2.3 COMFORT PROPERTIES OF KNITTED TEXTILES

2.3.1 Introduction

Clothing is an integral part of human life and has a number of functions: adornment, status, modesty and protection. However, the primary role of clothing is to form a layer or layer of barriers that protect the body against unsuitable physical environments. This protection of body fulfils number of functions, like maintaining the right thermal environment to the body, which is essential for its survival and preventing the body from being injured by abrasion, radiation, wind, electricity, chemical and microbiological substances. These traditionally classified functions of clothing clearly indicates that it plays a very important role at the interface between human body and its surrounding environment in determining the subjective perception of comfort status of a wearer[54]. Fabrics with high moisture management attributes are often specifically engineered or structured for applications such as active sportswear, outdoor clothing, work wear, intimate apparel and footwear in which the concept of moisture management is utilized to prevent or minimize the collection of liquid on the skin of the wearer due to perspiration. Today comfort is considered as a fundamental property when a textile product is valued. The comfort characteristics of fabrics mainly depend on the structure, type of raw material used, weight, moisture absorption, heat transmission and skin perception.

2.3.2 Clothing Physiology

Clothing physiology is the mechanism of interactions between the human body and its clothing system and it aims at providing information on the physiological properties of clothing. It is expressed in terms of comfort, performance capability and the health of wearer. The clothing is said to be physiologically right when it functions correctly while physical activity is taking place. Functionally correct clothing is only possible when there is a correct interaction of fibre, spinning, weaving or knitting parameters, fabric density, thickness and weight, colouration and finish, garment fit and making up technique. The need for high-performance protective clothing systems in space, polar, and underwater operations and in industrial environments has stimulated research in clothing physiology.

2.3.3 Perception of Comfort

The demands from fabrics have changed with the developments in textile technology and the rise of people's living standards. Now the requirement is not only style and durability, but also clothing comfort[55]. Clothing comfort, being a fundamental and universal need for consumers, may be defined as a pleasant state of physiological, psychological and physical harmony between a human being and the environment[56,57]. Physiological comfort is related to the human body's ability to maintain life, psychological comfort to the mind's ability to keep itself functioning satisfactorily with external help and includes the aesthetic appeal which depends on size, fit, colour, luster, style, fashion compatibility, etc., and physical comfort to the effect of the external environment on the body.

Upto now, there has been no clear definition of comfort, since this subjective feeling differs from person to person, but a lot of researchers have investigated comfort over the past years. For example, LaMotte stated that physical comfort might be greatly influenced by tactile and thermal sensations arising from contact between skin and the immediate environment[58]. Slater defined comfort as "a pleasant state of physiological, psychological and physical harmony between a human being and the environment"[59]. Li defined comfort as a holistic concept, which is a state of multiple interactions of physical, physiological, and psychological factors[60]. The term 'comfort' is a nebulous one, which defies definition, but the sensation of comfort is easily recognized by the person experiencing it. Many attempts have been made, without success as yet, to define the state in physical terms. Fourt and Hollies carried out an even more extensive survey, incorporating all the literature relating to comfort and that they could find, and again did not provide an objective definition of comfort[61]. It has been recognized for a long time that it is difficult to describe comfort positively, but discomfort can easily be described in terms of prickle, itch, hot and cold. Therefore, a widely accepted definition for comfort is stated as freedom from pain and from discomfort as a neutral state[62, 63, 64, 65]. For sportswear that has transferred to the mass market and may be worn on a daily basis, the psychological and sensorial functions are as important as the thermophysiological properties. However, these definitions only identify the factors influencing human sensory perceptions; the relationships between these factors and overall comfort have not yet been determined[66].

2.3.4 Concept of Clothing Comfort

Clothing comfort is dependent upon the low-stress mechanical, thermal and moisture transfer properties of the fabrics. There is a general agreement that moisture transmission through textiles has a great influence on the thermo-physiological comfort of the human body, which is maintained by perspiring both in vapour and in liquid form. Yoon & Buckley suggested that many of the transport and related properties of a fabric, such as air permeability, water transmission rate, thermal resistance and liquid water transmission properties are highly dependent on constituent yarn geometry[67].

Modern comfort science categorizes the clothing comfort into three independent sensory groups, such as:

Thermal wear comfort – mainly related to the sensations involving temperature and moisture. This factor responds mainly with the thermal receptors in the skin and relates to the transfer properties of clothing such as heat transfer, moisture transfer and air permeability.

The clothing wearer will usually be exposed to two different conditions.

1. During normal wear, insensible perspiration is continuously generated by the body. Steady-state heat and moisture vapour are generated and must be gradually dissipated to maintain thermo regulation and a feeling of thermal comfort. The clothing becomes a part of the steady-state thermoregulatory system.
2. In transient wear conditions, characterized by intermittent pulses of moderate or heavy sweating caused by strenuous activity or climatic conditions, perspiration and liquid sweat occur as well as evaporation of the sweat to cool the body. In this case, the clothing needs to manage heat, vapour, and liquid transports to keep the body regulated.

Tactile comfort: associated with the sensations involving direct skin-fabric mechanical interactions. This factor responds largely with the pain receptors in the skin and relates mainly to the surface characteristics of the fabric, its density, smoothness of the surface and the diameter of the fibre ends.

Pressure comfort: is more complex and involves a number of synthetic sensations. It mainly correspond to the pressure receptors in the skin and may come from some combination of a number of sensory responses. Stretch in fabrics falls into the category of pressure sensations[68].

Micro-climate is a general term that describes the temperature, humidity and microscopic air stream between the skin and the clothing. It is an important factor in wear comfort and depends on the properties such as moisture and heat transport through the material, physiological and environmental conditions. Micro-climate factors and interaction with the skin are shown in figure 2.11, while figure 2.12 illustrates the micro-climate regimes and the associated comfort levels[69].

