Textile Progress

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ttpr20

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To cite this article: Lebo Maduna & Asis Patnaik (2020) Heat, moisture and air transport through clothing textiles, Textile Progress, 52:3, 129-166, DOI: 10.1080/00405167.2021.1955524

To link to this article: https://doi.org/10.1080/00405167.2021.1955524

Published online: 15 Sep 2021.

TEXTILE PROGRESS
2020, VOL. 52, NO. 3, 129–166
https://doi.org/10.1080/00405167.2021.1955524

Heat, moisture and air transport through clothing textiles

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ABSTRACT

The body generates sweat and heat that must be removed from the surface of the skin to the outside environment in order to maintain body temperature. The transfer of sweat, heat and air through the fabric is important for the wearer's comfort. The fabric transports moisture by absorption or wicking processes. Moisture is absorbed by the fabric and when it evaporates it cools the body. Wicking occurs when moisture is transported in between the pores of the fabrics or by capillary action in yarns. Heat transfer involves conduction, convection and radiation and because air movement by convection facilitates the evaporation of sweat, it can make a substantial contribution to causing the body temperature to decrease. Clothing impairs the transfer of heat and moisture from the skin surface to the external environment. Restricting heat transfer to the external environment helps to keep the wearer warm but excessive accumulation of moisture causes clothing to stick to the skin, while the accumulation of heat causes heat stress making the wearer feel uncomfortable. Moisture, heat and air transmission are affected by fibres, fabrics and finishing properties and hydrophilic fibres absorb more moisture than lipophilic fibres. Rapid transportation of sweat and heat helps the body to cool down and the wearer to feel comfortable but protective clothing tends to have lower moisture, heat and air transmission and as a result the accumulation of moisture and heat makes them uncomfortable to wear. Traditional methods of evaluating the effects of moisture, heat and air transmission by clothing use bench-top tests on flat fabric, however, the more-recent use of manikins enables consideration to be taken of body shape as well as fit of the garments.

ARTICLE HISTORY
Received 23 March 2021
Accepted 21 June 2021

KEYWORDS
Air permeability; comfort; fabric; heat; moisture-transport

1. Introduction

The study of moisture, heat and air transport in the fabrics is important in fabric design because of their contribution to wearer comfort. The transfer is a complicated process as it not only depends on the physical interaction between the fabric and wearer but also involves the physiological interpretations of each individual. Comfort

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performance is subjective as it can vary from person to person and individuals wearing the same clothing can experience different comfort feelings. Studying the transfer of moisture, heat and air from the body through the clothing is not only complex but it is also time-consuming and often the results cannot be reproduced to predict the performance of clothing under different conditions.

The transfer of moisture, heat and air can be due to gradient differences or sorption processes (Li, 2001; Lim et al., 2015; Slater, 1977). Air, moisture and heat from the surroundings can penetrate the fabric through its pores and similarly moisture and heat generated by the body can also leave through these pores. Water vapour and moisture transfer involves vapour diffusion, moisture absorption, evaporation and capillary action, whilst heat transfer involves conduction, convection and radiation transport mechanisms (Ran et al., 2011; Salata et al., 2018) at low physical activity conduction is predominant, whereas for high activity levels heat lost to the evaporation of perspiration is dominant (Bedek et al., 2011).

It was reported that thermoreceptors in the skin, i.e. the receptors which respond to changes in temperature, are responsible for thermal comfort sensations. Other factors that can have an influence on the wearer comfort are softness, stickiness, roughness, itchiness, heaviness, stiffness and prickliness which involve the mechanoreceptors, i.e. the receptors which respond to mechanical stimuli. In the presence of moisture, the friction between the skin and fabric increases and the receptors in the skin are stimulated. It was reported that an even pressure applied to someone wearing tight clothing in a cold environment made a person feel damp even though the fabric was dry (Li, 2001).

The human body generates heat and sweat that must be transferred from the skin surface through the clothing to the outside environment. Sweating occurs when the body temperature rises and the body responds by increasing the sweating rate. When sweat evaporates from the skin surface, the body is cooled down. When the body's surface temperature decreases, the wearer experiences a cold sensation, however, continued cooling sufficient to bring about a fall in the body's core temperature may cause hypothermia. Because clothing serves as a barrier between the body and outside environment it obstructs the removal of moisture and water vapour. If sweat cannot be removed fast enough, clothing becomes wet and sticks to the skin and becomes uncomfortable. In impermeable clothing like waterproof garments, the clothing acts as a two-way barrier and internally-generated moisture can build up easily; when sweat does not evaporate quickly enough the garment becomes wet and uncomfortable to wear. It is important therefore that clothing assists moisture and heat transfer especially for protective and sportswear clothing. However, clothing not only provides protection to the human body against rain, wind and sun, it is a status and modest symbol (Huang & Qian, 2007; Raccuglia et al., 2018; Zhang et al., 2021). The transfer of moisture and heat can be influenced by the body shape, clothing drapability, air gap and contact area between the body and clothing. The factors become more complex for loose-fitting than for tight-fitting clothing (Behera & Hari, 2010; Raccuglia et al., 2018).

Due to the differences in daily physical activities and physical fitness, people generate different amounts of heat and moisture. It is important to design appropriate clothing for different environments which will allow them to disperse or retain heat and moisture easily. Protective clothing is more complex to design than general clothing as the former must be comfortable to wear while retaining high technical performance during operation. Protective clothing like that worn by firefighters is uncomfortable to wear for longer periods as it is typically heavy and stiff. On the other hand, general clothing's primary function is not to provide maximum protection so it can be made to be permeable, flexible, soft and light to maximise the comfort feelings of the wearer. In this issue of Textile Progress air, moisture and heat transfer through clothing and the various methods used to test them are discussed.

Friction, air, moisture and heat transmission are important factors that affect the comfort level of the wearer (Bedek et al., 2011). The body continuously generates heat and moisture (sweat) which must be removed from its surface. Wearing permeable clothing allows air, heat and water vapour to pass easily so that air from the outside can remove heat and moisture from the skin's surface. When fibres absorb moisture on the surface of the skin they transport it to the outside surface of the fabric which is dry if the air is dry, whereas more heat and increased humidity bring about accumulation of sweat on the skin, causing discomfort and contributing to the wearer experiencing physical and mental fatigue. The permeability of heat through the fabric from outside the garment is responsible for most of the injuries suffered by firefighters. Impermeable and semi-permeable fabrics or membranes act as barriers to reduce the amount of heat or moisture that can penetrate from the outside to reach the skin and cause severe skin damage. Semi-permeable membranes allow water vapour to pass through from the inside while preventing the penetration of liquid from the external environment (Chen et al., 2018; Irzmanska, 2015).

