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Review Article

Heat and Water Transport Through Knitted Fabric

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Abstract

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. Over the last few years, there has been growing interest in knitted fabrics due to its simple production technique, low cost, high levels of clothing comfort and wide product range. Fabric thermal resistance, thermal conductivity, thermal absorptivity, heat flow, relative water vapour permeability and air permeability are physical properties that need to be measured to obtain a better understanding of heat and water transport through fabric. Clothing physiology, perception of comfort, concept of clothing comfort, moisture management and the physical properties affecting the comfort properties of knitted fabrics have been reviewed.

keywords: Clothing comfort; thermal comfort; moisture management; air permeability

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 [1]. Over the last few years, there has been growing interest in knitted fabrics due to its simple production technique, low cost, high levels of clothing comfort and wide product range. Knitted fabrics not only possess stretch and provide freedom of movement, but they also have good handle and easily transmit vapor from the body. That's why knitted fabrics are commonly preferred for sportswear, casual wear and underwear. Sports garments, particularly the layer worn next to skin, are key to the physiological comfort of an athlete, and their attributes in this aspect are critical to the athlete's performance. Fabric thermal resistance, thermal conductivity, thermal absorptivity, heat flow, relative water vapor permeability and air permeability are physical properties that need to be measured to obtain a better understanding of heat and water transportation through fabric. Fabric comfort performance can be reflected by a combination of these properties which are governed by the same structural factors of fabrics [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.

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 [3]. 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 [4,5]. 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. 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 [6-8]. 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 [9].

Concept of Clothing Comfort

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.

a) 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.

b) 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.

c) 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.

d) Pressure comfort: is more complex and involves a number of synthetic sensations. This factor may mainly correspond to the pressure receptors in the skin and may come from some combination of a number of sensory responses. Fabric bulk, mechanical behavior and overall fit of the garment to the body may be responsible to this dimension of comfort. Stretch in fabrics falls into the category of pressure sensations [10].

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.

Thermal Comfort

Comfort involves thermal and non-thermal components, and it is related to wear situations, such as, working, non-critical and critical conditions. Comfort is related to complex interactions between the fabric, climatic, physiological and psychological variables. 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 [11,12]. 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 [13]. 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 above 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 [14]. 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 it should essentially help the wearer in his/her effort and not to give additional physical and heat stress. The thermal comfort of man depends on combinations of clothing, climate and physical activity. 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 Qmax, which the maximum heat flow while heat is still being transferred.

Physical Properties Affecting Heat and Water Transport

Thermal Conductivity (λ)

is the intrinsic property of a material which relates its ability to conduct heat. 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 expresses 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 ($\lambda_{air} = 0.025$) [15]. In general, the thermal conductivity of fibres is higher than that of entrapped air in fabric [16]. Therefore, as the amount of entrapped air in the fabric structure increases, the fabric provides lower thermal conductivity and higher thermal insulation. 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. The entrapped air is by far the greatest determinant of fabric conductivity, and within the range of typical textile fibre conductivities, the contribution of fibre is relatively small [17].

Thermal 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 [18]. 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:

a) The thermal resistance to transfer heat from the surface of the material,

b) The thermal resistance of the clothing material, and

c) 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 in normal fabrics appear to be thickness, enclosed still air and external air is the most significant factor in determining thermal insulation. The greater the thermal resistance of a fabric, the lower its ability to disperse body heat [19].

Thermal Absorptivity

Thermal absorptivity determines the contact temperature of two materials and indicates the warm-cool feeling of fabrics [20]. 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 [21]. 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 are the specific heat of fabric [22].

Moisture Management

Moisture management is an important aspect of fabric meant for apparels, which decides comfort level. An important feature of any fabric is how it transport, store, and dispose liquid water and moisture from the surface of the skin to the atmosphere through the fabric [23], is a complex process influenced by a variety of fabric characteristics, e.g., type of fibre (hydrophilic and hydrophobic), porosity, and thickness [24]. 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" [25]. 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 [26]. An ideal sportswear must transfer perspiration from the body followed by evaporating the moisture rapidly and keeping the body warm [27]. The most effective fabrics will spread moisture over a wide area to maximize the surface area available for evaporation and hence cooling [28].

Moisture management has the following functions:

a) Regulation of body temperature: When the human body core temperature exceeds 37°C, sweat is produced. Transporting the sweat away from the skin and evaporating it to the atmosphere, reduces body temperature.

b) 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 [29].

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. 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 [30]. The thermal insulation and the moisture resistance of a clothing system are governed both by the fit of the individual garments and by the characteristics of the textile material [31]. Clothing's heat and moisture transfer performance is affected not only by material properties, such as fabric thickness, weight and air permeability, but also by design, size and accessory and how a garment is worn. 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. The air gap between the skin and the material and the garment design, open or closed, are also important factors [32]. 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. Detailed knowledge of the moisture transmission properties of a fiber assembly is prerequisite for improving the comfort of apparel materials. 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 (ie. sweat). Li et al. showed that the heat transfer process, which is influenced by fabric thickness and porosity, significantly impacts moisture transport process [33].

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 [34,35]. 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 vapor 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 [36,37]. 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 [38].

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 [39-41].

Porosity

It is logical to expect that fabric structure has an impact on air permeability, namely, the porosity. 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 affected by the yarn number or yarn count number [42]. 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. Two parameters that characterize it are pore size and pore volume. 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 according to several methods. The most commonly used are air permeability, geometrical modeling and image processing. It can be given using construction parameters of the knit fabric (Benltoufa et al. 2007) using Eq:

$$\varepsilon = \frac{1}{2t} - \Pi d2\ell cw$$

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 [43].

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), e.g., the shape and sizes of pores, and finishing processes also influence air permeability. 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. 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 assumption is that vapours travel mainly through fabric spaces by diffusion in air from one side of the fabric to the other [44,45]. Adequate ventilation or air movement can reduce the insulation properties of clothing by 5 to 50% [46]. It is known that permeability to air depends on the fabric surface density, i.e., it depends on the knit's loop length and on the linear density of yarns.

Summary

With the possibility of various combinations of fabric constructions and yarns used, knitted fabric appears to be the ideal base for functionally adaptive sportswear. It is not a simple task to optimize sportswear as regards thermo-physiological and sensorial comfort. The PR requirements of ideal sportswear are rapid transport of perspiration away from the body and then its rapid evaporations. Actually, the comfort perceptions of clothing are influenced by the wetness or dryness of the fabric and thermal feelings resulting from the interactions of fabric moisture and heat transfer related properties. Detailed knowledge of the heat and water transport properties of a fiber assembly is prerequisite for improving the comfort of knitted sportswear fabrics.

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