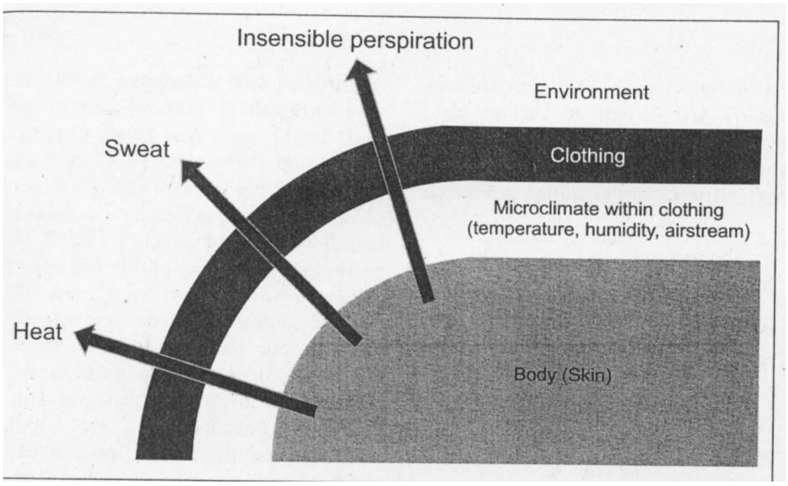

Figure 2.11: Microclimate factors

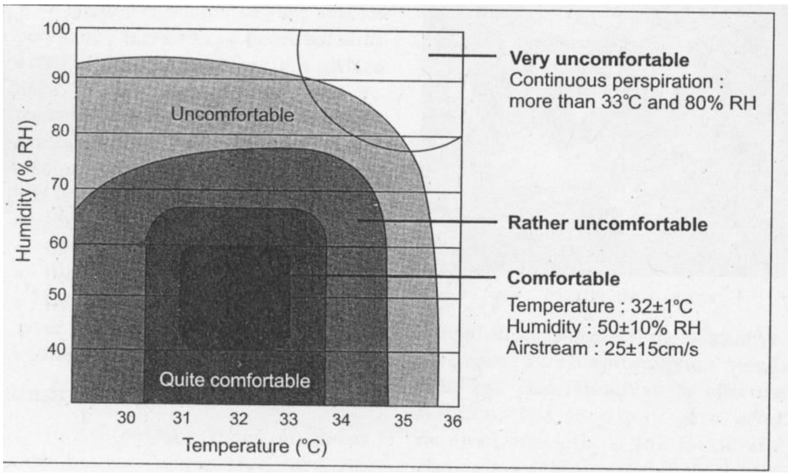

Figure 2.12: Microclimate regimes and the associated comfort levels

2.3.5 Thermal Comfort

Comfort involves thermal and non-thermal components and it is related to wear situations, such as, working, non-critical and critical conditions. A person feels comfortable in a particular climatic condition if his energy production and energy exchange with environment are evenly balanced so that heating or cooling of the body is within tolerable limits. The human organism is homoeothermic, which means that it has to maintain its core body temperature of approximately 37^{0}C. Hence, the body temperature is the most critical factor in deciding comfort[70]. During all kinds of activity, the human body produces a certain amount of heat in range of 80 W while sleeping to even over 1000W during intensive effort, such as participation in active sports. Heat is gained by the body from the sun or intermediate source of energy by means of internal metabolism, physical exercise or activity, or by involuntary contractions of skeletal muscles in shivering. The surplus energy can be transferred to the environment in three ways: respiration, release of dry flux (conduction, convection and radiation) and a latent flux produced by perspiration. Heat loss, depends partly on the temperature gradient between skin and environment, and this gradient is modified by varying the skin temperature. Blood flow near, and evaporation from, the body surface control the skin temperature, and one function of clothing is the support of these processes. The first flux depends on the insulation property of clothing while the second one depends on its moisture transport properties. The total heat loss at a mean temperature of 20 ^{0}C and relative air humidity of 50% can be divided as follows:

Evaporation - 20%; Convection - 25%; Radiation- 45%; Respiration - 10%.

The division of heat loss occurs during rest and when there is a lack of ventilation. At low temperature respiration can exceed 30% of the total heat loss, whereas at high ambient air temperature of 34-37 ^{0}C, the evaporation of sweat is the main cause of heat loss. Sweating is the most effective way the human body has of cooling down[71]. Excessive heat may be dissipated rapidly by vapourization of body water and the clothing system that hinders the free evapouration to any appreciable extent will thus be uncomfortable. On the other hand, undesirable heat loss can be prevented by increasing the thermal resistance of the barrier between the body and its environment and a fabric with low resistance will again result discomfort to the wearer. So it is clear that clothing is a key aspect for body comfort and should essentially help the wearer in his/her effort and should not give additional physical and heat stress. Factors influencing heat exchange between the human body and its surroundings are shown in figure3.13[72].

Supporting the thermal comfort of people is a multi-faceted complex problem. When a person feels neither too hot nor too cold in their environment, it is said they are thermally comfortable[73].Discomfort perception was related to lowering average skin temperature toward cold environments and increased sweating towards hot environments. ISO 7330 defines thermal comfort as that condition of mind, which expresses satisfaction with the thermal environment.

In 1969, Gagge et al. reported a study on comfort, thermal sensations, and associated physiological responses during exercise, temperature sensations from cool to hot were mainly correlated with skin and ambient temperatures; warm discomfort was related to skin sweating and skin conductance[74]. During steady state exercise, perception of temperature was dominated by sensory mechanisms in the skin, while warm discomfort was mainly determined by thermoregulatory mechanisms. The comfort and thermal sensations during thermal transients caused by the rise in metabolic rate at the start of exercise were correlated with the initial rise in mean body temperature. Thermal stress management and control of moisture vapour transmission are important to confer high levels of thermophysical and thermopsychological comfort to the wearers of knitted and woven garments[75].

Thermal and moisture sensations have been widely recognized as the important factors contributing to discomfort, and many researchers have studied the mechanisms involved[76]. Hensel pointed out the physiological basis of thermal comfort, and the difference between thermal comfort and temperature sensations[77]. Temperature sensations are mainly derived from cutaneous thermoreceptors, which are used to judge the thermal state of objects or the environment. Thermal comfort and discomfort reflect a general state of the thermoregulatory system, which is the integration of afferent signals from both cutaneous and internal thermoreceptors. Therefore, the measurements of the temperature sensations and of thermal comfort need to be distinguished. Two separate scales to study thermal sensations and thermal comfort, are summarized in Table 2.2[78].

Clothing thermal insulation is an important parameter in thermal comfort. It is used to determine the heat stress of a clothed person in a hot environment in terms of the required evaporation for thermal equilibrium, required sweat rate, and skin wetness, and to determine cold stress in a cold condition in terms of the required insulation[79]. Clothing thermal insulation measured or predicted in non-perspiring (or dry) conditions is used to calculate the heat transfer through clothing when the body is perspiring (or sweating) with the possibility of error.

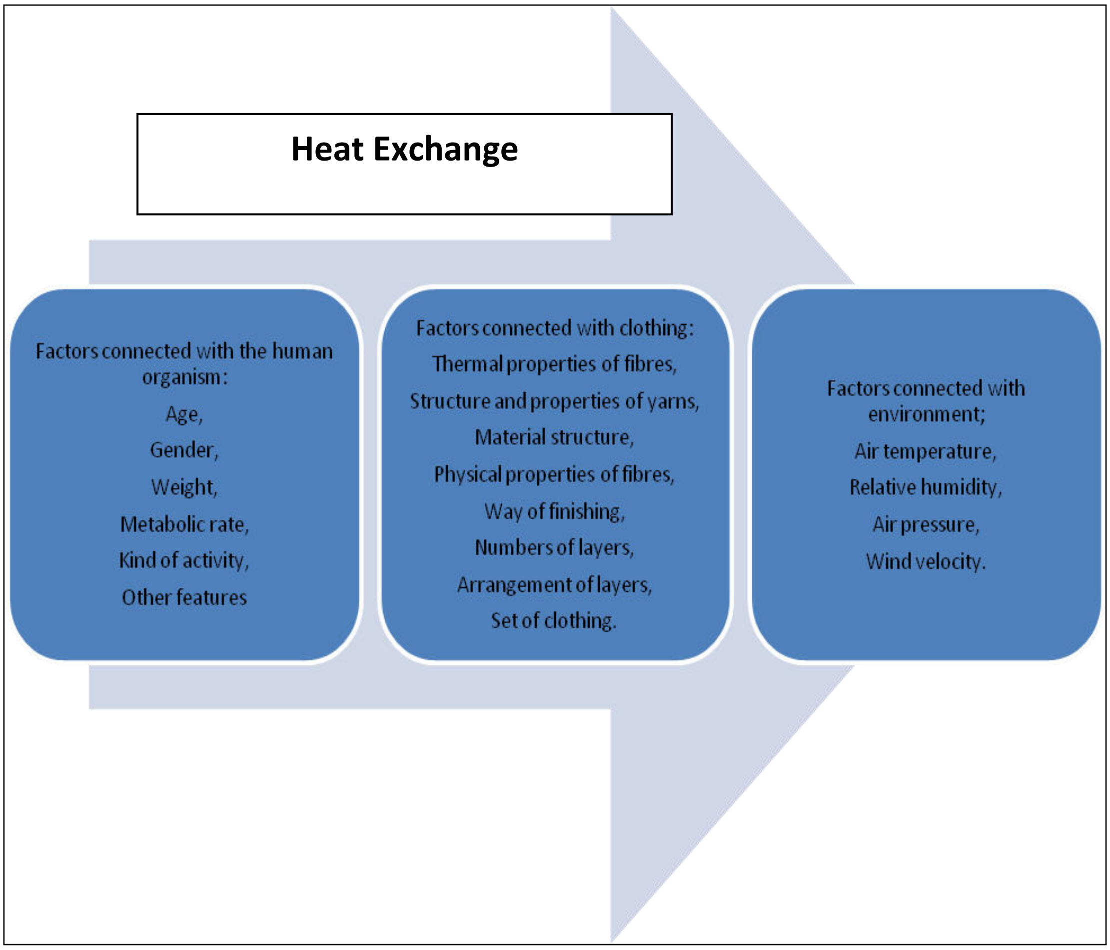

Figure 2.13: Factors influencing heat exchange between the human body and its surroundings

Table 2.2: Scales for Thermal comfort and thermal sensations

Thermal sensations		Thermal comfort
1.	Very cold	1. Uncomfortable cold
2.	Cold	2. Colder than comfortable
3.	Cool	3. Much cooler than comfortable
4.	Slightly cool	4. Slightly cooler than comfortable
5.	Neutral	5. Comfortable
6.	Slightly warm	6. Slightly warmer than comfortable
7.	Warm	7. Much warmer than comfortable
8.	Hot	8. Hotter than comfortable
9.	Very hot	9. Uncomfortably hot

It is generally believed that perspiration reduces clothing thermal insulation as a result of greater effective thermal conductivity, liquid water transport, and evaporation within wet clothing assemblies[80].