Protective clothing not only provides absolute protection but decreases the damage that can be experienced by serving as a barrier between the body and the external forces hence increasing thickness is an important factor which enhances protection against flame and radiation, however, this also reduces fabric breathability.

2. Heat transfer

Heat transfer in clothing is important in keeping the wearer comfortable. The amount of heat lost by the body is influenced not only by conduction, convection and radiation processes, but also by the evaporation of sweat. Heavy and thick fabrics have lower permeability and higher insulation properties. Factors that affect thermal comfort are metabolic rate, clothing construction, air temperature, wind speed and humidity. These factors are influenced by both human activity levels and heat loss and as a result clothing designed for a particular environment may not be comfortable to wear in a different environment (Varadaraju & Srinivasan, 2019; Xu et al., 2013) or in cases where the level of activity is very different. It has been reported that the temperature that is comfortable for humans is when their skin surface temperature is around ±33.4 °C (Tyurin et al., 2018).

Wearing clothing obstructs the removal of sweat and heat because the clothing acts as a barrier. Dry fabrics exhibit better insulation because of the lower thermal conductivity of the air trapped between fibres than that of the liquid which fills these spaces in wet fabrics. Even so, a fabric that is saturated with sweat causes a lag in cooling the body even when evaporation happens on the surface of the skin. In the case of wet fabrics, heat is removed from the body/garment combination when evaporation takes place from the fabric's surface. Evaporation from a saturated fabric in contact with skin occurs on the fabric's outer surface not on the skin. Evaporation of sweat is influenced by various factors such as humidity, heat transfer, fabric permeability, coverage area, fibre type, fabric type, yarn type, adsorption and absorption properties. Heat stress is responsible for decreased activity in humans and this happens when a person is performing activities that result in excessive sweating; it occurs when sweat cannot be removed fast enough to cool the body (Elson & Eckels, 2018; Guo et al., 2013; Tang et al., 2015).

In protective clothing, the ability of the clothing to prevent the penetration of heat and moisture from the outside environment while allowing the transfer of heat and moisture from the body is important for their performance. Firefighters are exposed to hazardous fire and chemicals and must wear appropriate protective clothing that will protect their lives, safety and health. Their clothing is heavy and comprises multiple layers to provide adequate protection. Heavy and thick fabrics have low permeability and high insulation. This restricts the transfer of heat but even though firefighters protective clothing is made of specialist fabrics, when exposed to extremely high temperatures the fabrics will lose their ability to provide protection. The protective clothing should be viewed therefore not as offering absolute protection but as a way of minimising life-threatening thermal hazards. In the USA about 68,000 firefighters experienced injuries during their fire and emergency rescuing operations, with about 100 losing their lives in the process (Fan & Wen, 2002; Su et al., 2019; Xu et al., 2019).

The thermal protection of protective fabrics is influenced by fabric structure and properties such as air permeability and thickness. Air gaps and increases in the thickness of the fabric enhance its thermal protection as they obstruct the transfer of heat from the body. In order to provide protection against hot liquid, impermeable fabrics are used, however, such fabrics will obstruct the transfer of heat and water vapour from the body, so instead, semi-permeable membrane layers that are permeable to air but impermeable to liquid are incorporated into the fabric because they allow the passage of water vapour and heat transfer. Chen et al. (2018) suggested that the air permeability of the fabric must be less than 5 cm^3/cm^2 s in order to have fabrics that can provide protection against hot liquids. Membranes like Gore-Tex™ have pores large enough to allow single water molecules in water vapour to pass through but are too small for clusters of water molecules, such as those which exist when water is in the liquid state, to penetrate. This allows the Gore-Tex™ membranes to be used in liquid-proof, breathable fabrics which ensures fabric comfort (Huang & Qian, 2007).

As discussed previously the presence of air gaps improves thermal protection as the entrapped air acts as an insulator to thermal heat transfer (He et al., 2017). An increase in pore diameter in bulky fabrics decreases the thermal conductivity as the trapped air in the pores obstructs the transfer of heat from the body (Kim & Kim, 2016) but such spaces can be eliminated by exposure to extremely-high temperatures due to thermal shrinkage. During exposure to flames and radiant heat, the stored thermal energy in the fabric is a secondary source of heat which can compromise the health and safety of the firefighters. It is this stored energy that is responsible for injuries and death of the firefighters. and it may be released onto the wearer when the clothing is compressed by contact with another surface or by flexing clothing due to the movement of limbs (He et al., 2017). Radiant heat from wildfires, gas fires and structures fires exposes firefighters to the possibility of thermal injury (skin burns and heat stress) as they approach the fires to fight them, or have to enter burning structures in order to rescue people trapped inside. Wearing appropriate clothing that can minimise injury or illness is a must for firefighters. Skin burns are due to heat flux, time of exposure and ineffectiveness of protective clothing. Skin burns can occur in radiant flux ranging from 5–20 kw/m^2. The stored energy has a huge influence on the performance of protective clothing. The clothing and skin surface reduce heat flux entering the skin hence the requirement to use several layers with each layer providing protection and distribution of heat in fire-protective clothing. The outside layer's function is to prevent contact with flames and to limit thermal and mechanical damage, with the inside layer providing wearer comfort. Moisture has a positive influence on thermal protection as it absorbs and stores heat. The presence of moisture inside the thermal layer reduces the flow of heat by absorbing it, but this may also cause the temperature of the inner layers to increase due to the inability of the vaporised moisture to escape through the outside thermal layer. It is this stored energy that can cause skin burns when it comes in contact with human skin.

Thermal protective clothing is evaluated by using:

a. the thermal protective performance test (TPP) as shown in Figure 1 for convective and radiant heat penetrating through a clothing, and
b. the radiant protective performance test (RPP) for a controlled radiant heat source penetrating the protective clothing (Fu et al., 2014; Li et al., 2012; Su et al., 2019).

