MOISTURE TRANSMISSION THROUGH TEXTILES
Part II: Evaluation Methods and Mathematical Modelling

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Abstract

The moisture transmission behaviour of a clothing assembly plays a very important role in influencing its efficiency with respect to thermophysiological body comfort. This paper is in two parts. Part I deals with the processes involved in moisture transmission and the factors at play. Part II is concerned with selecting 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.

Key words:

evaluation method, mathematical modeling, thermophysiological comfort, water vapour transmission, wetting, wicking.

1. Introduction

The thermal comfort of clothing is associated with the thermal balance of the human body and its thermal responses to the dynamic interactions with the clothing and environment systems [1]. Both the heat and the moisture transmission behaviour of a fabric play a very important role in maintaining thermophysiological comfort. The fabrics should allow moisture in the form of sensible and insensible perspiration [2] to be transmitted from the body to the environment in order to cool the body and reduce the degradation of the thermal insulation of the fabric caused by moisture build-up [3]. The fabric which is in contact with the skin should be dry to the touch; otherwise heat, which flow from the body will increase, causing unwanted loss in body heat and a clammy feeling.

For a particular end-use it is necessary to design fabrics with required moisture transmission properties. The chosen experimental procedure is the most important consideration to be followed during the evaluation of the moisture transmission properties of the fabric and clothing system. Moisture and heat transfer through a fabric is measured in two conditions – steady state and transient state. The steady state experiments provide reliable heat and mass transfer data for the non-active case, but they cannot explain the heat and moisture transfer mechanisms in actual wearing condition. The human body is rarely in a thermal steady state, but is continuously exposed to transients in physical activity and environmental conditions [1].

2. Evaluation methods

2.1. Methods of measuring vapour transmission

Water vapour can be transferred through textile layers by different processes, e.g. diffusion, absorption-desorption and forced convection.

The route of diffusion through a layer can be described by the following mechanism: (a) molecular diffusion through solid (polymeric phase), (b) surface diffusion of adsorbed molecules along the fibres and (c) molecular diffusion through the air spaces of the fabric [5]. A vapour is diffused from one side of a fabric to the other in response to a difference in the pressure gradient. The diffusion process through a porous material is governed by Fick's law [6], as shown below:

$$J_{Ax} = D_{AB} \frac{dC_A}{dx} \quad \text{, in g cm}^{-2}\text{ sec}^{-1} \tag{1}$$

Where, J_{Ax} is the rate of moisture flux, $\frac{dC_A}{dx}$ is the concentration gradient, and D_{AB} is known as the diffusion coefficient or the mass diffusivity of one component diffusing through another media. The dependency of the moisture diffusivity of a textile material has been discussed in a previous paper [4].

The absorption-desorption process plays a major role in vapour transport through hygroscopic materials.

In the presence of air flow, the forced convection process plays a significant part in carrying moisture from the skin to the atmosphere, through the fabric layers, specially in the case of highly porous textile layers. In the case of a windy atmospheric condition or movement of air under clothing, corresponding to an "inner wind" due to body movement (known as pumping effect), the amount of moisture transferred by convection increases. The confined air layer close to the skin does not behave as a passive barrier. This is a place where strong convective movements take place, due to its vertical dominant disposition and by the separation of a few centimetres between two surfaces (skin and internal fabric) with sufficient amount of pressure gradient.

The measurement of water vapour permeability is a slow and somewhat delicate operation. However, it can be carried out quite effectively. The different methods used for determining the water vapour permeability of textile assemblies are as follows: the evaporative dish method or control dish method (BS 7209), the upright cup method or Gore cup method (ASTM E 96-66), the inverted cup method, the desiccant inverted cup method (ASTM F 2298), the dynamic moisture permeable cell (ASTM F 2298), and the sweating guarded hot plate method, knowing as the skin model (ISO 11092) [7, 8].

In different methods, different terms are used to express the water vapour permeability of a material [9]. 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 [10, 11, 8 and 12] listed bellow:

- 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 20^0C and an atmospheric condition of 20^0C and 65% relative humidity; this standard is based on the control dish method (CAN2-4.2-M77) and the Gore modified disc method (BPI 1.4)
- The *Moisture Vapour Transmission Rate* (in g m^{-2} Day^{-1}) is used in the cup method (ASTM E96-66); it uses air at relative humidity of 50% and a recommended water temperature of 32.2^0C 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.

ISO 7933 and ISO 9920 refer to two methods of determination of the evaporative resistance of a clothing assembly (R_T) [13]:

- The use of Fpcl, which is a reduction factor for evaporative heat loss with clothing, compared to the nude body.
- The use of $i_{m,}$ the permeability index of clothing, which provides a relation between evaporative and dry heat resistance of clothing items or systems.

According to ISO 7933, the clothing vapour resistance (R_T) is calculated using F_{pcl} as a reduction factor for the latent heat exchange of the clothed person compared to the nude situation, using the following equation:

$$R_T = \frac{1}{\left(h_e \times F_{pcl}\right)} \text{, m}^2 \text{ kPa W}^{-1} \qquad (2)$$

Where h_e is the evaporative heat transfer coefficient for the nude person, given by

$$h_e = 16.7 \times h_c \text{, W m}^{-2} \text{ kPa}^{-1} \qquad (3)$$

the constant 16.7 is the Lewis number (^{0}C.kPa^{-1}) and h_c is the convective heat transfer coefficient (W.m^{-2}.^{0}C^{-1}).

The humid heat transfer energy (E) is written in the following form:

$$E = h_e F_{pcl} \left(P_{skin} - P_{air}\right) \text{, Joule} \qquad (4)$$

Where, P_{skin} and P_{air} are the moisture pressure at the skin and ambient air respectively; h_e is the evaporative heat transfer coefficient. Clothing can also absorb liquid sweat by capillary action or wicking, and therefore not all the latent heat of evaporation is available for cooling the skin. Fpcl goes from zero to unity; Zero means that the fabric is completely impermeable and unity is used for the absence of clothing. The thickness and porosity of a given textile affects its Fpcl and if the textile is wet, the porosity decreases while the heat loss from the body increases by direct conduction, thus decreasing the thermal resistance and increasing the Fpcl. The definition of the relation between R_T, i_m and I_T is given in ISO 9920 [14]:

$$i_m = \frac{I_T}{L \times R_T} = \frac{h_e}{L \times h_{tot}} \text{, kPa/}^0\text{C} \qquad (5)$$

Where i_m is the index for vapour permeability, h_{tot} is the total radiation and convective heat transfer coefficient of clothing, including air layers, and L is the Lewis number.

The governing equations showing the effect of clothing on heat and vapour transfer are:

$$\text{Dry heat loss} = \frac{t_{sk} - t_a}{I_T} \text{, W/m}^2 \qquad (6)$$

$$\text{Evaporative heat loss} = \frac{P_{sk} - P_a}{R_T} \text{, W/m}^2 \qquad (7)$$

Where:

t_{sk} is the skin temperature,
t_a is the air temperature and I_T is the clothing insulation, including air layers,
P_{sk} is the skin vapour pressure,
P_a is the air vapour pressure and R_T is the clothing vapour resistance, including air layers.