Generally, clothing thermal comfort is measured as clothing insulation and expressed in units of clo (1 clo = 0.155 m^2 C/w). One clo is the thermal insulation required to keep a sedentary person thermally comfortable at 21°C in a wind speed of 0.1 m/s[81]. The lowest clo value is 0 (naked body), while the highest practical clo value is 4 (Eskima clothing, fur pants, coats, head and gloves, etc.), the summer clothing has to be around 0.6 clo. The type of fibre, spinning technology, yarn count, yarn twist, yarn hairiness, fabric thickness, fabric cover factor, fabric porosity and finish are some of the factors, which play decisive role in determining the comfort properties of fabrics[82,83].

Amongst these, thickness plays a very important role in determining the functional value of clothing materials in connection with their 'warmth', i.e. the amount of heat insulation they provide, and their ability to allow the body to dissipate its insensible perspiration and sweat. Thermal insulation, it can almost be said, depends uniquely on fabric thickness[84]. Furthermore, the warmth of fabric is governed by the entrapped air; the thicker the fabric, the greater is the amount of entrapped air, and, provided that the surrounding air is stagnant, the greater is the thermal resistance of the fabric. However, thickness increases the resistance to the transfer of heat and moisture because of the large additional air volume present rather than the increased fibre content. It is also noted that, for a fibre thickness of 1 mm, there is a thermal retention of about 30%.

Clulow states that the factors that determine the warmth of a fabric are its thickness, its construction (i.e. weaving or knitting particulars), and its bulk density (the mass of fibres in a given volume)[85]. The thicker a fabric of a given construction, the greater is its heat-insulation value. In general, the greater its bulk density for a given thickness, the less is its warmth owing to the replacement of air by fibres having a greater heat conductivity. However, if the bulk density is very low, or if the fabric construction is sufficiently open, radiant heat from the skin can pass through the garment and reduce its warmth.

Another important factor is weight. The ‘warmth-to-weight factor’ of a material is defined as the ratio of its thermal resistance in togs to its mass in g cm^{-2}. A high value of this factor is obviously desirable for the provision of ‘lightweight warmth’. Thus, on the basis of equal thickness, the fabric with the most open construction is the least warm, but the reverse is the case on the basis of equal weight. Hence fabrics of cellular construction are eminently suitable for providing lightweight warmth if used under conditions where moving air is prevented from penetrating the structure. Moisture transport is also observed to exert a much greater influence on thermal transmittance than the relative-humidity ranges investigated.

There are many thermal measurements possible for fabrics, but, in general, they can be divided into two groups: transient-state thermal properties and steady-state thermal properties. The steady-state properties of thermal conductivity and resistance are perhaps the most widely understood and provide information on the warmth of a fabric. Transient heat transfer occurs when contact between the skin and a surface first takes place. Measurements classified as transient include the thermal diffusivity, which characterizes the temperature flow through the fabrics, thermal absorptivity, which is the quantity of heat penetrating a fabric during the time period when the temperature is raised rapidly, and Q_{max}, which the maximum heat flow while heat is still being transferred[86].

2.3.5.1Thermal conductivity (λ)

is the intrinsic property of a material which relates its ability to conduct heat. Heat transfer by conduction involves transfer of energy within a material without any motion of the material as a whole. Conduction takes place when a temperature gradient exists in a solid (or stationary fluid) medium. Conductive heat flow occurs in the direction of decreasing temperature because higher temperature equates to higher molecular energy or more molecular movement. Energy is transferred from the more energetic to the less energetic molecules when neighboring molecules collide. Conceptually, the thermal conductivity can be thought of as the container for the medium-dependent properties which relate the rate of heat loss per unit area to the rate of change of temperature[87].

Thermal conductivity is defined as the quantity of heat (Q) transmitted through a unit thickness (L) in a direction normal to a surface of unit area (A) due to a unit temperature gradient (ΔT) under steady state conditions and when the heat transfer is dependent only on the temperature gradient. In equation form it can be expressed as:

Thermal Conductivity = heat × distance / (area × temperature gradient)

$\lambda = Q \times L / (A \times \Delta T)$

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 compared to all fibres ($\lambda_{air} = 0.025$)[88,89]. Therefore, as the amount of entrapped air in the fabric structure increases, the fabric provides lower thermal conductivity and higher thermal insulation.

2.3.5.2Thermal Resistance

Thermal resistance is an indication of how well a material insulates. It is based on the equation:

$R = h / \lambda$

Where R is the thermal resistance, h is the thickness and λ is the thermal conductivity.

The thermal resistance of a certain fabric is inversely proportional to its thermal conductivity[90]. The resistance that a fabric offers to the movement of heat through it is of critical importance to its thermal comfort. In studying the thermal insulation properties of garments during wear, it is clear that thermal resistance to transfer of heat from the body to the surrounding air is the sum of three parameters: (i) the thermal resistance to transfer heat from the surface of the material, (ii) the thermal resistance of the clothing material, and (iii) the thermal resistance of the air interlayer.

It is obvious that heat transfer through a fabric is a complex phenomenon affected by many factors. The three major factors determining thermal insulation in normal fabrics appear to be thickness, enclosed still air and external air. Of the other factors that can affect the thermal resistance of a fabric, moisture is probably the most noticeable. Black and Mathew showed that thermal insulation reduced markedly as the moisture content increased from 0 to 75% of the dry weight[91]. Many authors argue that the thermal transmission of fabric depends mainly on the entrapment of still air within the structure and the thickness of fabric, if all other parameters are same. The greater the thermal resistance of a fabric, the lower its ability to disperse body heat[92]. The finer yarn in fabric results lower thickness which causes lower thermal resistance[93].

2.3.5.3 Thermal absorptivity

Thermal absorptivity determines the contact temperature of two materials and indicates the warm-cool feeling of fabrics[94].

When a human touches a fabric that has a different temperature from the skin, heat exchange occurs between the hand and fabric. If the thermal absorptivity of a fabric is high, it gives a cooler feeling at first contact[95]. Physically, it is a function of the thermal conductivity, density and specific heat of a fabric and can be expressed as:

$$B = (\lambda \rho c)^{1/2}$$

Where λ is the thermal conductivity, ρ is the fabric density and c is the specific heat of fabric[96].

However, this relation applies only for a short time of thermal contact between a fabric and skin. As time passes, the heat flow loses its dynamical (transient) character and its level falls to a steady state and thermal resistance takes place for the thermal characteristics.

Behera et al. compared the thermal comfort characteristics of friction-spun yarn fabrics vis-à-vis ring and rotor-spun yarns fabrics[50]. It is of interest to note that textile materials have a natural tendency to adjust their structure in accordance with the environmental conditions. Thus, in the winter, when the humidity close to the windows is often high, fibres will tend to swell and by doing so, improve the barrier-like characteristics of a curtain. In the summer, spaces between fibres will tend to become greater and provide for air circulation without detracting from light diffusion.

Yoon and Bukley concluded that the thermal insulation, air permeability and water vapour transport rate are dependent mainly on fabric geometrical parameters. They determined the thermal –transport properties of a series of polyester, cotton, and polyester/cotton blend fabrics in an effort to understand the physical basis of clothing comfort. The results indicate that both the fabric construction and the constituent fibre properties affect thermal transport[67]. They concluded that an ideal clothing fabric, in terms of thermal comfort, should have the following attributes: a. high thermal resistance for protection from cold, b. low water-vapor resistance for efficient heat transfer under a mild thermal –stress condition, and c. rapid-liquid-transport characteristics for transferring heat efficiently and eliminating unpleasant tactile sensations due to water under high thermal-stress condition.