3. Moisture transport

The removal of moisture by the fabrics in garments is important in keeping the skin dry and the wearer comfortable. Evaporation of sweat from the skin's surface cools the body which is important for thermal comfort (Morton & Hearle, 1993, 2008; Yoon & Lee, 2011). When moisture builds up, it is accompanied by an increase in cool feeling. However, an excessive accumulation of moisture will start to make the person feel uncomfortable so it must be quickly removed to keep the skin dry and the skin temperature kept at equilibrium in order to keep the wearer comfortable (Hes et al., 2018; Slater, 1977; Onofrei et al., 2011). Because the body has no moisture receptors to sense the removal of moisture, it uses the thermoreceptors to sense the removal of heat, and this occurs when the body cools down and the removal of heat is read by the body as the wetness the wearer feels (Tang et al., 2015). Some of the factors that can influence moisture transfer through the fabrics are fabric construction, pore size, porosity and thickness of the fabric (Yoon & Lee, 2011). Wearing clothing that facilitates the flow of heat and moisture is important since clothing acts as a barrier (Slater, 1977). Fabrics with high moisture absorption and wicking capacity remove moisture from the body faster even though the wearer might be sweating and the

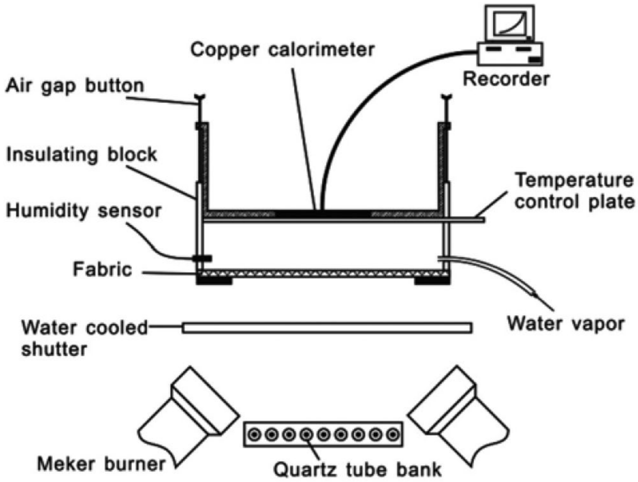

Figure 1. Schematic of thermal protective performance test (Li et al., 2012).

wearer will therefore experience a feeling of dryness because of the high rate of removal of moisture from the surface of the skin (Tang et al., 2015). For fibres, yarns and fabrics where the mechanical properties are important, the presence of moisture in them has a potential to reduce their strength (Morton & Hearle, 1993, 2008).

The transfer of moisture in fibrous materials is complex since the pores are not cylindrical and in addition the fibres are not always uniformly orientated (Zhu et al., 2013). The transfer of water vapour in fibres and yarns is attributed to the differences in vapour pressure gradient. Capillary action pulls moisture between the yarns or voids in a fabric to the surface of a fabric where it evaporates. Fabrics with high porosity tend to exhibit high moisture transfer. When moisture is removed from the skin it provides a cooling effect and decreases overall heat gain, however, in hydrophilic fabrics it has been reported that it can cause a greater gain in radiant heat than in lipophilic fabrics; there is more transfer of heat through lipophilic fabrics. Complicating the transfer of water vapour is that heat transfer is also taking place at the same time. At higher temperatures the body releases heat by sweating which is absorbed by the fibres. The temperature of the fibres quickly increases due to absorption of heat and then stabilises to the temperature of the moisture. Because moisture is a better conductor of heat than air, the presence of moisture in fibrous materials increases the thermal conductivity due to inter-fibre pores being occupied by moisture instead of air. This effect contrasts with the mechanism put forward by Fan and Wen (2002) who reported that dry fabrics have better thermal conductivity than wet fabrics because moisture is a barrier and decreases heat flux. They further discussed that initially when fabric porosity is increased, a decrease in heat flux can be observed due to a decrease in thermal conductivity. However, further increases in porosity may cause an increase in heat flux once water vapour transfer begins to increase.

When moisture starts to accumulate in a fabric, the fabric thermal insulation will begin to decrease due to moisture being not such a good insulator of heat compared to air. As a result, the thermal protection offered by clothing will vary according to the amount of moisture it contains, as water can easily transfer heat to and from the body and this can be very dangerous for firefighters exposed to external high temperatures in performing their duties (Fan & Wen, 2002; Ran et al., 2011; Salata et al., 2018; Slavinec et al., 2016; Zhu, 2020).

It was reported that fabrics with plain-weave structures have higher wettability than those with other woven structures such as twills or knitted structures such as ribs. This is attributed to the high number of yarn intersection points and tortuosity in plain weave structures which means there are fewer inter-yarn spaces to absorb water. Hydrophilic fibres such as cotton swell when they absorb moisture and this decreases the size of the pores in the fabric resulting in decreased wicking rate (Tang et al., 2015). Although a hydrophilic fabric will quickly absorb moisture from a wet surface, once it is saturated removal of moisture falls as obstruction to the moisture transfer is increased. The overall effect is to make the wearer feel uncomfortable because moisture is not being quickly removed.

Fibres with small radius and short inter-fibre distance are reported to possess higher water repellency (Beckham et al., 1997; Fan & Wen, 2002; Sampath et al., 2011) which can be attributed to smaller pores formed between fibres with small radius and short inter-fibre distance. Short inter-fibre distances are achieved by increasing the yarn twist. However, this holds for fibres that are packed in layers as single layers of fibres in parallel absorb less water. One of the main forces involved in the transfer of moisture is the capillary force which causes moisture to be transferred from one void to the next; it is dependent on fibre-water interfacial tension, pore size and surface treatment. The inner parts of a yarn display higher moisture transfer with wicking rate due to increased capillary pressure as a result of smaller pores in the inner part of the yarn. However, if the pores are too small or too large the transfer of moisture can slow down because of gravity which acts against capillary action. When two yarns are packed parallel to each other, wicking from one yarn to the other depends on whether the moisture can move from the inner region of the yarn to the outer region (Beckham et al., 1997; Fan & Wen, 2002; Sampath et al., 2011). Hollow-yarn fabrics were reported to have higher wicking rates than fabrics made from highly-twisted yarns because of increased porosity in hollow yarn fabrics. However, when it comes to drying time, the highly twisted yarn fabrics showed quicker drying due to the smaller amount of water contained in the fabric pores (Kim & Kim, 2016).

Waterproof breathable fabrics can be used for leisure, sports, military and health applications. These types of fabrics must ensure the wearer is comfortable by allowing water vapour to be transferred through the fabric to the outside environment whilst at the same time preventing the penetration of moisture from outside. In order to make clothing that meet these requirements, electrospun nanofibre membranes can be included as one of the fabric layers. Because nanofibre membranes are fragile, they need to be supported by a substrate layer, however, layered nanofibre fabrics with multiple layers show lower water-vapour transmission rates due to their high web density (Yoon & Lee, 2011).