The sweating guarded hot plate apparatus or "Hohenstein" skin model [10, 13] is used to measure the thermophysiological comfort of clothing. It simulates the moisture transport through textiles and clothing assemblies when worn next to the human skin. This model measures the water vapour resistance of the fabric by measuring the evaporative heat loss in the steady state condition. The temperature of the guarded hot plate is kept at 35^{0}C (i.e. the temperature of the human skin) and the standard atmospheric condition for testing (65% R.H. and 20^{0}C) is used. In this skin model, P_m is the saturation water vapour partial pressure at the surface of the measuring unit, P_a is the water vapour partial pressure of the air in the test chamber, H is the amount of heat supplied to the measuring unit of the water vapour resistance, ΔH_c is a correction factor and R_{et0} is the apparatus constant. The water vapour resistance of the fabric (R_{et}) may be calculated as follows:

$$R_{et} = \frac{A\left(P_m - P_a\right)}{H - \Delta H_c} - R_{et0} \text{, m}^2\text{Pa/ W} \qquad (8)$$

Hes [15] has developed a new fast response measuring instrument (skin simulator), the PERMETEST, for measuring of the water vapour permeability of textile fabrics, garments, nonwoven webs and soft polymer foils, by measuring the evaporative heat resistance. It works on the principle of heat flux sensing. The temperature of the measuring head is maintained at room temperature for isothermal conditions. The heat supplied to maintain the temperature of the measuring head, from where the supplied water gets evaporated, is measured. The heat supplied to maintain a constant temperature with and without the fabric mounted on the plate is measured. This instrument provides the relative water vapour permeability (%) of the fabric in the steady state isothermal condition.

$$\text{Relative water vapour permeability (\%)} = \frac{\text{Heat lost when the fabric is placed on the measuring head}}{\text{Heat lost from the bare measuring head}} \times 100$$

The PERMETEST can be used according to both BS 7209 and ISO 9920 standard. If the ring above the measuring head is used, a separating air layer will be created between the measuring head (simulated skin) and the fabric layer, thus providing the measuring condition according to BS 7209. On the other hand, if the ring above the measuring head is not used, the fabric will be in direct contact with the measuring head, i.e. according to the conditions used for the ISO 9920 standard.

In the dish method, the water vapour permeability of the fabric is measured by a gravimetric method. The specimen under test is sealed over the open mouth of a dish containing water and placed in the standard atmosphere for testing. After a period of time used to establish equilibrium, successive weighing of the dish is made and the rate of water vapour transfer through the specimen is calculated. In this method, the steady state water vapour permeability is also measured. The relative permeability of the sample is calculated comparing it with a reference fabric.

$$\text{Water vapour permeability (WVP)} = 24M / A.t, \ \text{g m}^{-2}\ \text{day}^{-1}$$

$$\text{Relative water vapour permeability index\%} = (WVP)_f \times 100 / (WVP)_r$$

where:

M is the loss in mass, g
t is the time between weighings in h
A is the internal area of the dish, m^2
$(WVP)_f$ and $(WVP)_r$ are the water vapour permeability of the test fabric and reference fabric respectively.

In the case of the upright cup method the fabric is placed and sealed above a cup, 2/3rd of which is filled with water and then the cup is placed in a wind tunnel at a standard atmosphere on a weighing balance and the change in mass of the fabric at a time interval is measured. In the case of the inverted cup method the cup with the fabric is placed in such a way that the fabric will be in the lower side of the water. The inverted cup method is designed for use with waterproof samples, because the fabrics which allow the passage of liquid water, may not be inverted as they will leak [7].

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 measures the humidity generated under controlled conditions as a function of time. The change in humidity at a time interval gives the moisture vapour transmission rate (T) of the fabric.

$$T = \left(269 \times 10^{-7}\right)\left(\Delta\%RH \times \frac{1440}{Time\ \ Interval}\right) \text{ g in}^{-2}\ \text{day}^{-1} \qquad (9)$$

Li and Holcombe [16] have set up an experimental apparatus, known as the sorption cell to measure moisture transfer through a textile material by the sorption process. The temperature and humidity of the cell is simultaneously controlled by immersing it in a hot water bath and feeding dry and wet nitrogen according to the required proportion. The sorption capacity of the fabric is measured from the reading obtained from the balance, from which the fabric has been hung. The temperature change due to water vapour sorption was measured by inserting a fine thermocouple into the surface layer of the fabric. A sorption cell gives the transient moisture content of the fabric sample and the moisture flux across the fabric, thus measuring the moisture sorption of the fabric and the moisture flux simultaneously in a transient condition [17, 5].

Gibson et al. [18, 19] developed a dynamic moisture permeable cell (DMPC), which is capable of evaluating the transport properties of textiles under various conditions such as pure diffusion, combined diffusion as well as convection and pure convection. The convective flow has been evaluated by measuring the relative pressure drop at the bottom outlet. The convective flow through hygroscopic porous materials is complicated, due to the tendency of the fibres to take up water vapour and experience fibre swelling. The change in the fabric connective flow properties has been taken as a function of relative humidity. The increment in the Darcy´s flow resistance with relative humidity is much less in the case of hydrophilic materials [20]. The DMPC can be used to obtain both steady state and dynamic state data.

The resistance to the water vapour transfer depends on the resistance of the air layer and the outer clothing. The resistance offered by the fabric layer in vapour transmission from the skin to the atmosphere is much lower than that offered by the external boundary air layer, and often much lower than that of the inner confined air layer between the skin and the fabric. So, in order to measure the flow resistance of a textile, we also need a precise determination of the surrounded air layers. Berger et al. [21] has developed a holographic bench technique, which can measure the mass flow with high accuracy using a micro-weighing technique. It separately measures the water vapour flow resistance offered by different air layers; thus it provides the precise vapour resistance value of the textile layer.

From comparative studies of the different methods used for water vapour permeability determination, it is concluded that the average WVTRs for all fabrics were lowest when measured with the upright cup, followed by the DMPC, and finally by the inverted cup method. The upright cup test and the dynamic moisture permeation cell were very highly correlated, and the desiccant inverted cup test and the sweating hot plate test were also highly correlated [7]. An inverse relationship exists between the resistance to evaporative heat loss and the water vapour permeability index of the fabric [8].

Both the water vapour permeability (W_d) and the water vapour transmission (WVT) have a direct relationship with the water vapour transfer across the fabric. The water vapour permeability (W_d) indicates the quantity of water vapour that has been moved through a unit area of the sample material in a certain point in time as a result of the pressure gradient between the two sides of the sample. The water vapour transmission value (WVT) also indicates the water vapour flow through the sample within a given time interval, but without reference to the water vapour pressure difference exerted during the measurement. The water vapour resistance (R_{et}) describes a material's resistance to moisture or evaporative transport through the material; therefore it is inversely proportional to the other two values.

From the experimental analysis of water vapour permeability of 30 different fabrics, using different available methods, Williams [22] has found that there are good correlations for the Control Dish using BS 7209 (0.979), the Skin Model (0.925) and the Gore Cup (0.995) methods as shown in Figure1, despite the differences in measuring techniques.

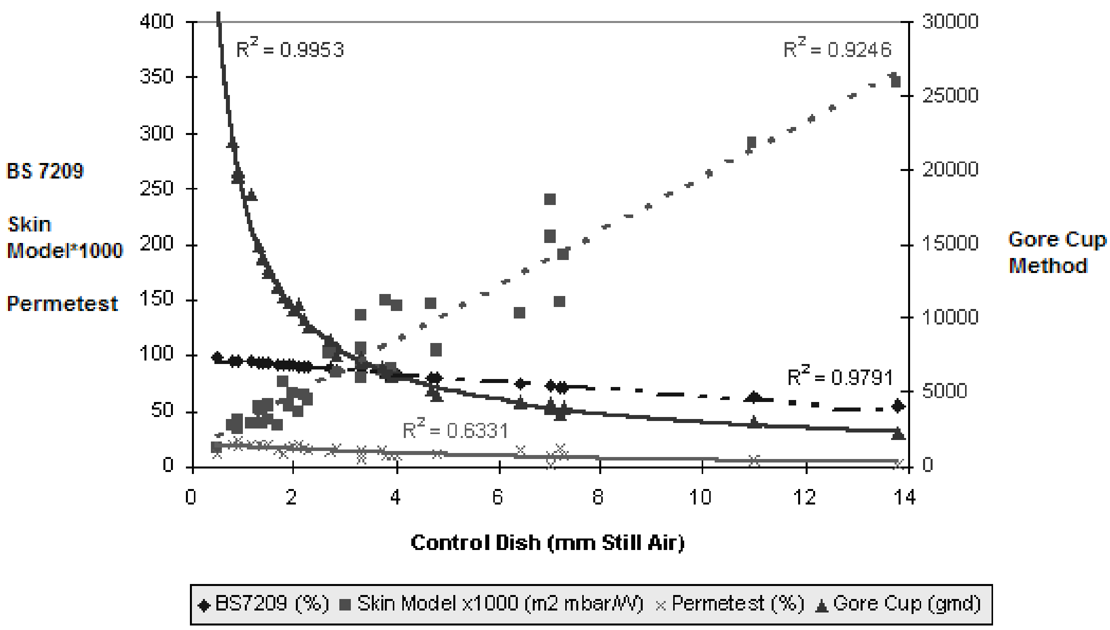


Figure 1. Water vapour transmission correlations

Depending on the water vapour resistance Congalton classified garments in three classes [11]