Ozdil et al. investigated thermal properties of 1x1 rib fabrics knitted by using various yarns having different properties with all details. It was observed that yarn properties like count, yarn twist and combing process of cotton affect thermal comfort properties. As the yarn twist and yarn count increase, thermal resistance value decrease and water vapour permeability values increase[97]. Ucar and Yilmaz studied the thermal properties of rib knitted fabrics and noted that the rib number and fabric density influence thermal comfort[88].

Holcombe and Hoschke showed that a relationship exists between the thermal conductivity of the fabric and the thermal conductivities of air and fibre, together with the packing factor of the construction[98]. Bivainytė et al, reported that the structure of the knit highly influences the heat transfer process through double-layered fabrics at a higher level[99].

2.3.5.4 Measurement of thermal conductivity

The transmission of heat through a fabric occurs both by conduction through the fibre and the entrapped air and by radiation. Practical methods of test for thermal conductivity measure the total heat transmitted by both mechanisms. The insulation value of a fabric is measured by its thermal resistance which is the reciprocal of thermal conductivity (transmittance) and it is defined as the ratio of the temperature difference between the two faces of the fabric to the rate of flow of heat per unit area normal to the faces. As can be seen from this definition it is necessary to know the rate of heat flow through a fabric in order to be able to measure its thermal resistance. In practice the measurement of the rate of flow of heat in a particular direction is difficult as a heater, even when supplied with a known amount of power, dissipates its heat in all directions. Two different methods are in use to overcome this problem: one is to compare thermal resistance of the sample with that of a known standard and the other is to eliminate any loss in heat other than that which passes through the fabric being tested. It is important that any measurements of thermal resistance made at temperatures close to those that are likely to be encountered in use as the thermal conductivity of materials varies with the temperature. This is due to the variation in thermal conductivity of the air with temperature and also the dependence of the heat loss through radiation on temperature. Most successful heat transport measuring instruments are: Togmeter, Guarded hot plate and Alambeta instrument[100].

To determine the air resistance

The heater and the fan are switched on and the apparatus is allowed to reach thermal equilibrium with no specimen present. The top plate is placed underneath the apparatus shielded from radiation by a foil-covered plate, in order to measure the air temperature. The temperature should remain steady at each thermocouple for 30 minutes. It may take some time for an equilibrium to be reached. Thermal resistance of air:

$$R_{air} = R_{stand} \times \frac{T_2 - T_3}{T_1 - T_2}$$

Where R_{stand} is the thermal resistance of the standard.

To determine the sample resistance

The above experiment is repeated with the test sample placed on the bottom plate and the apparatus again allowed to reach thermal equilibrium.

Guarded hotplate method

The guarded hotplate is used to measure thermal transmittance which is the reciprocal of the thermal resistance. The apparatus consists of a heated test plate surrounded by a guard ring and with a bottom plate underneath. All three plates consist of heating elements sandwiched between aluminium sheets. All the plates are maintained at the same constant temperature in the range of human skin temperature (33-36 ^{o}C). The guard ring and bottom plate, which are maintained at the same temperature as the test plate, ensure that there is no heat loss apart from that which passes upwards through the fabric under test. The whole apparatus is covered by a hood to give still air conditions around the specimen. The whole surroundings of the apparatus is maintained at fixed conditions between 4.5 and 21.1 ^{o}C and 20 and 80% RH, the exact conditions being specified as part of the test. With the test fabric in place the apparatus is allowed to reach equilibrium before any readings are taken. This may take some time with thick specimens. The amount of heat passing through the sample in watts per square metre is measured from the power consumption of the test plate heater. The temperature of the test plate and the air 500mm above the test plate are measured (figure 2.14)[101].

The measured thermal transmittance consists of the thermal transmittance of the fabric plus the thermal transmittance of the air layer above the fabric which is not negligible. Therefore the test is repeated without any fabric sample present to give the bare plate transmittance. The transmittance of the air layer above the plate is assumed to be the same as that of the air layer above the sample[102].

Combined transmittance of specimen and air U_1:

$$U_1 = \frac{P}{A \times (T_p - T_s)} \quad W/m^2\,K$$

Where: P = power loss from test plate (W),

A = area of test plate (m^2),

T_p= test plate temperature (^{o}C),

T_s = air temperature (^{o}C).

The bare plate transmittance U_{bp} is similarly calculated and then the intrinsic transmittance of the fabric alone, U_2, is calculated from the following equation:

$$\frac{1}{U_2} = \frac{1}{U_1} - \frac{1}{U_{bp}}$$

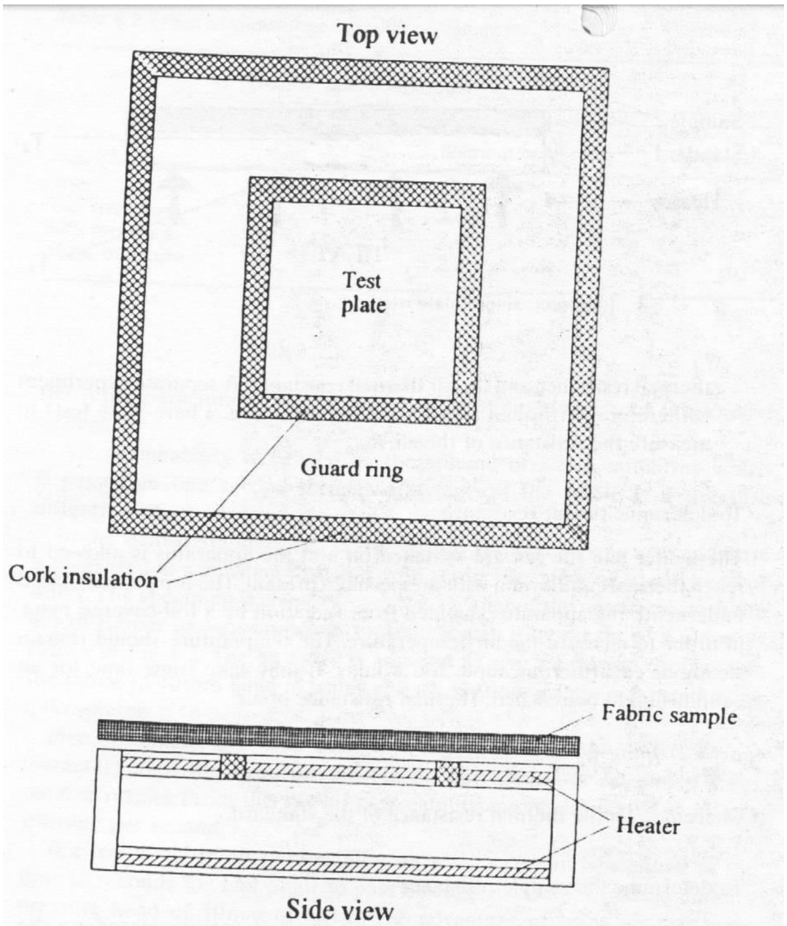

Figure 2.14: The guarded hotplate

2.3.6 Moisture Management

Moisture management is an important aspect of fabric meant for apparels, which decides comfort level. An important feature of any fabric: how it transport, store, and dispose liquid water and moisture from the surface of the skin to the atmosphere through the fabric is often referred to as Moisture Management, which is a complex process influenced by a variety of fabric characteristics, e.g. type of fibre (hydrophilic and hydrophobic), porosity, and thickness, absorption capacity, evaporation [103, 104].

Moisture management could be defined as “the controlled movement of water vapor and liquid water (perspiration) from the surface of the skin to the atmosphere through a fabric”[105]. To evaluate the moisture management of a textile one has to know about both the basic temperature regulation of the human body, and about the properties of the textile required by this regulation.

Temperature regulation of the body

The human body has different ways of trying to maintain its temperature. For example, in a cold environment, blood circulation in the arms and legs is reduced, in order to minimize heat exchange with the surrounding atmosphere. If the body warms up, the blood circulation increases in an attempt to release surplus heat, and we start to sweat. During perspiration water (containing salt and other substances) is transmitted through the pores of the skin, from which it then evaporates. Through the cold which is generated during evaporation, the warmth surplus is consumed – in this way the body cools down again, and its temperature is re-adjusted.

Function and problems of clothing

Clothing is supposed to protect humans- in accordance with their environment – from cold, heat, wind and weather. If possible, it should fulfil this function without inhibiting the evaporation of humidity caused by perspiration (good moisture management), and thus not interfering with the temperature regulation of the body.