Composite materials are increasingly being used to enhance properties of the manufactured product. One example is glass-fibre reinforced polyester used to make structures for vehicles. The structures must be able to operate in wet conditions (Pollard et al., 1989). The presence of moisture in fabrics affects its mechanical strength and lifetime as the fabric deteriorates faster. In composite materials, the absorption of moisture into micro-cracks and pores in the matrix or filler or liquid flow into these open spaces reduces the strength of the composite materials as it decreases the bonding. However, the severity of the effect is dependent on the type of the matrix being used as they may have different water absorption properties; polyester resins for example exhibit low water absorption (Roy et al., 2001).

4. Air transport

The air permeability of the fabric plays an important role in ensuring that the wearer feels comfortable (Ho et al., 2008) and it also plays an important role in the evaporation of moisture (Vasile et al., 2019). Fabric air permeability is the rate at which air passes through a particular fabric area under a given pressure drop between the two sides of the fabric. It indicates the ability of a fabric to allow air to pass through it and that is important because air movement facilitates the exchange of heat and moisture between the body and outside environment, thereby allowing the body to cool down. A fabric's air permeability is influenced by factors such fibre type, pore size, yarn type, fabric thickness, finishing treatment and yarn twist. Figure 2 shows the factors that affect fabric air permeability (Malik et al., 2017) and therefore how heat and moisture can be transferred through the fabric. Different fabrics have different air permeabilities, with lighter and thinner fabrics having higher permeabilities than thicker and heavier fabrics. Fabric deformation can also have an effect, for example stretching knitted fabrics biaxially increases pore sizes and as a result air permeability increases, whereas certain textile finishing processes that are performed to enhance particular aspects of fabric performance are reported to decrease fabric porosity due to their bringing about a decrease in pore size.

When the air pressure is higher on one side of a fabric than the other (say in a breeze or under windy conditions), the air will enter the fabric and leave on the side where the pressure is lower. This flow of air will remove heat from the body if the outside temperature is lower than the inside temperature and the body therefore cools down. The removal of heat and moisture by the penetrating air is good for those residing in warmer climates, however, for those who reside in colder climates such removal is likely to cause discomfort.

Summer clothing is designed to facilitate the penetration of air from outside the garments whereas permeable clothing is preferred for winter and in places where it is windy. Lower external temperatures cause the body to lose more heat to the outside environment but when the ambient temperature is closer to the body skin temperature of 33 °C, the loss of heat is minimal. To minimise loss of heat, thicker fabrics are preferred as they provide better insulation, but it has been reported that increasing the thickness above 4 cm causes only a small further increase in insulation. The permeability of clothing for firefighters is low in order to provide resistance to hot air or liquid (Braganca et al., 2018; Fan & Wen, 2002; Haleem et al., 2013; Li & Wong, 2006; Santos et al., 2018; Song, 2011; Song & Wang, 2019; Vasile et al., 2019), but a fabric that is air and water impermeable and insulating, obstructs the removal of moisture and heat from the body (Kumar et al., 2015). By contrast, fabrics with high air permeability allow mass transportation of moisture and heat from the body to the outside environment. Fabrics with low packing density have least resistance

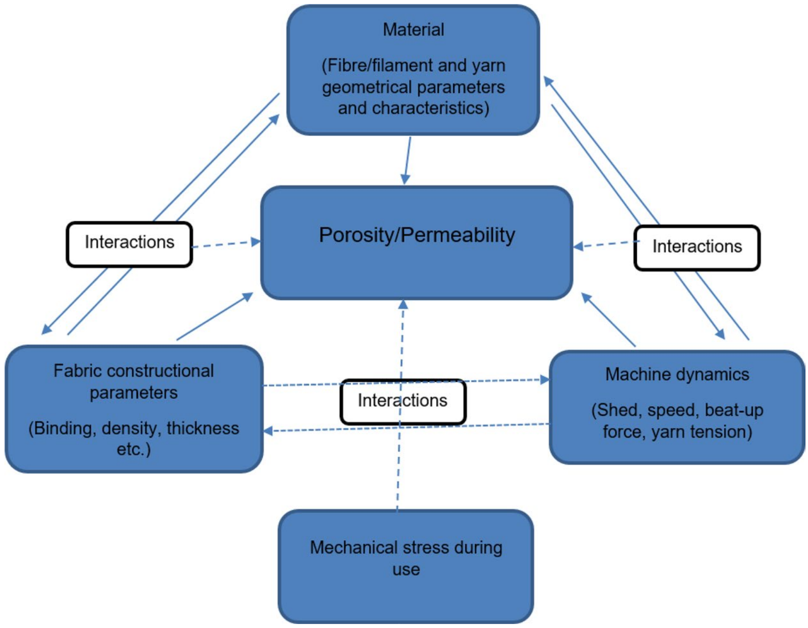

Figure 2. Factors affecting fabric air permeability (Malik et al., 2017).

to air and allow mass transportation of moisture and heat (Kumar et al., 2015). A fabric showing low levels of air permeability can be an indication that it will cause discomfort, especially in situations where the garments are worn when performing high levels of physical activity (Song, 2011; Yoon & Lee, 2011). The air permeability of fabrics made with hydrophilic fibres is seen to change with the amount of moisture that is absorbed. When hydrophilic fibres absorb moisture they become swollen and reduce the air permeability. The air permeability of woven fabrics can be increased by increasing yarn twist which reduces yarn diameter and if the sett (threads/cm) is kept the same, the fabric's cover factor is lowered. However, with circular yarns tightly packed together, the air permeability is decreased (Afza et al., 2014; Li & Wong, 2006). Fabrics with high air permeability have faster drying times than those with low permeability because any accumulation of heat and moisture is removed when air passes through (Bedek et al., 2011; Park & Shin, 2011); a plain weave fabric subjected to repeated laundering was found to be able to retain its air permeability (Slater, 1977).

In general, when a fabric's area weight and thickness is increased its air permeability falls because of increased resistance to the passage of air. Slater (1977) reported that with an increasing air permeability, there is a maximum air permeability point beyond which any further increase will bring about a reduction in fabric thermal resistance. Any rise in wind speed will reduce the thermal resistance offered by the fabric because of the removal of air that would otherwise be trapped in the fabric's pores.

Air permeability affects the performance of technical fabrics such as parachutes, filters and airbags (Haleem et al., 2013). For garments, fabrics with low air permeability make the wearer feel uncomfortable as the fabric tends to stick to the body because of low rates of transfer of water vapour from the body (Malik et al., 2017). Outdoor clothing items especially those intended for sportswear are made with breathable fabrics to maximise transfer of moisture and heat from the skin surface to the outside environment even while the body is sweating excessively (Kumar et al., 2015).