Class	R_{et}, m^2Pa/W
1	$150 < R_{et}$
2	$20 < R_{et} \leq 150$
3	$R_{et} \leq 20$

Whener et al. [5] developed a new experimental apparatus for the simultaneous measurement of moisture sorption by a fabric and moisture flux through a fabric during the transient period after the fabric has been exposed to a humidity gradient; based on the experimental results, a theoretical model has been developed. Gibson et al. has developed an automated apparatus, the Dynamic Moisture Vapour Permeation Cell (DMPC) to measure the combined vapour transfer through a fabric by diffusion and convection. The DMPC can be used to obtain both steady state and dynamic state data [19].

2.2. Methods of measuring liquid moisture transmission

Liquid moisture transfer through a textile material consists of two processes – wetting and wicking. In the wetting process the fibre-air interface is replaced with a fibre-liquid interface and wicking starts as the liquid enters into the capillary formed by two adjacent fibres or yarns. The forces in equilibrium at a solid-liquid boundary are commonly described by the Young-Dupre equation, given below [23]:

$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta \tag{10}$$

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. The wettability of a fibre by a particular liquid is determined by measuring either the wetting force in the fibre at the time of dipping it in the liquid or by the contact angle.

2.2.1. Methods used to determine the wettability of a textile material

i. 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 [24].

ii. 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 [25]. The developments of Automated Contact Angle Tester (ASTM D 5725-99), HTHP contact angle tester and drop analyzer tester have been based on this principle. In the case of the drop analyzer tester two processes are used, namely the static wetting angle measurement and the dynamic wetting angle measurement [26]. The dynamic contact angle is used as a boundary condition for modeling 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.

In many experiments, the dynamic contact angle is measured directly through low-power optics, but it leads to manual error. It is known from experiments that the dynamic contact angle depends on the spreading velocity of the contact line. To investigate the dynamic contact angle of impacting liquid droplets, a series of experiments were conducted by Sˇikalo et al. with individual droplets impacting onto solid dry and smooth surfaces [27, 28]. To observe the spreading of a droplet, a high resolution CCD camera (Sensicam PCO 1240×1024 pixels) equipped with a magnifying zoom lens is used. The magnification can be manipulated so that the image can accommodate the maximum spread of a droplet [29]. Kamath et al.[30] has set up an experimental apparatus to measure the wettabillity of filament specimens using a liquid membrane technique. The force exerted by the liquid membrane on the filament specimen, as the ring with a liquid membrane moves up or down the filament specimen is evaluated by this instrument, thus measuring the wetting force. The University of Manchester developed the UMIST wettability tester, which gives the wettability as well as initial wicking rate of the fabric.

The skin dynamic wetness is a very important factor determining the contact comfort feeling of the skin. The clothing vapour resistance has been related with skin wetness and metabolic rate by the following equation [31]

$$w = \frac{E_{sw}}{E_{\max}} + 0.06 \qquad (11)$$

Where E_{sw} is the regulatory sweat evaporation rate, $E_{\max}$ is the maximal evaporation rate possible in the ambient climate with the present clothing and skin temperature for a totally wet skin and 0.06 is the minimal skin wetness (or moisture evaporation) due to diffusion through the skin. ISO 7730 is used to determine skin temperature, sweat rates and ambient temperatures for comfort at various metabolic rates. In ISO 7730, the required sweat evaporation at comfort is given as a function of the metabolic rate [32]:

$$E_{sw} = 0.42\ (M\text{-}58)\ ,\ \text{watt/m}^2 \qquad (12)$$

Where M is the metabolic rate.

Scheurell et al. [33] has developed a technique to measure fabric dynamic wetness. In this method they made it possible to observe the dynamic moisture change in the fabric by treating it with cobaltous chloride before the experiment and observed the change in the colour due to the absorption of moisture during the test.

2.2.2. 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 [23]. 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 [24]. 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 [34]:

1. BS 3424:1996, Method 21 – specifies a very long time period (24 hours) and is intended for coated fabrics with very slow wicking properties.
2. DIN 53924, 1978 – specifies a much shorter time of 5 minuets 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 20^0C temperature and 65% relative humidity.

Normally the terms and units used for measuring absorption and wicking of fabrics are:

A. For bulk absorption:

1. Bulk material absorption (BMA) g g^{-1} – records the total absorption capacity of the fabric.
2. Bulk absorption rate (BAR) g $g^{-1}s^{-1}$ – calculates the amount of water absorbed vertically by 1 gram of fabric.
3. Bulk absorption time (BAT) s – records the time in seconds it takes for the water to be absorbed vertically into the fabric.

B. For wicking:

1. Amount of water wicked (AWW) g g^{-1} – determines the wicking capacity of the fabric away from the absorption zone.
2. Surface-water transport rate (SWTR) $gg^{-1}s^{-1}$ – calculates the amount of water wicked by 1 gram of fabric per second.

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

The various test methods used for the evaluation of absorption are the aqueous immersion test, the saturation value test and the drop test.

The heterogeneity of the test methods and of the time scales used to determine wetting, wicking and absorption have led to difficulties in the interpretation of the results.

Spontaneous transplanar [23] or transverse wicking [35, 36] has been deemed the term used when the transmission of a liquid is through the thickness of the fabric, that is, perpendicular to the plane of the fabric. Several techniques, but no standards, have been developed to measure transplanar liquid transport into fabrics. A test is used to measure the moisture accumulation associated with the wicking of liquid moisture from sweating skin [37]. The apparatus consists of a horizontal sintered glass plate kept moist by a water supply whose height can be adjusted so as to keep the water level at the upper surface of the plate. The specimen is placed onto the porous glass plate, and the uptake of water is measured by timing the movement of the meniscus along a long horizontal capillary tube. This type of test has been used to simulate a sweating skin surface [35].

In the case of in-plane wicking, the fabric surface stays in contact with the wetting liquid at a point from where liquid flows through the capillaries along the fibre axis. An instrument has been developed by IIT Delhi in order to measure in-plane wicking of fabrics. The instrument works on the siphonic principle and the water uptake by the fabric sample with time is recorded. The fabric sample is placed on a horizontal base plate which is connected to a liquid reservoir by means of a siphon tube. The fabric is covered by a glass top plate, so as to ensure intimate contact between the base plate and the fabric [38]. A similar instrument has been developed by Adams et. al. [39] to measure the in plane flow of fluids in a fibrous network. They have used an image analysis technique to obtain the shape and position of a radially advancing fluid front, which can define the directional permeabilities in the plane. Using this type of in plane wicking apparatus Johan et al. [40] have determined three principal permeabilities of a fibrous layer by a parallel saturated flow method using two flow cells, one for in-plane and the other for out-of-plane or transplanar measurements. From their experiment using card webs; it is observed that the out-of plane permeability is almost an order of magnitude lower and it contains more scatter than the in-plane permeability.

There is a limitation with the above type of instrument due to the use of the upper plate. A possibility may arise in which air bubbles might be trapped in the fabric or between the plates and the fabric, as there is no other pathway for the air to escape other than the edges of the fabric. This could introduce an uncontrollable error. Another source of error with this type of method is as both top and bottom plates stay in contact of the fabric, two extra capillaries are formed; one between the bottom plate and the fabric and the other between the fabric and the top plate.