When we start to sweat, our body humidity is more or less absorbed by the textile we are wearing. If the humidity remains in the fabric and is not transported to the surface for evaporation, cooling cannot occur. The body warms up and even more sweat is produced. After its exercise, the body cools down and sweating ceases. However, any humidity retained in the clothing evaporates after awhile, even if the body does not need to be cooled any more. Then we start to freeze.

Goals for optimized sportswear

In consequence of the described problems in temperature regulation, goal in the development of the optimized sportswear is

- To transport humidity to the outer surface as fast as possible

In order to evaporate, the humidity has to reach the surface of the fabric first. This occurs by capillary force, also called wicking. The capillary force increases as the gaps between the individual fibres become thinner. That means the finer the fibres, the smaller the gaps are, and the better the humidity transport.

- To evaporate the humidity as quickly as possible

Contrary to what is frequently assumed, the evaporation of humidity absorbed does not depend on the type of fibre, but on the surface area of the textile used. The larger the surface – in other words, the finer the fibres and more fibres there are at the surface – the faster the humidity evaporation. Thus, humidity evaporates from a hydrophobic polyester fibre just as it does from a hydrophilic cotton fibre of the same fineness.

- To make the skin feel dry

Clothes which have a humid feel about them are unpleasant to wear. However, there are differences between materials as to the level from which water content makes the textile feel humid. Whereas cotton can absorb a certain volume of water without feeling humid, polyester feels wet and clammy even with small amounts of humidity stored in it. Moreover, thick textiles – on the basis of their mass alone – absorb more humidity compared to thinner fabrics, and their surface does not significantly expand in the process. That's why drying thick fabrics takes considerably longer.

Liquid water released by the body is known as sensible perspiration. To be removed from the body it must be wicked through the fabric structure and then evaporate from the outside of the fabric. When it evaporates heat is removed which helps to control the temperature of the body[106]. During exercise, both insensible perspiration and sensible perspiration are produced, but the latter increases in response to rising body temperature producing liquid at the surface of the skin. Moisture vapour can pass through openings between fibres or yarns. This action prevents perspiration from remaining next to the skin. In hot conditions, trapped moisture may heat up and lead to fatigue or diminished performance. In cold conditions, trapped moisture will drop in temperature and cause chilling and hypothermia.

Moisture transmission through textiles has a great influence on the thermo-physiological comfort of the human body which is maintained by perspiring both in vapour and liquid form. Recently there is an increasing demand for sportswear and sports related textiles due to significant increases in interest of people in active indoor and outdoor leisure pursuits. If moisture cannot evaporate from the skin, both the skin temperature and discomfort increase. An ideal sportswear must transfer perspiration from the body followed by evaporating the moisture rapidly and keeping the body warm[107]. The most effective fabrics will spread moisture over a wide area to maximize the surface area available for evaporation and hence cooling.

The ability of a fabric to allow perspiration in its vapour form to pass through it is measured by its moisture vapour permeability in grams of water vapour per square metre per 24 hours. The clothing worn should allow this perspiration to be transferred to the atmosphere in order to maintain the thermal balance of the body. When a wearer begins to perspire, the liquid moisture management properties of the material are more important than vapour moisture management properties[108].

Moisture management has the following functions-

Regulation of body temperature – when the human body core temperature exceeds 37^{o}C, sweat is produced. Transporting the sweat away from the skin and evaporating it to the atmosphere, reduces body temperature.

Control of cloth weight increase- absorbing the moist generated by the body increases cloth weight, making it uncomfortable and with a negative effect on performance. Moisture management avoids this effect[109].

When a textile product incorporates thermally active materials or specially designed fibres, it can provide enhanced thermal and moisture management performance in addition to the existing passive characteristics of the structure to keep the body in the comfort state. Fabric liquid moisture transport properties in multi-dimensions, called moisture management properties influence the human perception of moisture sensations significantly.

2.3.6.1Principle of Operation

The Moisture Management Tester (MMT) is an instrument to test the liquid moisture management capabilities of textiles such as knitted and woven fabrics. The liquid moisture management properties of a textile are evaluated by placing a fabric specimen between two horizontal (upper and lower) electrical sensors each with seven concentric pins. A predetermined amount of test solution (synthetic sweat) that aids the measurement of electrical conductivity changes are dropped onto the center of the upward-facing test specimen surface. The test solution is free to move in three directions: radial spreading on the top surface, movement through the specimen from top surface to the bottom surface, and radial spreading on the bottom surface of the specimen. Moisture Management Tester is designed to sense, measure and record the liquid moisture transport behaviors in these multiple directions.

During the test, changes in electrical resistance of specimen are measured and recorded. The electrical resistance readings are used to calculate fabric liquid moisture content changes that quantify dynamic liquid moisture transport behaviors in multiple directions of the specimen. The summary of the measured results are used to grade the liquid moisture management properties of a fabric by using predetermined indices.

The Moisture Management Tester utilizes the electrical resistance technique, which is based on the substantial difference in electrical conductivity of air (non-wetted fabrics) and water (wetted fabrics): as the liquid wicks through and / or absorbs into the fabric sample, the electrical resistance of the sample reduces. The Moisture Management method assumes that the value of the electrical resistance change depends on two factors: the components of the water content in the fabric, thus when the influence of the water components is fixed, the electrical resistance measured is only related to the water content in the fabric. It is important to note that the electrical resistance of wet textile fabrics also depends on the fabric fiber composition and content, fiber polymer (where fibres themselves exhibit differential electrical conductivity or virtually no conductivity), and also different fiber sorbtion properties, thus the Moisture Management testing method has to be considered in context of the fiber conducive properties. The fabric being tested was placed between the two sensors. An amount of test solution (synthetic sweat) is to be introduced onto the top side of the fabric.

The MMT measures the liquid transfer in one step in a fabric sample in multi-directions; outward on the top (next to skin) surface of the fabric, through the fabric sample from the top to the bottom (opposite) surface, and outward on the bottom surface. Gravity unquestionably has an influence on the transfer of moisture through the fabric from the top surface to the bottom surface, but as the tests are conducted under the same conditions, the influence of gravity could be considered constant for all fabrics. The possible presence of air gaps between the skin and the fabric, and also the possible ‘boundary’ wetting resistance between the skin and the fabric during real wear are not taken into consideration in the study.

2.3.6.2Moisture Management Tester Indices

A series of indexes are defined and calculated to characterize liquid moisture management performance of the test specimen.

Absorption rate – (AR_t) (top surface) and (AR_b) (bottom surface), - the average speed of the liquid moisture absorption for the top and bottom surfaces of the specimen during the initial change of water content during a test.

Accumulative one-way transport capability-(AOTI) – the difference between the area of the liquid moisture content curves of the top and bottom surfaces of a specimen with respect to time.

Bottom wetted radius-(MWR_t) and (MWR_b) (mm) –the greatest ring radius measured on the top and bottom surfaces.

Moisture management – for liquid moisture management testing, the engineered or inherent transport of aqueous liquids such as perspiration or water (relates to comfort) and includes both liquid and vapor forms of water.

Overall (liquid) moisture management capability (OMMC) – an index of the overall capability of a fabric to transport liquid moisture as calculated by combining three measured attributes of performance: the liquid moisture absorption rate on the bottom surface (AR_b), the one way liquid transport capability (AOTI), and the maximum liquid moisture spreading speed on the bottom surface (SS_B).

$$OMMC = 0.25\ AR_b + 0.5AOTI + 0.25\ SS_b$$

The larger the Overall (liquid) moisture management capability is the higher the overall moisture management capability of the fabric. Liquid moisture management capacity shows that liquid sweat can be easily and quickly transferred from next to the skin to the outer surface to keep the skin dry. If the Overall (liquid) moisture management capability of one fabric is in 0.6-0.8 range it means that the liquid moisture management capacity is very good. Also, for the fabric having the value higher than 0.8, the overall capability of the fabric is defined as excellent.

Spreading speed- (SS_i)- the accumulated rate of surface wetting from the center of the specimen where the test solution is dropped to the maximum wetted radius.

Top surface – (T), for testing purposes, the side of a specimen that, when the specimen is placed on the lower electrical sensor, is facing the upper sensor. This is the side of the fabric that would come in contact with the skin when a garment is worn or when a product is used.