5. Fibre types

Moisture and heat must be quickly transferred from the body through the fabric to the outside environment as their accumulation causes the person to feel uncomfortable. The transfer of moisture, heat and air is dependent on the fibres as well as on the fabric structure. When a fabric is not removing moisture quickly and moisture builds up on the surface of the skin, the wet fabric sticks to the surface of the skin and friction increases making a person uncomfortable (Salata et al., 2018).

Moisture absorption causes fibres to swell resulting in changes in fibre stiffness, size and shape. This in turn affects the permeability of the fabrics (Morton & Hearle, 1993). The transfer of moisture through fabric is complicated as the absorption of moisture causes the fibres to swell and the fabric pores are reduced resulting in fewer open spaces being available to enable the rapid removal of heat and moisture through the fabric to the outside environment. When sweat does not evaporate on the surface of the skin it is absorbed or wicked away by the fabric which is in direct contact with the skin (Ghali et al., 1995). Finer fibres have much larger surface areas compared with the same weight of coarser fibres and make smaller pores which facilitate moisture transport and evaporation from the surface of the fabric. Trapped air in the fabric is reported to have a higher influence on fabric thermal insulation than the polymer of which the fibres are composed. Using fibres with irregular surfaces and cross-sections and also loosely-twisted and hairy yarns to construct a thick and loosely constructed fabric is reported to increase insulation (Behera & Hari, 2010; Kavitha et al., 2014). In some recent publications, uni-directional moisture transport by fabrics has been reported (Babar et al., 2020; Wang et al., 2018), wherein moisture is transported only from the lipophilic side to the hydrophilic side. One method used to achieve the required effect is electrospraying, where the nanoparticles are sprayed to form a lipophilic layer on the surface of a fabric (Babar et al., 2020; Wang et al., 2018).

The moisture retained by a fabric obstructs the transfer of heat from the body by air. Cotton fabric possesses good water absorption and it absorbs moisture more quickly than synthetic polymer fabrics, however, due to the cotton fibre's high moisture retention and slow moisture transfer the rate of moisture evaporation is not high. By contrast, fabrics made from polyester which has a much-lower moisture-regain value, allow less accumulation of moisture and the fibres absorb less moisture resulting in its increased evaporation. When a person is performing intensive exercises, the body generates sweat and their comfort needs to be managed so synthetic-polymer fibres like polyester are increasingly being used in sportswear fabrics in order to facilitate the transfer of moisture from the body as they have less moisture retention than cotton fibres (Brazaitis et al., 2010).

Wool fibres are elastic and have good insulation properties with thermal conductivity ranging from 0.036–0.067 W/mK while that of cotton ranges from 0.026–0.065 W/mK (Zhang et al., 2021). Fabric thermal resistance increases with the thickness of the fabric due to the increased availability of space to entrap air and it ranges from 0.023–0.024 m^2 °C W^{-1} (Xu et al., 2019). The wool fibres have a maximum moisture absorption capacity of about 35% (Kumar et al., 2015). Cotton has high thermal conductivity and water absorption whilst polyester has high water-vapour and air permeability (Tsuji et al., 2014) so cotton fibres absorb more moisture more easily than polyester making the cotton fabrics more comfortable to wear than polyester fabrics.

Fibres with small radius and short inter-fibre distance tend to have higher water repellency. Short inter-fibre distance can be achieved by increasing the twist but this holds for fibres that are packed in layers as single layers of fibres in parallel absorb less water than the ones that have higher twist (Beckham et al., 1997). Finer fibres with larger area spread enable more evaporation. Finer fibres have high surface tension and hold onto water leading to increased transportation of water in the lateral direction. Finer fibres have more inter-fibre space rather than water holding capacity and this leads to increased spread of water in the lateral direction (Sampath et al., 2011). Microfibres are finer fibres and in order to improve moisture and heat management, they are used to make fabrics that are light, soft and comfortable to wear especially for high-perspiration activities. Microfibre fabrics have higher moisture transport and permeability than traditional fabrics due to a higher surface area and a larger amount of pores resulting in increased capillary action. Microfibres that are tightly packed can form a yarn with a small diameter enabling the formation of small voids that enhance capillary action, and as a result, fabrics made of microfibres can exhibit high moisture removal. Some of the microfibres that are available are made from polyester, nylon, rayon and acrylic, and they can be blended with natural fibres like cotton, silk and wool (Senthilkumar et al., 2012).

Blending of fibres can be used to manage moisture, heat and air transport. Blending of wool with polyester or polypropylene provides both insulation and moisture removal alongside improved durability. The wool provides insulation while polyester and polypropylene removes the moisture from the body, and capillary action increases which is attributed to the ability of polyester fibres to create more channels for moisture transport. Blending of wool and cotton enables increased moisture absorption by cotton and increased moisture transport by wool. Similarly blending of viscose rayon and polyester is reported to increase moisture transfer due to rapid moisture absorption by the viscose rayon fibres and high capillary action of the polyester fibres (Senthilkumar et al., 2012).

Tsuji et al. (2014) indicated that blending of cotton and polyester (35/65) moderates thermal conductivity, water absorption, water vapour and air permeability (Tsuji et al., 2014). Depending on the blending method, a lipophilic or hydrophilic layer can be incorporated on the inside or outside of the fabric. In most cases, the inside layer will be composed of hydrophilic fibres whereas the outer will be lipophilic. For wool and polyester high-performance clothing, the wool fibres can be used on the inside of the garment to provide insulation with polyester fibres are used on the outer side to remove moisture from the wool layer (Senthilkumar et al., 2012).

5.1. Hydrophilic fibres

Natural fibres swell when they absorb moisture and the fibres must become saturated first before they can transport moisture by wicking, but this is not the case with lipophilic fibres such as polyester. Saturated hydrophilic fibres swell to increased diameters which impairs the moisture-transfer process (Ghali et al., 1995; Kumar et al., 2015). Since hydrophilic fibres have high surface energy, they attract moisture better than lipophilic fibres which have low surface energy (Senthilkumar et al., 2012). Fabrics made from hydrophilic fibres such as cotton absorb more moisture than lipophilic fabrics made from fibres such as polyester (Raccuglia et al., 2018). Clothing items like t-shirts have low total moisture vapour resistance and are able to release more heat from the body by having more open structures which help in the transfer (Ho et al., 2008). During physical activity, with wearers wearing hydrophilic or lipophilic t-shirts, it was found that the middle parts of both types of t-shirts absorbed more moisture than the lower parts. The high moisture absorption of middle parts of the fabric was attributed to high contact of the t-shirts with this part of the body. The low moisture level in the lower parts of the garment was attributed to the large air gap between the clothing and the body as the clothing in these parts is loose and has less contact with the body. Most of the moisture found in the lower parts was due to the migration of sweat from the upper parts (Raccuglia et al., 2018).

