow wicking properties.

DIN 53924, 1978 specifies a much shorter time of 5 minutes maximum and is therefore more relevant to the studies of clothing comfort involving the transfer of perspiration. Testing is undertaken at the standard atmospheric condition of 20°C temperature and 65% relative humidity.

Normally terms used to measure wicking are

Amount of water wicked (AWW) gg^{-1} determines the wicking capacity of the fabric away from the absorption zone.

Surface-water transport rate (SWTR) $gg^{-1}s^{-1}$ calculates the amount of water wicked by 1 gram of fabric per second.

Wicking time (WT) s is the time in seconds for the water to wick across a specified distance (3.25 cm).

Need for Heat and Moisture Management

Energy expended by a person engaged in normal routine indoor activity is 50 watts/square meter/hour. This metabolic heat generated gets dissipated as sweat through clothing. During sporting activity e.g. tennis or cycling, the metabolic heat increases six times and perspires 14 times. There is increase in human body humidity during sweating which ultimately reduced the absorbency of the textile apparels. If humidity of fabric remains unchanged there will be no transportation to the surface for evaporation, so cooling cannot occur. So, body get warmer which results, more sweat. To maintain a uniform heat and moisture transfer the fabric worn next to skin should have two important properties. First property required is to evaporate the perspiration from the skin surface and second one is to transfer this into atmosphere and make the wearer feel comfortable. According to researcher the clothing required for such purpose should feel soft and supple and also not cause any irritation to skin such as scratching or itching. Even when the skin is wet with sweat, the clothing should not stick to the skin.

Desired Attributes of Heat and Moisture Management Fabric

A good moisture management fabric must have following positive attributes.

- Optimum heat and moisture regulation
- Absence of dampness
- Good air and water vapour permeability
- Durable
- Rapid moisture absorption and conveyance capacity
- Breathability and comfort
- Raping drying to prevent catching cold
- Easy care performance
- Dimensionally stable when wet
- Light Weight
- Soft and pleasant touch
- Smart and functional design

Influencing Factors of Heat and Moisture Management

There are various factors which affect heat and moisture management properties. Main factors which influence the comfort characteristics of heat and moisture management in fibers, yarns and fabrics are given in Table 1.

Conclusions

Clothing thermophysiological wear comfort is an important issue for general consumers, technical textiles, active athletes and clothing with varying end use application. Clothing should possess good water

Sr no.	Structure/Property	Thermal Behaviour	Moisture behaviour
1	Fibre		
1.1	Type of fibre	Little Effect	-
1.2	Moisture regain of fibre (increase)	Decreases	Lower (Swelling)
1.3	Bulk of fibre (higher)	Increase	Higher
1.4	Density of fibre (increases)	Reduces	
1.4	Specific heat of fibre (high)	Increase	-
1.5	Finer the fibre with low density material (higher surface to volume ratio)	Increase	-
1.6	Shape of fibre like Hollow fibre/flat fibre	Increase/Decrease	Increase/Decrease
1.7	Higher crimped fibres create more interstices in yarn	Increase	-
1.8	Cross section of yarn (permit to form many voids)	Increase	Tortuosity Increases Ultimately Wicking
2	Yarn		
2.1	Type of yarn like textured and spun yarn hold more air	Increases	-
2.2	Yarn Twist (higher, lower will be the air volume)	Lower	Increase (Due To Capillary Action)
2.3	Fibre geometry /orientation (Parallel and Perpendicular)	Improve	-
2.4	Hairiness (surface entrapment of air)	Increases	-
2.5	Packing density (decrease)	Increase	-
3	Fabric		
3.1	Fabric structure (piled over knitted over woven)	Reduces	-
3.1	Thread Spacing (increase /woven)	Reduces	-
3.2	Fabric thickness increase (all type of fabrics)	Increases	Reduces
3.3	Density of fabric (lower)	Increases	-
3.4	GSM of fabric (increase)	Slight Increase	-
3.5	Porosity and Air permeability (Higher) and bulk density	Depend On	Increases
3.6	Surface characteristics (finishing treatments, texture)	Depend On	Not Significant
3.7	As Fibrous material compressed	First Fall Then Raises	
4	Other (Garment/multilayer)		
4.1	Gap between skin and garment increases up to 0.4 inch	Increase	-
4.2	Area of contact between fabric and hot body surface	Reduces	-
4.3	Rate of evaporation of water form skin or fabric	Depend On	-
4.4	External atmospheric condition like Temperature, R.H., Moment of surrounding air.	Depend On	-
4.5	Increase in wind velocity	Reduces	-
4.6	Pressure of surrounding air	Depend On	-
4.7	Rate of heat gain by absorption of water by fabric (moisture regain value of fibre, bulkiness)	Depend On	-

Table 1: Structure and property relation.

vapour as well as liquid moisture transmission property, along with transfer of heat generated within human body for providing the thermophysiological wear comfort. Heat and moisture transmission behaviour of clothing may be modelled mathematically for predicting their performance in actual wear condition. For such purpose heat and moisture transmission mechanism through clothing need to analyse along with material properties and other influencing parameters. Evaluation of heat and moisture transmission is very tough part. So, knowledge of instruments used to evaluate the heat and moisture transmission through clothing is of utter importance. As, there are lot of methods available to measure heat and moisture transmission through clothing but due to different testing conditions, parameters measured and unit used their results cannot be compared. As manufactures of sports and active outdoor wear, strive to improve the functionality of their collection by shifting their attention towards better heat and moisture management fabrics than existing ones. The discussion made in this article is useful for the textile researchers as a tool for further development of heat and moisture management fabrics.

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