Total water content – (U) (%), - the sum of the percent water content of the top and bottom surfaces.

Wetting time – (WT_t) (top surface) and (WT_b) (bottom surface), - the time in seconds when the top and bottom surfaces of the specimen begin to be wetted after the test is started.

According to AATCC Test Method 195-2009, the indices are graded and converted from value to grade based on a five grade scale (1-5). The five grades of indices represent: 1-poor, 2-fair, 3-good, 4-very good, 5-excellent (see table 2.3)[110, 111, 112, 113].

Gamze Süpüren et al investigated the moisture management properties of the double face fabrics, with cotton-cotton, cotton-polypropylene, polypropylene-cotton and polypropylene-polypropylene for face and back sides respectively. Moisture management properties and the changes of the thermal absorptivity values, which determine the warm-cool feeling of the produced fabrics were determined and statistically analysed. The results indicate that the polypropylene (inner), cotton (outer) fabric has better moisture management property, provides high levels of comfort and can be preferred for summer, active and sportswear[114]. Raul et al investigated the influence of wool fibre proportion on the performance of blend and observed that the coolmax based fabrics show the best capillarity performance, and the wool fibre based fabrics show lower water absorption performance[115].

TABLE 2.3: Grading of Indices

Index		**Grade**				
		1	**2**	**3**	**4**	**5**
Wetting time	**top**	≥120	20-119	5-19	3-5	<3
		No wetting	Slow	Medium	Fast	Very fast
	Bottom	≥120	20-119	5-19	3-5	<3
		No wetting	Slow	Medium	Fast	Very fast
Absorption rate	**Top**	0-10	10-30	30-50	50-100	>100
		Very slow	Slow	Medium	Fast	Very fast
	Bottom	0-10	10-30	30-50	50-100	>100
		Very slow	Slow	Medium	Fast	Very fast
Max wetted radius	**Top**	0-7	7-12	12-17	17-22	>22
		No wetting	Slow	Medium	Large	Very large
	Bottom	0-7	7-12	12-17	17-22	>22
		No wetting	Slow	Medium	Large	Very large
Spreading speed	**Top**	0-1	1-2	2-3	3-4	>4
		Very slow	Slow	Medium	Fast	Very fast
	Bottom	0-1	1-2	2-3	3-4	>4
		Very slow	Slow	Medium	Fast	Very fast
AOTI		<-50	-50 to 100	100-200	200-400	>400
		Poor	Fair	Good	Very good	Excellent
OMMC		0-0.2	0.2-0.4	0.4-0.6	0.6-0.8	>0.8
		Poor	Fair	Good	Very good	Excellent

2.3.6.3 Moisture transport mechanism

The moisture transport process of clothing under humidity transience is one of the most important factors influencing the dynamic comfort of a wearer in practical wear situations[116]. However the moisture transport process is hardly a single process; it is always coupled with heat transfer process under dynamic conditions due to energy changes involved with the phase change of water molecules[117]. Clothing's heat and moisture transfer performance is affected not only by material properties, such as fabric thickness, weight and air permeability, the air gap between the skin and the material but also by design, open or closed, size and accessory and how a garment is worn[118]. The nature and thickness of the materials reduce the permeability of clothing and, consequently, inhibit the evaporation of moisture from the body. The clothing weight, as well as its stiffness, thickness and bulkiness, can increase the wearer's metabolic heat production during activity as well as restrict heat exchange between the body and the environment. Due to the tenor body activity, the body can put out as much as 1 L sweat an hour; therefore, the fabric worn next to skin will get wet. This moisturized fabric reduces the body heat and makes the wearer uncomfortable. So, the fabric worn next to the skin should assist for the release of moisture quickly to the atmosphere.

The fabric worn next to the skin should have two important properties. The initial and the foremost property is to absorb perspiration from the skin surface, and the second is to transfer the moisture to the atmosphere and make the wearer feel comfortable.

The most important factors which affect moisture transport are: fibre type; cloth construction or weave; weight or thickness of the material and presence of chemical treatments. There are three possible ways the moisture may migrate along the direction of the concentration gradient, when a water vapour concentration gradient is applied across a fabric: travelling of the water moisture through the fiber interiors, along the surfaces of the fibers, or through the air spaces between the fibers and the yarns.

As long as the water remains in the vapor state, bulk transport of liquid by capillary action can be neglected, and these routes may be described by the following three mechanisms: a) molecular diffusion through the polymeric phases, b) surface diffusion of absorbed molecules along the fibers and c) molecular diffusion through the air spaces of the fabric. Perspiration moisture collects in and passes through clothing as worn. Both the collection and passage of this moisture is influenced by the properties of clothing fabrics. The measurement of moisture properties related to comfort in wear is very important.

Generally, in responding to external humid transients; a piece of dry fabric exhibits three stages of transport behavior. Two fast processes are dominated in the first stage: water vapor diffusion and liquid water diffusion in the air filling the interfiber voids in which steady states can be reached in a fraction of a second. Throughout this period, water vapor diffuses into the fabric because of the concentration gradient across the two surfaces. In the meantime, due to the surface tension force, the liquid water starts to flow out of the regions of higher liquid content to the drier regions.

The second stage, which is a relatively slow process features the moisture sorption of fibers and takes a few minutes to a few hours to be completed, depending on the hygroscopicity of the fibers. In this period, water diffuses into the fabric by sorption of water into the fibers, which increases the relative humidity at the fiber surfaces. After liquid water diffuses into the fabric, the surfaces of the fibers are saturated because of the film of water on them, which again enhances the sorption process. Throughout these two transient stages, the heat transfer process is coupled with the four different forms of moisture transfer due to the heat release or absorption during sorption/desorption and evaporation/condensation, which, in turn, are affected by the efficiency of heat transfer.

At last, the third stage is reached as a steady state, in which all four forms of moisture transport and the heat transfer process become steady and the coupling effects among them become less significant[119]. The liquid moisture flow through textile materials is controlled with two processes, i.e. Wetting and wicking. The wetting and wicking behavior is a critical aspect of the performance of products such as sportswear, hygiene disposable materials and medical items[120].

Wetting of a fabric can occur from either the external environment of the wearer or from the internal environment when the wearer is perspiring. Wetting is the initial process, involved in fluid spreading; it is controlled by the surface energies of the involved solid and liquid. Wetting is a complex process further complicated by the structure of fibrous assembly. The curvature of fibres, crimps on fibres and orientation and packing of fibres in fibrous materials make the evaluation of wetting phenomena of fibrous assemblies more complicated. The curvature and roughness of contact surfaces are two critical factors for the wetting phenomena in fibrous materials, which are porous media of intricate, tortuous and yet soft, rough structure. A liquid that fully wets a material in the form of a smooth planar surface may not wet the same material when presented as a smooth fibre surface, let alone a real fibrous structure. Clothing comfort also depends on the wetting behavior of fibrous structure.

The mechanism by which moisture is transported in textiles is similar to the wicking of a liquid in capillaries. Capillary action is determined by two fundamental properties of the capillary: its diameter; and surface energy of its outside face.

The smaller the diameter or the greater the surface energy, the greater the tendency of a liquid to move up the capillary. In textile structures, the spaces between the fibres effectively form capillaries. Hence, the narrower the spaces between these fibres, the greater the ability of the textile to wick moisture. Fabric constructions, which effectively form narrow capillaries, pick up moisture easily. Such constructions include fabrics made from micro fibres, which are packed closely together. However, capillary action ceases when all parts of a garment are equally wet.

The surface energy in a textile structure is determined largely by the chemical structure of the exposed surface of the fibre, as follows:

- Hydrophilic fibres have a high surface energy. Consequently, they pick up moisture more readily than hydrophobic fibres;
- Hydrophobic fibres, by contrast, have low surface energy and repel moisture.

In general, wicking takes place when a liquid travels along the surface of the fibre but is not absorbed into the fibre. Physically, wicking is the spontaneous flow of a liquid in a porous substrate, driven by capillary forces.