Millar and Tyomkin [41] have introduced alterations to reduce the error that may cause by air entrapment when using the above instrument. They have replaced the non-porous solid top plate with an alternative kind of top plate, which consists of a set of 25 metal pins (1 mm diameter), evenly spaced, mounted in the same kind of plastic cover plate as before; the sample is attached to the pin tip where contact with the fabric occurs. A comparative study has shown that no significant difference has been obtained in the uptake rate or other kinetic parameters, but the total capacity of the fabric seems to be somewhat lower when the pins are used. They have used this type of top plate in a transplanner wicking tester.

Konopka and Pourdeyhimi [42] have developed an in plane wicking tester which has been able to overcome the entire above mentioned problems. This instrument works on a gravimetric principle and has a camera mounted above the plate to record the spreading of the liquid. The instrument is placed on a compression load cell, and is connected to the bottom of a plate using a plastic tube. This instrument replaces the electronic controls with an A/D interface card and appropriate software, which automatically maintains the platform height at the same level, maintaining a constant pressure head for testing. They have developed new types of plates to eliminate the extra capillaries and determine the intrinsic wicking ability of the fabric. In the middle of the plate there is a cylinder where the liquid enters the system and that is the initial point of absorption/wicking coinciding with the only point at which the fabric touches the plate. The liquid spreading distribution is determined by analysing the image captured by the attached camera.

D´Silva et al. [34] have developed a test method which provides information on both absorption and in plane wicking simultaneously. The absorption-wicking curve obtained form this typical instrument is given in Figures 2 and 3.

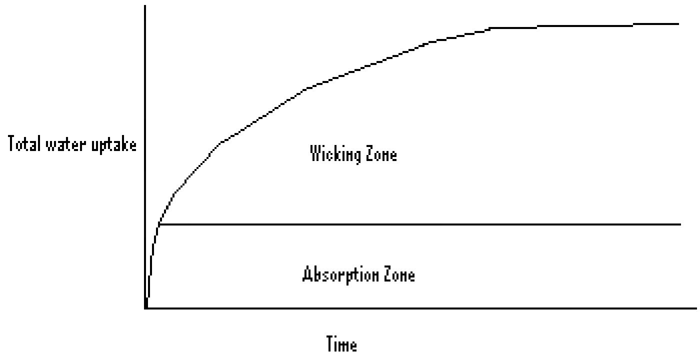


Figure 2. Typical combined bulk absorption and wicking curve of fabric

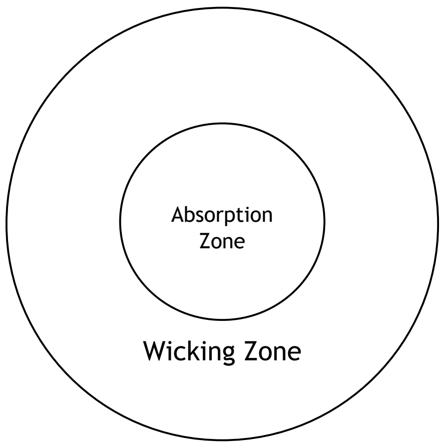


Figure 3. Plan of observed absorption and wicking in fabric

Vertical wicking can be measured by several techniques. In the visual observation method, the movement of the liquid along the sample is observed. The sample is hung from a glass rod that is attached horizontally to a ring stand and lowered vertically into a reservoir. The sample comes into contact with the contents of the reservoir in a perpendicular direction. A little amount of dye is added in the water, which can enhance the clear observation of the liquid. The movement of the liquid, in terms of height wicked by the water is measured as a function of time [38]. Microscopic observation has also been used by some researchers [43, 44, 45]. A load should be hung at the lower end of the sample so as to keep it straight.

Ansari and Kish [46] have developed an apparatus to study the water transport behaviour along a yarn, using electrical resistance technique. This technique is based on the difference in electrical conductivity between air and water. The electrical conductivity of water is 18 times higher than that of air; so, as the liquid wicks along the sample, the electrical resistance is reduced. The rise of the liquid water in the sample triggers an electrical circuit which is coupled with a personal computer, so that the rise of the liquid as a function of time may be recorded. The technique based on the measurement of the electrical resistance of fabrics was also used by other authors [47, 48]. J. Hu et al. have developed a moisture management tester to characterise fabric liquid moisture management properties, based on the same principle; measuring the electrical resistance of a fabric by this tester has been correlated with the fabric moisture content. Ten indexes have been introduced to characterize liquid moisture transmission. This method is also used to measure the liquid water transfer of a fabric in one step, in a multidirection way, as the liquid moisture spreads on both surface of the fabric and transfers from one surface to the opposite one [49].

Water transport along textile fibres has also been studied by various scientists using the electrical capacitance technique. Ito and Muraoka [50] have developed an apparatus based on the electrical capacitance technique. A similar apparatus was also developed by Tagaya et al. [51]. The dielectric constant of water is 80 times higher than that of air, and so, the water transport can be sensitively detected by measuring the change in electrical capacitance between the condensers. The electric current generated by the change in electric capacitance, which is caused by the transport of water, is converted into voltage by a current to voltage converter circuit. Molly et al. [52] developed a technique to study the moisture transport and to determine the mechanism by which moisture is transported between layers of fabric under transient conditions.

2.2.3. Liquid used for wicking

The liquid to be used for testing the wicking of a fabric or a yarn (for fabric comfort purposes), should simulate human sweat. Research has suggested that, for clothing physiology studies, the test should be conducted with a liquid with surface energy properties similar to human perspiration and heated to the human skin temperature of 35^0C [35]. Literature [53] states that the main electrolytes in sweat include sodium chloride (sodium chloride is table salt) and potassium chloride which is often used as a table salt substitute. Most human sweat contains at least 700 milligrams of sodium per liter, and probably averages around 1000 milligrams of sodium per liter. In an experiment conducted by Simile [54] in order to simulate sweat, a saline solution was produced with sodium chloride in water. Sodium chloride (NaCl) has an atomic mass of 58 g/mol with the sodium atom occupying 40% of that mass; therefore, 1 gram of sodium per liter equals 2.5 grams of NaCl per liter. Converting volume into milliliters, the solution becomes 0.0025 grams NaCl/ml or a 0.25% solution. This solution was used in a horizontal-downward wicking test with a fabric sample (7×1.5 cm). Comparing the results obtained by the perspiration simulant, distilled and tap water, it has been shown that testing with distilled water can give a good indication of how a fabric would act when in contact with liquid perspiration, as shown in Figure 4. The slope of the distilled water curve is 0.0082 cm/sec, while the slope of the simulant and tap water curves are 0.0081 and 0.0079 cm/sec, respectively. Hernett and Mehta [35] also found minor differences in their results comparing heated human perspiration with distilled water.