5.2. Lipophilic fibres

The surfaces of the fabric can be treated with chemical finishes to increase or decrease the surface energy in order to manage moisture transfer. In general, lipophilic fibres have low moisture absorption and moisture regain making them uncomfortable to wear as sportswear during high physical activity because less moisture can be removed from the body. Though polyester fibres are lipophilic and form weak bonds with water, it was reported that water can flow with less resistance in polyester fabrics resulting in increased wicking rate (Kumar et al., 2015; Senthilkumar et al., 2012; Zhao et al., 2018). In order to improve moisture absorption of polyester fabrics the fibres are treated with hydrophilic alkaline agents, enzymes and plasma, but this weakens their mechanical properties because treating polyester with alkali to improve its wettability through the creation of carboxyl and hydroxyl groups is achieved only by scission of some of the ester linkages in the polymer-chain backbone. Enzymes improve wettability of polyester fabrics by hydrolysing polyester fibres. As is the case with other lipophilic fibres like polypropylene the polyester fibres have low thermal conductivity and transport less heat generated by the body. In order to improve thermal conductivity, finishing agents such as graphene are applied to polyester fabrics (Kumar et al., 2015; Senthilkumar et al., 2012; Zhao et al., 2018). Hydrophilic finishing agents suffer from low washing durability and make the fabric have a low hand feeling.

6. Clothing

For 2020 annual global clothing sales are estimated to be worth about $1.5 trillion US having grown from $1.3 trillion US in 2015 as the demand for clothing increased. The three largest markets are China, United States and Europe (Cruz-Cárdenas, Guadalupe-Lanas, & Velín-Fárez, 2019). As countries develop, more people are pulled out of poverty and people start demanding higher-quality clothing that complements their safety and health (Yan et al., 2019). Such clothing needs to be designed to fit the body, be easy to wear and take off and to meet the aesthetic and comfort levels expected by the user; clothing is regarded as a form of self-expression, whereby individuals express themselves through fashion styles. Advertising has a huge influence on changing trends in fashion especially for young people and mass production and lower cost have made it possible for clothing to be sold at cheaper prices, so often it is not easy to differentiate between qualities of clothing items based on pricing alone unless one is an expert in the field. By contrast, technical clothing items intended for sport and protection are designed to meet the primary function of enhancing the performance and protection of the athletes or firefighters wearing them. Sports clothing must also be comfortable, durable and fit the athlete while also expressing the desired style (Braganca et al., 2018; Coates, 2016; Morton & Hearle, 1993, 2008; Salata et al., 2018; Slater, 1977). Even though polyester fibres are lipophilic they are widely used in sportswear because of their enhanced ability to transport moisture from the body by the capillary action (Kumar et al., 2015). Depending on the local climate, people tend to wear different clothes, with those from warmer regions likely to wear lighter clothes than those from colder regions. Those from warmer regions have the luxury of wearing clothes that do not cover all their body parts unlike those from cold regions who must wear clothes that cover the whole body to provide insulation to preserve heat. In cold environments, clothing with high thermal resistance is important in preventing the loss of heat from the body and clothing can be thought of as acting as a heat reservoir against the external environment (Yan et al., 2019).

High moisture transport in one direction (away from the body) in sportswear and workwear apparel is important as it can affect the performance and comfort of the wearer due to thermal resistance and the cooling effect when moisture evaporates (Slavinec et al., 2016). One way of making fabrics transport moisture in a particular direction is to make use of different layers that have different properties. A combination of hydrophilic and lipophilic layers is arranged in such a way that it allows moisture to be transported from the hydrophilic side to the lipophilic side before the hydrophilic layer becomes saturated with moisture. When a fabric becomes saturated with moisture, the rate of moisture transportation slows down and the material clings to the surface of the skin. It is important that the layers are arranged in such a way that they facilitate the transportation of moisture from the surface of the skin to the outside environment where it can evaporate (Lao et al., 2020).

6.1 Factors to be considered when designing technical clothing

- Allow movement of limbs
- Low levels of electrostatic charge,
- Protection against hot and cold conditions,
- Allow transport of moisture and heat (Braganca et al., 2018)

There are three mechanisms of moisture transfer:

i. The inter-yarn spaces—it is the main transportation which is influenced by the moisture between the inter spaces and the outer surface of the fabric. How easily or resistant the fabric is to the transportation of moisture to the outside is affected by the number of pores and their sizes and also the fabric thickness,

ii. Intra-yarn spaces—moisture and diffusion through individual fibres, and
iii. moisture is absorbed on the inner side of the fabric (Kavitha et al., 2014).

Moisture is transported by capillary force or wicking to the surface of the fabric and when the fabric pores decrease the capillary force increases and this becomes an important consideration during high-intensity physical activities like exercising and hard labour which cause the body temperature to increase. The body releases large amounts of heat to keep the core body temperature steady and excess sweat is produced which needs to be transported away so that the body cools down when it evaporates. The clothing acts as barriers obstructing the transfer of heat and moisture. (Senthilkumar et al., 2012; Yi et al., 2017). The average sweating rate of a person performing moderate exercise is 1000 g/m^2 per hour which is higher than the 460 g/m^2 per hour of moisture vapour transmission rate found in commercial water repellent breathable fabrics (Lao et al., 2020). When sweat evaporates from the skin surface it removes heat, but if sweat is not removed it accumulates on the surface of the skin, making the fabric stick to the skin and the wearer feel uncomfortable, but moisture also makes the fabric heavy and an interaction with the skin of those individuals with a sensitive skin can cause skin irritation. Hence it is important that clothes must facilitate the transfer of moisture in the form of liquid or water vapour quickly to keep the skin dry and make the body cool faster due to increased evaporation and this can be done by selecting appropriate materials to make the clothing. The transportation of moisture, heat and air through the fabric can be enhanced by modifying fibre surfaces, cross sections and by fabric finishes because different fibres have different moisture absorption and heat transfer rates and yarns and fabrics with more compact structures and thickness have more influence on moisture while heat transfer is influenced more by pores size (Babar et al., 2020; Kavitha et al., 2014; Priyalatha & Raja, 2018; Senthilkumar et al., 2012).