Good moisture absorption and release can be found in fibers with greater specific surface area. Such rapid transportation of moisture or diffusion of sweat in the form of steam from the body towards the outside enables good moisture absorption and release, thus maintaining dryness and comfort of the fiber properties. Natural fibers such as cotton and viscose are hydrophilic, meaning that their surface has bonding sites for water molecules. Therefore, water tends to be retained in the hydrophilic fibres, which have poor moisture transportation and release. On the other hand, synthetic fibers such as polyester are hydrophobic, meaning that their surface has few bonding sites for water molecules. Hence, they tend not to get wet and have good moisture transportation and release. Neither natural nor synthetic fibrs can perform well in both moisture absorption and release at the same time. To achieve such would require moisture absorption and release finishing through which the structural design and quality of fibres are modified so that the textile products thus manufactured can have good performance in absorbing, transporting and dissipating moisture[121].

A knitted fabric construction is not a completely solid structure, but is complex and porous shape. The complex contours formed by the fibres in the yarn and the yarns in the fabric constitute the boundaries of the channels along which moisture flows[122]. It has been reported that the most important mechanism of fabric wicking is the motion of liquid in the void spaces between the fibres in yarn[123]. Due to the laws of capillarity, the much larger pores between yarns do not contribute to the long-range motion of liquid. It has also been concluded by Minor & Schwartz that the yarn intersections act as new reservoirs, and feed all branches equally. This finding will become increasingly important when different types of knit structures are compared.

Detailed knowledge of the moisture transmission properties of a fiber assembly is prerequisite for improving the comfort of apparel materials. It has been theorized by many researchers that the flow of fluid in a fabric is largely governed by the network structure of fabric and not by the fibre type. In any system, where capillarity causes relative motion between a solid and a liquid, the shape of the solid surfaces is an important factor, which governs the rate and direction of liquid flow. The rate of travel of liquid water is governed by the fibre arrangement in yarns, which controls capillary size and continuity[124]. The assumption that the fibre type does not contribute to capillary flow is not an entirely true statement, because fibre type also contributes to the overall structure. Fibre type, under certain circumstances, can drastically change the structure of the yarn by changing the wicking properties of the fabric[125].

Das et al. studied the effects of yarn fineness, shrinkable acrylic proportion and twist level on various properties of cotton-acrylic blended bulk yarns and found that vertical wicking heights for all the bulked yarns were found to be higher than comparable 100% cotton yarns[126, 127]. Wang and Zha investigated wicking property of the yarns and found that the wicking behavior of the yarns improved with the increase in cross-sectional area due to a large number of capillaries in yarns[128]. Moreover, another study showed that wicking velocity increased with the increase in cross-sectional area of yarn and decrease in liquid viscosity. The studies on the wicking performance of knitted fabrics and on the influence of yarn wicking on fabric are scanty. Moreover, mainly, ring spun and / or filament yarns have been studied for their wicking performance[129].

Crow and Osczevski conducted similar transfer wicking experiments on a range of knitted and woven fabrics used for activewear. They reported that the amount of water that wicked from one layer to another depended on the pore sizes and their corresponding volumes[130].

Ito & Muraoka investigated the water transport along textile fibres, as measured by an electrical capacitance technique[131]. Adler & Walsh reported the mechanisms of transient moisture transport at low moisture content is vapour diffusion and wicking between fabrics does not take place until there is a sufficient amount of water to fill capillaries that are formed between fibres and yarns[132]. Tara Punna & S. Amsamani studied moisture transmission properties of polyester and viscose blended single jersey fabrics and reported that the liquid moisture transmission is strongly influenced by the enzymatic treatments[133].

Together with wetting and wicking mechanisms, the drying behavour of fabrics was also studied by some scholars who were interested in the comfort properties of fabrics. Fourt et al. in their research focused on drying behavior of cotton and continuous filament fabrics, showed that the fabrics dried at the same rate (expressed as weight of water evaporating per unit area per unit time) under the conditions defined in the study, but that the time of drying was dependent on the amount of water held originally, so that some fabrics dried sooner than others[61]. They also stated that the kind of fibre and / or large differences in moisture affinity affected the water holding capacity, although the factors did not have an effect on the rate of drying since it was controlled by the resistance of air layers to the passage of heat; they concluded that the rate governing factor was the thickness of the films of relatively still air near the fabric surface[134]. Laing et al. concluded that drying time correlated positively both with fabric thickness and the mass of water retained in the fabric following the wetting treatment[135].

The outdoor exercise market for apparel worn next to the skin continues to stimulate interest, much revolving around better understanding of the relationships between fabric structure (typically knits) and permeability to water vapour / water (i.e sweat). Li et al showed that the heat transfer process, which is influenced by fabric thickness and porosity, significantly impacts moisture transport process[136]. Wiah Wardiningsih and Ogla Troynikov studied the moisture transport responses to plain jersey fabrics produced from bamboo yarns and determined the relationships between cover factors and moisture management properties. They observed that as the cover factor of the fabric increased, the wetting time increased, maximum wetted radius decreased, rate of absorption decreased, spreading speed decreased and overall moisture management capacity decreased[137]. Woodcock developed the moisture permeability index to describe the efficiency of fabrics or fabric systems in transferring moisture and its associated latent heat[138]. Miller et al investigated a method of measuring liquid transfer through fabrics[139].

2.3.7 Water vapour permeability

Also known as ‘breathability’, water vapour permeability is defined as a fabric’s ability to transport water vapour from the skin surface through the fabric to the external environment [140, 141, 142]. This fabric property is important for fabrics used in sportswear. The human body has its own mechanism for cooling itself when overheating through insensible perspiration (in form of water vapour) and / or sensible perspiration (liquid sweat) to balance the body heat generated from daily activities of varying intensities. Ultimately its purpose is to maintain a constant body temperature. Body heat evaporates the perspiration; however, if the vapour cannot escape to the surrounding atmosphere, the relative humidity inside the clothing will increase, which will cause a wet feeling on the skin and an uncomfortable sensation[143].

It is an important property for fabrics to be used in clothing systems intended to be worn during vigorous activity. Hatch defines water vapour permeability as “the rate at which water vapour diffuses through a fabric”[144]. This should occur spontaneously because of the vapour pressure gradient. The water vapour dissipates from the high vapour pressure region (humid body surface) to the lower vapour pressure region (drier external environment). The flow of liquid moisture through textiles is caused by fibre-liquid molecular attraction at the surface of the fibre materials, which is mainly determined by the surface tension and the effective capillary pore distribution and pathways. Transport of liquid moisture across textiles increases their thermal conductivity and changes the heat transfer and moisture absorption of the fibres. Measuring permeability to water vapour (and water) has presented a challenge for many years, and several test methods have been developed and reviewed. The basic method of water vapour permeability is a dish method (ASTM E96, 2000; BS7209, 1990;ISO 11092, 1993). The lost water at certain durations can be measured, with which water vapour permeability can be calculated. This is a direct measurement of water vapour permeability and recognized as a reliable method[145, 146].

Permetest instrument developed by Sensora, working on skin model principle as given by the ISO 11092 determines the relative water vapour permeability, that is the percentage of water vapour transmitted through the fabric sample compared with that through the equivalent thickness of air. It also measures the resistance to evaporative heat loss of a fabric with its associated layer of air.

Prahsarn et al considered water vapour transport during the % RH equilibrium state occurred through air spaces in fabric, and was largely independent of fibre hygroscopicity, whereas the time required for the microclimate humidity to return to the original level following exposure ("drying time") was considered a function of fabric porosity and thickness, and possibly fibre hygroscopicity[147, 148].

2.3.8 Water vapour resistance

Water vapour permeability is indirectly related to water vapour resistance. The latter property can be described as the amount of resistance against the transport of water vapour through a fabric[149, 150, 151].

In some cases, not only the total amount of liquid that can be absorbed is important, but, also the speed of the absorption process is important. Moisture vapor transmission rate (MVTR) is the speed or rate at which moisture vapour moves through a fabric and is typically determined by measuring the amount of moisture vapour in grams that pass through $1m^2$ of fabric in 24 hours with a specific driving force (e.g. humidity). Moisture vapor transmission is primarily a function of fabric thickness and porosity. At rest, a body will give off a quarter of a cup (2 ounces, about 60 ml) of water vapour per hour at ambient conditions. Moderate exertion (walking, etc.) will increase the amount to one point (16 ounces, about 450 ml) per hour. It is an important factor related to thermal comfort especially for summer clothes and sportswear.