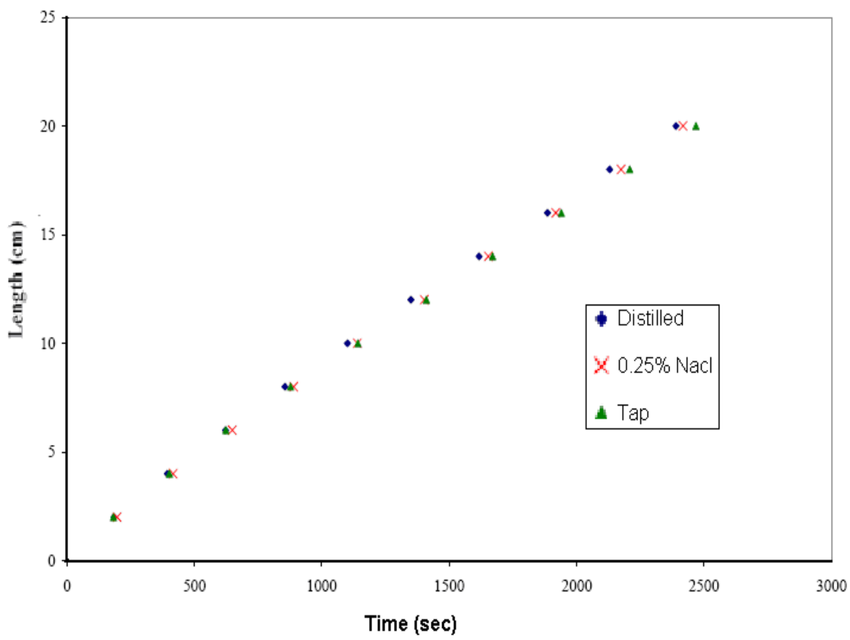


Figure 4. Downwards wicking comparison using distilled water, tap water, and a sweat stimulant, as wicking fluid

2.3. Measurement of combined heat and moisture transfer

Three methods are available for testing heat and moisture comfort of textiles: the micro climate method, the thermal manikin method, and the wear trial method. The micro climate method is used to evaluate the heat and moisture comfort of fabrics, whereas the thermal manikin method is used for clothing and wear trial method for subjective measurement. The evaluating methods of heat and moisture comfort of clothing are more complex than those used for fabrics. To evaluate the heat and moisture comfort of clothing, it is required to consider the human body, the clothing to be worn, the environment, and the other factors [55]. The thermal manikin has been developed to simulate the human body. The manikin acts as a heat transfer sensor that mimics a real three-dimensional body. It senses the difficult-to-model local sweat evaporation, convection and radiation processes that are highly dependent on local microclimate. The manikin is also used to accurately depict the sweat transport of a clothed human and analyse other effects of clothing.

Manikins are usually designed with the following capabilities and characteristics:

- Detailed spatial and rapid temporal control of surface heat output and sweat rate.
- A surface temperature response time approaching that of the human skin.
- A human like geometry and weight with prosthetic joints to simulate human motion
- Breathing with inflow of ambient air and outflow of warm humid air at realistic human respiration rates.

Two types of manikins are normally available: the sweating manikin and the dry manikin. With the dry manikin it is only possible to measure the dry heat flow, both in transient and steady condition. With the sweating manikin it is possible to measure the evaporated heat loss and the dry heat loss in both transient and steady state conditions [56].

The results obtained from thermal manikin testing are useful for [57]***:***

- Detailed assessment of thermal stress in environments with human occupancy;
- Determination of heat transfer and thermal properties of clothing;
- Prediction of human responses to extreme or complex thermal conditions;
- Validation of results from human experiments regarding thermal stress;
- Simulation of responses in humans exposed to thermal environments.

The thermal resistance of textile materials is measured in terms of S.I. units in degrees Kelvin meters-square per watt ($K.m^2/W$), defined as the ratio of the temperature difference between the two faces of the material to the rate of heat transfer per unit area of the material, normal to the faces. The Tog is an European unit of thermal insulation, and is one tenth of the S.I. unit. Another commonly used unit is the clo, which is approximately equal to 1.55 togs, and is defined as the resistance of clothing which provides comfort to a sitting – resting subject in a standard ventilated room at 21^0 C [58].

The International Standards Organisation (ISO) has produced an integrated series of international standards for the assessment of human responses to thermal environments, which include standards for the assessment of thermal comfort, heat stress and cold stress. ISO 7243 is used for the monitoring and control of hot environments. ISO 7933 is used to analyze the heat exchange between a worker and his or her environment. ISO 9886 is used in the establishment of personal monitoring systems of workers exposed to hot environments. ISO 9886 provides guidance on physiological measurement and interpretation. The ISO system therefore covers almost all exposures to hot environments [59].

Wang and Li [55] have developed a new method for measuring dynamic fabric heat and moisture comfort. Normally the indices which are used to characterize clothing and fabric comfort are CLO value, moisture permeability index (I_m) and evaporative cooling efficiency index. In their study they have used a microclimate method and they calculated the heat and moisture ratio (HMR) and the relative thermal diffusion ratio (RTDR) to evaluate the heat and moisture transmitting property of the fabric. They have introduced an advanced testing instrument, which can simulate both the latent and the apparent sweating states. Using this instrument they have experimentally found the relationship between the microenvironment and the dynamic H & M comfort of a fabric and their characteristics.

The Hohenstein Skin Model [10] and the PERMETEST can measure both the water vapour resistance and the dry heat transfer through a fabric. The former, evaluates the thermal resistance of a fabric under steady state conditions, by measuring the dry heat transfer from the guarded hot plate through the fabric using the following equation:

$$R_t = \frac{A(T_m - T_a)}{H - \Delta H_c} - R_{a0} \text{ , } m^2K/W \qquad (13)$$

where:

R_a is the thermal resistance of the fabric, and

R_{a0} is the intrinsic thermal resistance of the instrument,

T_m and T_a are the temperature of the guarded plate and air respectively,

H is the heating power supplied to the measuring unit, and

ΔH_c is the correction for heating power of thermal resistance.

The dry resistance of the fabric is evaluated by the PERMETEST by measuring the difference in the heat flow with and without sample, as follows:

$$R_t = (T_1 - T_0) \times \left[\frac{1}{S.u_1} - \frac{1}{S.u_0} \right] \text{, m}^2\text{K/W} \qquad (14)$$

where:

T_1 and T_0 are the temperatures with and without samples respectively,

u_1 and u_0 are the output voltages with and without sample,

S is the sensitivity of the instrument.

2.3. Measurement of condensation in clothing

Condensation is a phenomenon which takes place in the presence of a very high gradient of vapour pressure and temperature. It is a direct result of a fabric being saturated by liquid perspiration [60]. It occurs within the fabric whenever the local vapour pressure rises to the saturation vapour pressure at the local temperature [61]. 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 skin model is used to determine the condensation in the fabric for both steady and transient state conditions [62, 63]. In the sweating skin model, to analyze the unsteady heat and moisture processes two different types of procedures may be used - in one procedure, liquid water is injected close to the hot side of the sample; it evaporates there and re-condenses toward the cold impermeable side of the slab; in the 2nd procedure the hot plate is directly exposed to the moist air flow. Transient temperature changes are monitored and the total amount of absorption and condensation is measured after a specific time. Based on the sweating skin model Xiaohong et. al. [64] developed an apparatus to investigate whether condensation occurs on the fabrics. The sweating skin within the microclimate was simulated by the use of a fully wetted qualitative filter paper heated to the skin temperature of 32^{0}C using a hot plate. Two sensors are used to record and display temperature and relative humidity, simultaneously. The dynamic vapour pressure is calculated using the data of relative humidity and temperature, by using the following equations:

$$\phi = \frac{P}{P_s} \times 100\% \qquad (15)$$

$$P_s = 4.607 \exp\left[17.06 \left(\frac{T - 273.15}{T - 40.25} \right) \right] \text{, mm Hg} \qquad (16)$$

where:

P is the water vapour pressure (mmHg) at temperature T (K);

P_s is the saturation vapour pressure at the same temperature, and

ϕ is the relative humidity (%).

The relationship between the water vapour pressure and the water droplet radial when condensation occurs is given by the following equation:

$$\ln \frac{P}{P_s} = \frac{2\sigma}{\rho_w RT} \cdot \frac{1}{r} \qquad (17)$$

where:

r is the radius of the water droplet,

σ is the surface force of water,

ρ_w is the density of water,

R is a constant.

The Pressure (P) – Temperature (T) diagram of wetted air is used to record the condition of the microclimate and study whether condensation is formed on the inner surface of a fabric. In theory, condensation occurs under the conditions where the water vapour pressure present exceeds the saturation vapour pressure. The saturation line is described as the water vapour pressure which gives rise to 100% relative humidity at a specific temperature. A typical saturation line (P-T curve) is shown in Figure 5.