Phase-change materials like octadecane and heptadecane (paraffin waxes) are being incorporated into fabrics in order to control heat loss or gain when there is a sudden change in temperature. Incorporating them on the outside rather than on the inside is found to enhance a better cooling and heating by blocking the penetration of moisture from the outside. Coating with phase-change materials can entrap sweat and accumulation of sweat will make the wearer feel uncomfortable. When the body perspires, water vapour condenses and causes discomfort. Coating nylon or cotton with ceramics was found to improve their hygroscopic properties, however, there is an optimal amount that can be incorporated as further increases beyond that amount brings about a decrease in the hygroscopic properties of cotton. The slight improvement in moisture absorption is attributed to the ability of ceramics to absorb moisture even though they are considered to be lipophilic (Park & Shin, 2011). The application of the finishing agent amino silicone to polyester improved the transportation of moisture of knitted polyester fabrics and made them more comfortable to wear (Sampath et al., 2011) and fabrics treated with nano materials to facilitate moisture transfer were found to have faster drying time than the untreated material, a feature which is important because faster drying improves moisture transport (Yi et al., 2017).

Heat and moisture management plays an important role in the comfort of sportswear, because when a wearer feels uncomfortable their performance may be affected. This occurs when the clothing is not able to remove excess heat and moisture from the surface of the skin. Sportswear worn for activities that generate lots of heat and moisture need to have more open structures to maximise the transfer of moisture and heat from the skin surface to the outside environment (Ho et al., 2008; Lim et al., 2015). Sportswear with less open structures provide good insulation against wind but moisture tends to accumulate in them so they are used in physical activities that do not cause the body to generate lots of sweat. When moisture accumulates on the surface of skin it makes the clothing uncomfortable to wear as a result of a cold feeling. In extreme low temperatures this can cause frostbite or hypothermia (Lim et al., 2015).

In addition to the heat that the body generates due to natural biological processes, it receives radiant heat from the surrounding environment like the sun. Wearing clothes that have high reflectiveness is essential in reducing the amount of radiant that can penetrate to reach the skin since some of the radiant heat is absorbed by the fabric. When cool air hits the surface of the fabric, it removes some of the absorbed heat. Some of the properties of the fabrics that can reduce the effect of heat on the wearer are emissive power, lower transmitting power for radiant heat, high reflective power and high moisture and air permeability (Morris, 1953). White fabrics absorb only slightly less radiant heat than black fabrics despite the intention that they may be more comfortable when outdoors by reflecting more radiant heat. They are often not sufficiently thick or dense enough to provide sufficient blocking to infra-red radiation.

Since clothing acts as a barrier, it increases heat storage in the microclimate which exists in the small open space between the inner fabric layer and the surface of the skin. This can be undesirable in situations where the body needs to get rid of heat and water vapour (Tsuji et al., 2014). Movement of the body helps some of the heat trapped in the air and moisture of the microclimate to be circulated and transferred from the body and the removal of that heat causes the body to cool down (Ho et al., 2008). Loose-fitting clothing allows easier removal of heat and sweat from the skin's surface by convection as there is less contact between the body and the fabric (Santos et al., 2018). Tight clothing restricts body movement and the body works harder in moving it eventually causing fatigue, and the wearer will feel uncomfortable unlike with loose-fitting clothing (Yan et al., 2019).

Sportswear items are usually produced by knitting to be extensible to accommodate movement of body limbs. When tension is released the fabric must quickly recover to its original relaxed state. Sportswear must have good air permeability, low thermal and moisture resistance to make the wearer feel comfortable. Fabrics with high air permeability facilitate heat transfer and moisture evaporation. The loops in the knitted fabric structure form more-open structures and knitted fabrics have higher permeability than woven fabrics. However when knitted fabrics are saturated with moisture their air permeability decreases due to the fabric shrinkage and reduced pore size. Increasing the compactness and thickness of fabrics decreases air permeability due to less air penetrating the fabric to evaporate moisture on the skin surface. When cotton was blended with spandex, it was reported to decrease the air permeability of cotton fabrics. This was attributed to increased weight and thickness of the spandex. The use of elastane also showed similar behaviour (Vasile et al., 2019).

It is suggested when designing clothing one should use different fabrics or fibres to make different parts of the clothing as different sites of the body sweat and generate heat differently (see body-mapping clothing below); for example, the chest generates less sweat than the back of the body. The incorporation of spacer and meshed fabrics in shirts is reported to improve fabric permeability compared with those without, because the spacer and mesh fabrics facilitate the transfer of heat by convection from the body. Another way to facilitate the removal of heat and moisture from the body is to design clothing that have slits to facilitate the removal of moisture and heat from the body when air enters through the slits. Slits are incorporated in positions where they facilitate the transfer. Clothing without slits causes the air to escape the clothing through the neck whereas those with slits, air can escape in them to facilitate the transfer. Varadaraju & Srinivasan, 2019 reported that long-sleeved polyester and cotton shirts were found to have the greater sweat removal efficiency but that the thermal and sweating sensations were lower for polyester than for cotton (Lim et al., 2015; Varadaraju & Srinivasan, 2019; Yi et al., 2017). A permeable fabric made of lipophilic fibres was found to have high water-vapour evaporation and heat transfer (Guo et al., 2013).

6.2. Body-mapping clothing

Sweat production varies according to the site on the body and as a result the amount of evaporation that takes place on the different body parts varies. Men and women are known to have different sweating rates. Women sweat more than men on the lower arm, lateral lower back and upper central back. In order to take into consideration the different body parts and sweat generated by these different body parts, body-mapping clothing (BMC) technology can be used to better understand and manage heat and sweat distribution in the different body parts. Using BMC technology, different parts of the clothing are designed and placed at appropriate places based on the local comfort, heat and moisture needs of the different body parts. Because most traditional clothing is made with the same fabric structure and materials throughout the garment, it is not necessarily capable of meeting the local needs of the different body parts which sweat differently. The three different ways of producing BCM for the different body parts are (i) different fabric materials, (ii) combinations of different fabric structures e.g. woven and knitted structures within one fabric part and (iii) combinations of both of the previous two techniques. Because females and males sweat differently, the BMC can be used to design different clothing to suit the sweating behaviour of each gender. Female clothing can be designed differently to that of males in the upper arm, lateral lower back, and upper central back in order to enhance the removal of sweat as females have higher sweat rate in these body parts. A sports T-shirt with a mesh structure and spacer was reported to have improved the thermal comfort by 11% when compared to the one without.

The commercialization of BMC technology has not yet been fully adopted as its effects on the wearer are not fully understood. Wang et al., (2014) reported that some commercial BMC performed no better in heat loss terms than non BMC but can be used to manage local thermal and comfort sensations (Varadaraju & Srinivasan, 2019; Wang et al., 2014).