Skenderi et al investigated knitted fabrics using 100 percent cotton, 50/50 percent cotton/modal, 100 percent viscose and 100 percent Tencel® yarns of 20tex. The results of measurement of water vapour resistance carried out on a sweating guarded hot plate indicate the influence of environmental condition (temperature and relative humidity) on the transfer of water vapour that occurs due to the conditions[152].

The ASTM moisture vapour test (open cup test) is one of a number of test methods for moisture vapor transmission rate. In this test, fabric is placed tightly over cups of water where the water, the air above water and the room environment are at the same temperature and pressure. The humidity of the room must be controlled. The rate of water vapour that passes through the fabric is determined by weighing the cups.

In Sweating guarded hot plate method, the water vapour transmission is measured in terms of evaporative heat resistance (Ret) of the material, i.e. amount of power required to maintain the heated plate at skin temperature (35^{o}C) when moisture vapour evapourates from the plate and diffuse through test sample place kept on top of it. A sample measuring 5 inch x 5 inch is placed on the hot plate (or membrane) that is saturated with water to simulate sweating. The heat resistance (Ret) is given by the equation

Ret (m^{2}Pa W-1) = A(Ps –Pa)/H

Where, A = test area in m^2, Ps = vapour pressure at plate surface, Pa = vapour pressure in air, and H = input power.

Another method, Dynamic moisture permeation cell (ASTM F 2298) measures the moisture vapour diffusion resistance of the sample by passing mixture of dry and wet-saturated nitrogen streams above and below the sample. By carefully measuring the relative humidity of input and output streams the vapour diffusion resistance is determined. A humidity gradient of 90%, air temperature of 20$\pm$ 1^{o}C and gas flow rate of 200 cm^3/sec is maintained throughout the experiment.

Greyson[153] and Havenith[154] mentioned that the heat and water vapour resistance increase with material thickness and air entrapped in the fabric. In other research (Li et al), investigated the physical mechanisms involved during the perception of fabric dampness by studying the heat and moisture transfer in the fabric and at the fabric-skin interface[155].

2.3.8 Porosity

The performance property called ‘fabric permeability’, which is the result of the flow in fabric, is the function of firstly the pore properties of fabric and some environmental factors such as heat, pressure, moisture and the function of the properties of the fluid material that pass through the fabric, such as viscosity and surface tension. It is logical to expect that fabric structure has an impact on air permeability, namely, the porosity. Accordingly, the prediction of the permeability performance of the fabric used in a certain area can be obtained by the control of the pore properties. It is extremely important in terms of production development, time and cost to be able to predict the performance property during the designing period especially in the technical textiles where permeability performance has a great importance during usage, such as airbags, geotextiles, filtration textile and sportswear[156].

Knitted fabrics are the preferred structures in athletic wear in which demand for comfort is a key requirement. Heat and liquid sweat generation during athletic activities must be transported out and dissipated to the atmosphere. A key property influencing such behaviors is porosity[157]. Two parameters that characterize it are pore size and pore volume. Airflow through textiles is mainly affected by the pore characteristics of fabrics. The pore dimension and distribution in a fabric is a function of fabric geometry. The yarn diameter, knitting structure, course and wale density, and yarn linear density are the main factors affecting the porosity of knitted fabrics[158, 159]. It was determined that the loop length of a knitted jersey has more influence on porosity than the stitch density and the thickness. Porosity is determined by calculating the difference between the total volume of a fabric specimen and the total volume of fiber in it. The difference between these two values is considered as air space and when calculated as a percentage of the total volume gives the calculated porosity value.

The porosity of textile fabrics can be evaluated by several methods. The most commonly used are: air permeability; geometrical modeling and image processing. Many models have been proposed to characterize the geometry of knitted structure and can be classified as shown in Table 2.4.

Table 2.4: Knitting geometry modeling

Purely geometrical	Energy methods	Elasticity theory	Empirical
Chamberlain	Postle & Munden	Semnani et al.	Tompkins
Pierce	Shanahan & Postle		Dutton
Dalidowitch	Hepworth & Leaf		Sokolnikoff
Doyle	Hepworth		Munden
Leaf & Glaskin			
Suh			

Image processing method is based on taking pictures using a camera CCD. Images are represented on the grey scale and analysed using specific software to determine porosity. The device of imagery is composed of: a microscope and a camera CCD; a device ensuring the fixing of knitting under microscope; a display screen and a computer to record and analyse images.

Porosity can also be given using construction parameters of the knit fabric using *Eq*:

$$\varepsilon = 1 - \frac{\Pi d^2 \ell c w}{2t}$$

Where:

t : sample's thickness (cm) ;

ℓ : elementary loop length (cm) ;

d : yarn diameter (cm) ;

c : number of Courses per cm ;

w: number of Wales per cm[160].

Dias and Delkumburewatte created a theoretical model to predict the porosity of a knitted structure. It was determined that porosity depended on fabric parameters and relaxation progression[161].

2.3.10 Air Permeability

Permeability is a property composed of performance and thickness of a material in [$m^3/s.m^2$] in SI system. Air permeability is defined as the volume of air in millilitres which is passed in one second through 100mm^2 of the fabric at a pressure difference of 10mm head of water.

The fabric structural parameters have an impact on air permeability by causing a change in the length of airflow paths through a fabric. Density (porosity), eg. the shape and sizes of pores, and finishing processes also influence air permeability[162, 163]. However, porosity evaluated with air permeability testing does not necessarily correlate closely with other assessment of porosity, e.g. structural porosity, since the resistance to the passage of air does not depend directly on the percentage of fabric that is porous. Different surface textures on either side may exhibit different air permeability depending upon the direction of airflow.

The reciprocal of air permeability, air resistance, is defined as the time in seconds for a certain volume of air to pass through a certain area of fabric under a constant pressure. The advantage of using air resistance instead of air permeability is to be able to characterize the air resistance of an assembly of a number of fabrics as the sum of the individual air resistances while air permeability is just characterizing a fabric.

The ease or otherwise passage of air is of importance for a number of fabric end uses such as industrial filters, tents, sailcloths, parachutes, raincoats, shirtings, downproof fabrics and airbags. In outdoor clothing it is important that air permeability is as low as possible because it should function as a wind protection. In sportswear, high air permeability is desirable.

Generally, the air permeability of a fabric can influence its comfort behaviours in several ways. In the first case, a material that is permeable to air is, in general, likely to be permeable to water in either the vapour or the liquid phase. Thus, the moisture-vapour permeability and the liquid-moisture transmission are normally related to air permeability. In the second case, the thermal resistance of a fabric is strongly dependent on the enclosed still air, and this factor is in turn influenced by the fabric structure.

Air permeability is an important factor in determining the comfort level of a fabric as it plays a significant role in transporting moisture vapours from the skin to the outside atmosphere. The air in the microclimate between individual items of clothing also has a physiological function. When the body is at rest, this air in the microclimate contributes upto approximately 50 percent of the effective thermal insulation properties of the clothing. When the body is in motion, approximately 30 percent of the heat and moisture can be removed by air convection in the microclimate and air exchange via the clothing. The assumption is that vapours travel mainly through fabric spaces by diffusion in air from one side of the fabric to the other[164, 165].

Most of the previous studies investigated the relationship between the air permeability and structural characteristics of plain knitted fabrics. Marmarali investigated the air permeability of cotton/spandex single jersey fabrics within their dimensional and physical properties and compared results with fabrics knitted from cotton alone. It proved that the air permeability of fabrics containing spandex was lower[64]. Thermal properties and thermal behavior of cellulosic textile fabrics and air permeability, porosity were investigated by Stankovic et al., in which they found that air permeability and heat transfer through fabrics is closely related to both the capillary structure and surface characteristics of yarns. Adequate ventilation or air movement can reduce the insulation properties of clothing by 5 to 50%[166]. It is known that permeability to air depends on the fabric surface density, ie. it depends on the knit's loop length and on the linear density of yarns.

Mikučionienė D. et al, investigated the influence of knit structure, i.e. linear density of yarns, loop length and tightness factor of the knit on permeability to air and reported that the correlation between the tightness factor of the knit and its air permeability is strong[167].