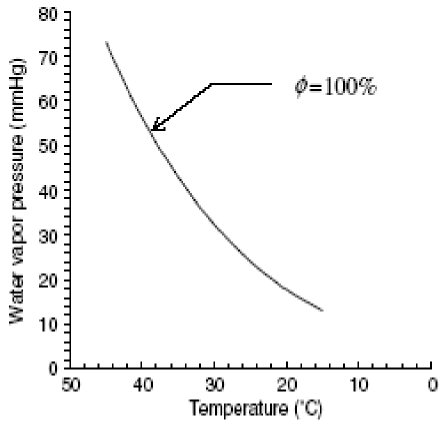


Figure 5. The saturation line

Keighley [65] and Ruckman [66] also suggested that the condensation occurring on the fabrics may be predicted by using a saturation line and a water vapour concentration line. Keighley [65] developed a method which involved the measurement of water vapour concentration using infrared absorption at the specific frequency of strong water vapour absorption. Ruckman provided a solution to the problem of condensation on the inner surface of a fabric by using a perforated metal cylinder simulating the perspiring human body, to investigate the couple mechanisms of water vapour transfer and heat transfer.

Fan et al. [67] and Murata [68] have set an experimental apparatus to measure the condensation in a fibrous material maintaining a hot and humid surface in one side and a cold surface in the other. Fukazawa et al. [69] have developed an apparatus to measure the water vapour resistance of textiles with and without temperature and pressure differences imposed on both sides of the fabric, and also to see the effect of the temperature and pressure differences on the condensation in the textile material.

3. Mathematical modelling

Prior to mathematical modelling of moisture transmission through fabrics (porous media), the dependency of the relevant material characteristics and the interface phenomenon among solid, liquid, gaseous vapour and air and liquid-vapour equilibrium must be considered. The coupled heat and moisture transfer in textile fabrics have been widely recognised as being very important for understanding the dynamic thermal comfort of clothing during wear. Moisture transmission through textiles is highly interrelated with the heat transfer phenomena, due to its hygroscopic nature. Clothing heat and vapour resistances are important inputs for standards and models dealing with thermal comfort, heat- and cold-stress [13, 70].

A general mathematical model on heat and mass transfer through porous media is constructed by using the conservation equations of heat and mass transfer. So, the models developed on vapour and liquid transmission also contemplate the heat transfer. Heat and mass conservation equations in porous media are coupled and, in general, solved by using the values of temperature and moisture content from previous iterations to calculate the source terms.

3.1. Modelling of vapour transmission

Several models have been developed by many researchers for better understanding of the diffusion phenomenon through textile materials. The mechanism of the transient diffusion of heat and moisture into an assembly of textile fibres was first proposed and analyzed by Henry [71]. He developed a system of differential equations to describe the processes involved, derived from the conservation of mass and heat transfer.

$$\varepsilon \frac{\partial C_a}{\partial t} + (1-\varepsilon)\frac{\partial C_f}{\partial t} = K\frac{\varepsilon}{\tau}\cdot\frac{\partial {C_a}^2}{\partial x^2} \quad (18)$$

$$C_v \frac{\partial T}{\partial t} - \lambda \frac{\partial C_f}{\partial t} = Q\frac{\partial T}{\partial x^2} \quad (19)$$

where:

C_a and C_f are the water vapour concentration in the air filling the interfibrous pores and in the fibres of the fabric respectively,

C_v is the volumetric heat capacity of the fabric,

ε is the porosity of the fabric, and

Q the thermal conductivity of the fabric.

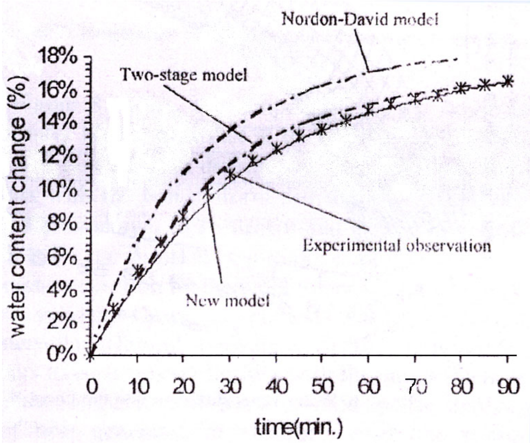
Using those two basic equations Nordon and David [72] have developed a model on coupled diffusion of moisture and heat in hygroscopic textile materials. They proposed an exponential relationship between the rate of change of water content of the fibres and the absolute difference between the relative humidity of the air and that with which the fibre would be in equilibrium. They have considered the two stage sorption process of the hygroscopic materials and expressed the equation for the two stage sorption taking the relative humidity difference into account. They have taken a parameter S which controls the pseudo equilibrium towards which the first stage of sorption tends. They have taken two rate constants k_1 and k_2, appropriate for first and second stage sorption.

$$\frac{1}{\rho(1-\varepsilon)}\cdot\frac{\partial C_F}{\partial t} = k\left(y_A - y_F\right) \quad (20)$$

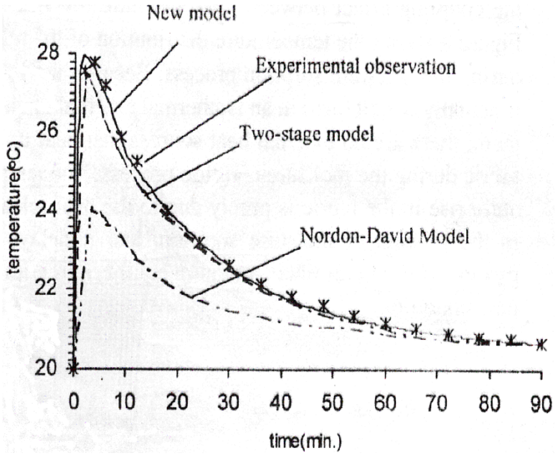
$$\frac{1}{\rho(1-\varepsilon)}\cdot\frac{\partial C_F}{\partial t} = \left[k_2 + k_1\left(S - \frac{y_F}{y_A}\right)^2 \frac{C_F}{\rho(1-\varepsilon)}\right]\left(y_A - y_F\right) \quad (21)$$

Here y_A and y_F are the humidity of the air and that of the fibres in the fabric respectively. k_1, k_2 and k_3 are rate constants for mass transfer, ρ is the density of the fibre and S is a parameter controlling pseudo equilibrium.

Whener et al. [5] presented two mathematical models of the diffusion of vapour through a textile material, considering that: (1) the moisture diffusion within fibres is very rapid (2) the moisture diffusion within fibres is very slow. The 1st model predicts that the total rate of removal (flux plus sorption) from the more humid side approaches its steady state value from a higher value, which matches with the experimental results. His 1st model seems to under estimate the length of the non-steady state period. In the 2nd model the intra fibre diffusion resistance has been taken into account and the whole period of diffusion has been considered as Fickian in character, whereas Li et al. [73] have considered the two stage sorption process. They have explained two sets of variable of diffusion co-efficient: a moisture content dependent co-efficient for the 1st stage and a time dependent co-efficient for the 2nd stage. Their model fits well with the experimental data as shown in Figure 6.



(a)



(b)

Figure 6. Theoretical prediction of water uptake (a) and temperature (b) at the fabric surface in comparison with experimental observations

Li et al [74] have also developed a mathematical model on the simultaneous heat and moisture transfer, considering, moisture sorption, condensation, and capillary liquid diffusion in porous textiles. They have taken a series of complex coupling effects between heat transfer and moisture transfer processes, including heat transfer by conduction and moisture transfer by water vapour diffusion, liquid capillary action, and moisture sorption of fibres. They describe the diffusion co-efficient of the moisture vapour in the fibres of the fabric; the liquid diffusivity has been determined by the following equation:

$$D_l(\varepsilon_l) = \frac{3\sigma \cos\phi \sin^{2\beta} d_c \varepsilon_l}{20\eta\varepsilon} \tag{22}$$

where:

d_c is the largest effective radius of the capillary, determined by the pore size distribution in the fabrics,

σ is the density of the fibre, and

η is the viscosity of the liquid.

Woo et al. [75] developed two models on heat and moisture transfer in nonwoven fabrics. In the first model they found the mathematical expression to describe the heat transfer through nonwoven fabrics. They have found the contribution of different transfer processes in the total transfer and also the effect of fibre size, fibre fineness, fibre conductivity, fibre volume fraction, fabric thickness, fibre anisotropy and fabric orthography on heat transfer. For the experimental purpose they have used a specially modified Kawabata Thermolab. Their model shows a good agreement with the experimental results. They have developed a second model to describe water vapour diffusion through non woven fabrics composed of non-hydrophilic fibres. They have used the analogy with the thermal conductive model. The model has considered the tortuosity of the diffusion path. It appropriately describes the diffusion through fabrics whose structural geometry can be approximated by a single homogeneous unit structure. They have also used this model to gain a deeper understanding of the effect of fibre volume fraction, fibre shape coefficient, fabric thickness and fibre diameter on water vapour diffusivity through non woven fabrics.

The heat released or absorbed within a hygroscopic textile layer with the change in humidity or temperature, is often physiologically very significant. The equilibrium amount of moisture absorbed by a fibre assembly is a function of relative humidity and temperature. Le et al. [76] developed a model for the interactive heat and mass transfer in the time of forced convection of the steam through an absorbing fibrous media. They have calculated the changes in the temperature in the condensing front due to the flow of the steam. They have used Darcy's law of fluid flow to describe the steam penetration through the media, but only the forced convectional flow of moisture, which is in the gas phase, has been considered. Dimensional natural convection and gravitational effects are ignored. It is considered that the diffusion of the moisture in gas phase is negligible and the liquid phase is in thermal equilibrium with the solid phase.

Gibson et al. [77] have developed a mathematical model of the convection and diffusion processes in textiles with inclusion of humidity dependent air permeability. They developed a set of partial differential equations to describe time dependant heat and mass transfer through porous hygroscopic materials; incorporating different important factors such as swelling of the fibre due to water imbibitions and the heat of sorption evolved when the water is absorbed by the polymer matrix, in the appropriate conservation and transport equations. They have used the controlled volume finite difference method to solve the system of equations representing the convection/diffusion process and for the experimental purpose the Dynamic Moisture Permeable Cell (DMPC) has been used to validate the theoretical results. Their approximation for the humidity dependant permeability works well for the situation where the high humidity flow is being forced through the fabric but does not match the experimental data as closely in case of low humidity flow. They have also developed a model using the volume average technique to predict the transient temperature changes and equilibration time during vapour transmission through a hygroscopic porous material, in the presence of convective flow [20].

The movements of the air under clothing correspond to an inner wind. Its velocity is a parameter difficult to be measured. It depends on the measuring site and on the air gap width. Body movement and wind speed both play important roles on the intrinsic air speed value. Backward and forward motions of clothing relatively to the body, during exercise and in a windy environment create a pumping effect [78]. The air penetrates through the pores and apertures, stays some time under the garment, then is evacuated and replaced by another volume of the ambient air. With the increase in the activity level, the time the air is trapped becomes shorter leading to increased convective mass losses. The convection coefficient in the air gap is a linear relation of the square root of the intrinsic wind speed [79].

$$h_{cl} = 8 + 17.5\sqrt{v_{in}} \qquad (23)$$

where:

h_{cl} is the convection co-efficient in $Wm^{-2}K^{-1}$, and

v_{in} is the intrinsic velocity.

The relative motion [56] has investigated the effect of forced convection on heat flow using a physical model (manikin) of a human body including heating and sweating. Curves obtained from their experimental results have been given bellow in Figures 7 and 8; which reflect that convection plays an important role in reducing the body temperature.

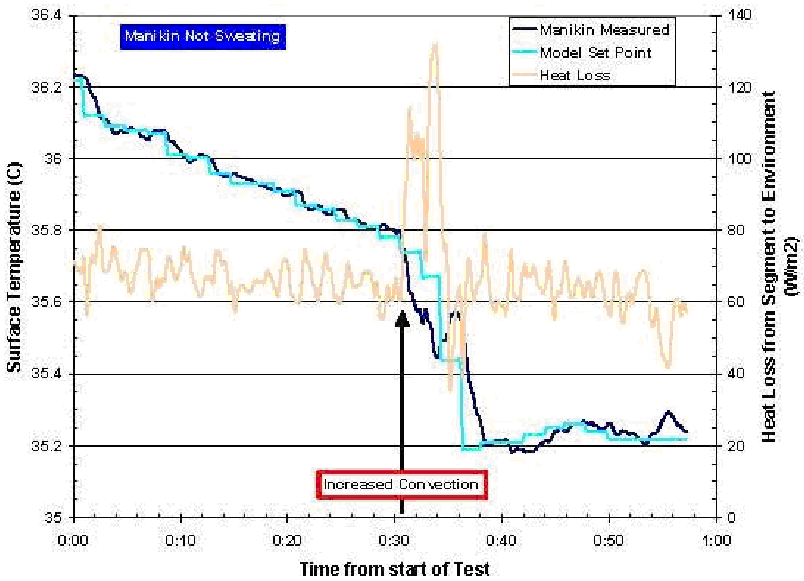


Figure 7. Forced convection cooling of a segment

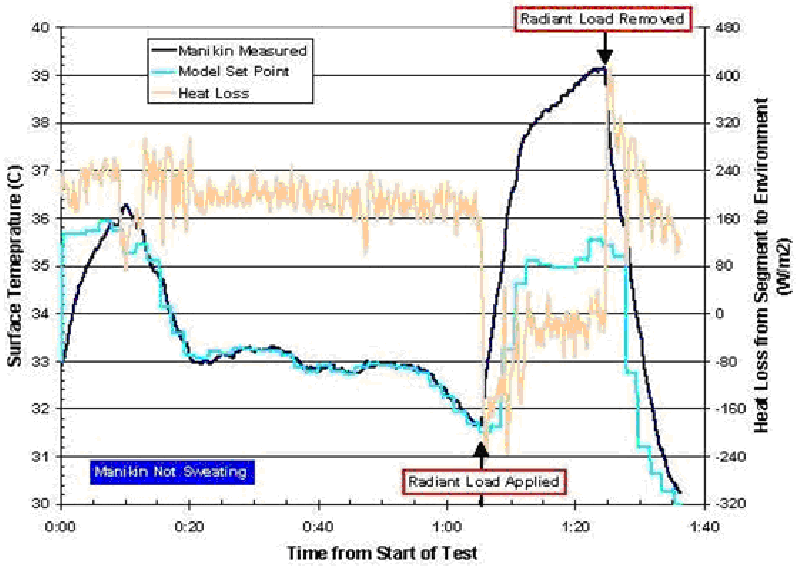


Figure 8. Radiant heating of segment

3.2. Modelling of liquid transmission

The fluid flow through the porous medium is normally determined using Darcy's law [81], as given in equation 24:

$$Q = -K \frac{\Delta P}{L_0} \tag{24}$$

The liquid rise in a capillary attributed to capillary pressure (*P*) which is equal to the internal wetting force(F_w) / unit area, is given by the following Laplace equation [80, 81].

$$\Delta P = \frac{2\gamma \cos\theta}{R_c} \tag{25}$$

where:

Q is the average flow velocity,
K is a proportionality constant related to the flow conductivity of the porous medium with respect to the fluid,
ΔP is the net pressure head that causes the flow, and
L_0 is the length of the sample in the direction of flow. The pressure difference can be obtained from Laplace equation.

The volume rate at which a liquid moves through a porous channel is related to the driving force by Poiseuille´s law [41]:

$$\frac{dV}{dt} = \frac{\pi r^4}{8\eta x} \Delta P \tag{26}$$

where:

r is the effective pore radius, and
x is the distance within the pores,
V is the volume of liquid that has been flown.

The relation between the liquid front position and the time of the droplet wicking has been given by Lukas-Washburn [48]:

$$L^2 = \frac{\gamma R \cos\theta_a}{2\eta} t \tag{27}$$

where:

L is the liquid front position or wicking height,

γ and η are the surface tension and viscosity of the liquid respectively,

θ_a is the apparent contact angle and t time.

From the above equation, Reed and Wilson have determined the time required by a liquid to reach a height x above the reservoir [82]. They have not considered the inertia effect.

Ghali et al. [83] have used the term saturation to express the fluid flow through a medium. They have measured capillary pressure and permeability over a wide range of saturations:

$$S = \frac{M_w - M_d}{v \times \rho - M_d / S.G.} \tag{28}$$

where:

S is the saturation,
M_w and M_d are the mass of the wet and dry samples;
v is the volume of the specimen, and
ρ is the density of water and S.G. is the specific gravity of the fibre.

The one dimensional vertical flow equation in the y-direction through a porous medium of uniform cross section can be obtained by combining the laws of conservation of water and a differential form of Darcy's equation:

$$\frac{\delta S}{\delta t} + \frac{\delta}{\delta y}\left[\frac{K}{\phi}\left(\frac{\delta h}{\delta S}\cdot\frac{\delta S}{\delta y} - 1\right)\right] = 0 \tag{29}$$

Yarlagadda and Yoganathan [84] developed a mathematical model for fluid spreading in a composite web structure. They have used the mass equation for this purpose. They have considered an analogous three-dimensional transient heat transfer model with varying thermal conductivities and heat capacities, to represent the actual phenomenon of fluid spreading in the composite web. A web structure with varying porosities in the layers and pores with certain preferred orientations is considered. They developed a set of parameters that best represents the spreading phenomenon. They have used three different models in their study to predict the dynamic fluid advancement in a web section:

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} + K_z \frac{\partial^2 T}{\partial z^2} = \rho C_p \frac{dT}{dt} \tag{30}$$

K_x, K_y and K_z are the thermal conductivity of the material in the corresponding directions.

Ghali et al. [85] developed a model for simulating the heat and mass transfer in fabrics during the wicking process. The model shows that, as the water is wicked through the fabric specimen, two temperature zones are formed. Within the region the temperature gradient is small but between the regions it is significant. Unlike the temperature, the variation of the fractional saturation is continuous along the specimens. To develop the model they have taken a number of assumptions to reduce the complexity of the problem of the transport process. Here, they considered that the evaporative energy becomes the dominant energy effect causing the temperature of the fabric to decrease. This numerical model is capable of simulating the temperature distribution of the fabric specimen during the wicking process and it can also predict the temperature front. Here, mechanical swelling and shrinkage of the fibres have not been taken into account. This model is developed considering the liquid is Newtonian in nature:

$$\frac{\partial(\varepsilon_1 \rho_1)}{\delta t} + \frac{\partial}{\partial z}(J_1) + \frac{\partial}{\partial z}(J_v) + \frac{2h_m}{\partial}(P_v - P_\alpha) = 0 \tag{31}$$

$$\begin{aligned} &\rho C_p \frac{\partial T}{\partial t} + J_1 \frac{\partial}{\partial z}(h_1) + Q\frac{2h_m}{\partial}(P_v - P_\alpha) \\ &+ \frac{2h_c}{\partial}(T - T_\alpha) + Q\frac{\partial}{\partial z}(J_v) = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) \end{aligned} \tag{32}$$

where:

J_l and J_v are the mass flux in liquid and vapour form,
h_l is the enthalpy of liquid water,
h_m and h_c are the moisture and heat transfer coefficients.

Young-Laplace theory is based on solid planner surface wetting, but there are a number of important differences between the wetting of a solid planner surface and a fibrous structure. Lukas et al. [86] have pointed out the unique features and the problems of fibre wetting. They have developed a model which applies the so-called Ising model and Kawasaki thermodynamics, combined with the Monte Carlo computer simulation technique to study the liquid fibre inter action and wetting behaviour of fibre networks. The Ising model is a tool used to study the ferromagnetic phase transition. Lukas et al. have introduced the various interactions occurring in a liquid-fibre mixture and the energy components associated with these interaction. They considered the problem of liquid fibre mass wetting as two dimensional regular and square lattice cells. This model is only suitable for the two-dimensional case.

Wheiner and Dejlova [87] proposed a model on liquid wicking into a fibre bundle. The proposed model is based on the simplified description of the thread structure and works with the textile description of its structure and the textile parameters are fibre fineness, number of fibres in the cross section of the thread, fibre shape factor, pores in the threads, hydrostatic pressure, cylinder radius, filling, fineness of fibres and interfacial tensions:

$$H_{\max} = \frac{\sigma_{LG} \times \cos\theta \times 2 \times \mu - \left(\frac{2}{100} \times \sigma_{LG} \times \sqrt{\frac{\mu}{N}} \right) \times \left(Q \times \cos\theta + P \right)}{R_v \times (1-\mu) \times g \times \rho} \tag{33}$$

Here,

H_{max} is the equilibrium suction height,
N is the number of fibres in the bundle,
R_v is the radius of the fibre, and
P is the part in percent of liquid from the surface of the bundle, %.

The proposed model allows for the functional dependence of suction height as the thread parameters to be expressed in an analytical form. Though this problem still has not been completely solved, it will be very helpful for further study. In this model the entire course of moisture sorption is considered to be Fickian in character; the heat of sorption and the complex sorption behaviour of the fibres have been simplified.

3.3. Modelling on condensation

Condensation is associated with the coupled heat and moisture transfer with phase change. Ogniewicz and Tien [88] were the first contributors on this subject using theoretical modeling and numerical analysis and for this purpose they have assumed that heat is transmitted by conduction and convection and the condensate is in a pendular state. The analysis was limited to a quasi-steady-state, as the temperature and vapour concentration remain unchanged with time, before the condensate becomes mobile. Later Motakef and Shapiro [62, 89] analyze the unsteady heat and moisture transport processes through the calculation of quasi-steady fields in time-varying domains. Murata [68] analyzed the heat and water vapour transfer with condensation in a fibrous insulation slab both theoretically and experimentally. Murata's model considered the condensation falling under gravity. Bouddour et al. [90] revisited the model of heat and water vapour transfer in wet porous media in the presence of evaporation–condensation by using the homogenization method of asymptotic for periodic structure.

Fan et al. [91, 92] have developed a numerical model on heat and moisture transfer with sorption and phase change through multi-layered fibrous battings based on their experimental results, conducted at -20^{0}C on a novel sweating guarded hot plate. The theory and the experimental results have been used for better understanding the phenomenon of condensation of perspiration and its evaporation, which causes the post exercise chill discomfort. Their model considers that the moisture movement is induced by partial water vapour pressure, a super saturation state in the condensing region as well as by the dynamic moisture absorption by the fibrous material and the movement of the liquid condensate. They have assumed that there is no liquid water movement. The model predicts condensation increases from the inner region to the outer region of the batting.

4. Conclusions

The liquid and water vapour permeability of a material plays an important role in determining clothing performance and in maintaining human body comfort. The evaluation method is of the utmost importance in determining the material properties accurately. The experimental apparatus and the testing methods should simulate the wear conditions very closely. Many methods are available to measure the ability of a fabric to transmit moisture through textiles; but the results obtained by the different methods cannot be compared directly due to the different testing conditions, the parameters measured and the units used. The moisture transmission behavior of fibrous assemblies may be mathematically modeled to predict the clothing behavior in actual wear conditions. For mathematical modeling purposes both the moisture and heat transfer mechanisms through the textile materials are required to be considered along with the material properties and other influencing parameters. Both the predicted results given by the mathematical model and those given by the experimental analysis are very useful in understanding the parameters involved and the science behind a specific behavior of a material, and thus are extremely useful in product development.

Acknowledgement

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