6.2.1. Protective clothing

Firefighters' clothing is thick and heavy in order to provide protection from flames, heat and other potential hazardous materials or substances. The clothing is composed of three or more layers, the outer (flame and fluid resistant) layer, the middle (moisture barrier) layer and the inner (thermal) layer. Each layer serves a specific function which obstructs the transfer of heat from the body to the outside environment. The protective clothing has these several layers to reduce heat flux from reaching the skin but at the same time heat and moisture must be transferred through the layers. Each layer provides protection and distribution of heat. The outside layer's primary function is to provide protection from flame, thermal, chemical and mechanical damage whereas the inside layer is responsible for making sure that the wearer has some level of comfort when wearing the clothing. The presence of moisture inside the thermal layer reduces the heat by absorbing it, however, this causes the temperature of the inner layers to increase due to the inability of the vaporised moisture to escape through the outside thermal layer. It is this stored energy that can cause the skin to burn when it makes contact with human skin (Fu et al., 2014; Li et al., 2012). When firefighters are exposed to extremely-high temperatures, the heat and moisture generated by the body are not quickly released from the body due to low permeability of firefighting clothing. This results in heat energy being stored and moisture being retained instead of being dissipated quickly. Clothing configuration—wearing short sleeve T-shirt and short pants instead of the traditional long sleeve T-shirts and long pants under the firefighting clothing is claimed to reduce heat stress but no difference in burns suffered by those who wore the short and the long inner clothing (Barr, Gregson, & Reilly, 2010).

Protective clothing is designed to protect either the whole or some parts of the body from objects, radiant heat, flame, hot air, molten metal substances and chemical splashes in order to minimise damage or illness (Chen et al., 2018; Shen et al., 2018). Flame burns are responsible for about 20% while hot splashes are responsible for 65% of the damage (Chen et al., 2018). Some of the protective clothing is treated with coatings to make them superamphiphobic and chemical repellent by virtue of being coated with perfluoroalkyl-containing polymers or silanes which make the fabric both water and oil repellent; water or oil makes a contact angle of more than 150 °C with these treated surfaces making it easier for it to slide off the surface when the fabric surface is tilted (Shen et al., 2018).

Firefighter's protective clothing must not only provide protection to flame and radiation, in addition they must have good abrasion and tear resistance (Udayraj et al., 2016). When extinguishing fires, firefighters are exposed to extreme heat which can be radiative and conductive for longer periods of time. Firefighters wear specialized protective clothing to protect themselves from thermal skin burns. The multi-layered clothing has several layers to ensure adequate protection from outside heat and may have three or four layers each separated by a thin open-air space. To study the transfer of moisture and heat from the skin surface in detail, manikins are used which mimic the human body. Manikins have several sensors mounted on the body and are dressed in the clothing being tested. When heat is applied, the sensors transfer the signal for analysis to predict heat transfer. In bench-top tests the fabric is placed on a material that mimics human skin as shown diagrammatically in Figure 3 (Furmanski & Lapka, 2017); the heat is applied on the top side and temperature of the top and under sides is measured by thermocouples.

As stated previously heat transfer from the body surface through the fabrics is a complex process because heat can be transferred by a combination of conduction, convection and radiation. Conduction and convection are the dominant forms of heat transfer from a fabric close to the wet skin surface. If the surrounding temperature is lower than the skin temperature the body loses heat to the surroundings but when the surrounding temperature is higher the body gains heat. Complicating the transfer of heat is that moisture is being transferred at the same time and it can absorb energy on changing its phase into water vapour when it evaporates. Another consideration is that excessive heat causes thermochemical reactions of materials and changes may occur which lead to changes in thermo-physical properties of the materials in the protective clothing (Furmanski & Lapka, 2017; Ghali et al., 1995; Zhang et al., 2021).

Firefighters are exposed to high ambient temperatures, radiant heat flux, flames and toxic fumes. The body responds by increasing the metabolic rate and heat is released by the body. Firefighting clothing reduces the effective transfer of heat and moisture from the body and this causes the body to sweat even more. Due to the high ambient temperature and moisture, the microclimate temperature can increase causing moisture to become a hot steam that burns the skin surface. The presence of moisture is known to negatively affect the thermal performance of fabrics depending on the heat exposure and radiant heat flux. For radiant heat flux of 6.3 kW/m^2 and 84 kW/m^2, the presence of moisture decreases the thermal protection of the fabric while for wet flame-retardant cotton a radiant heat flux of 16.8 kW/m^2 increases the protection. Moisture in the air increases the thermal conductivity due to convection heat transfer compared with dry air, but the presence of moisture particles decreases heat transfer by radiation as the particles absorb infrared radiation (Li et al., 2012).

6.2.2. Types of burn injuries caused by heat

Thermo-physiological comfort and safety of people such as firefighters, soldiers, racing car drivers and factory workers wearing protective clothing is very important in enabling them to perform their duties under hazardous conditions. Exposure to medium and high heat levels decreases their performance and sudden cardiac arrest is one of the main reasons for high fatality in firefighters while performing hazardous duties (Udayraj et al., 2016). When the temperature of the skin rises above 40 °C the person starts experiencing thermal pain (Li et al., 2012). Skin-burn injuries are measured by the degrees of burn with a higher degree of burn indicating the severity

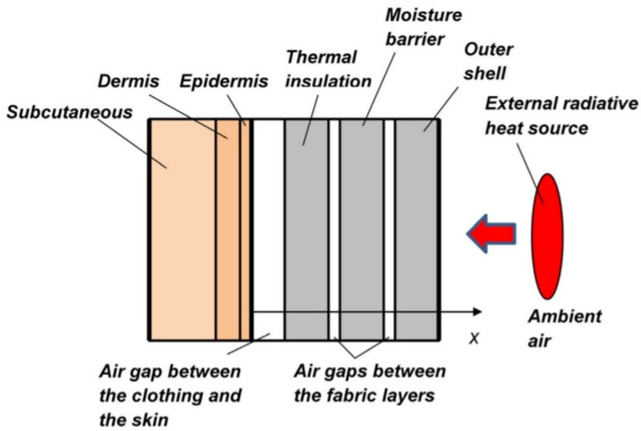

Figure 3. Schematic of showing protective fabric and skin layers (Furmanski & Lapka, 2017).

of burn. The three types of burn are first, second and third degree as shown in Figure 4 (Udayraj et al., 2016).

- The first degree burn is the most common type; it affects the outer layer or epidermis. It is similar to sunburn.
- The second degree burn affects the epidermis and dermal layers resulting in blisters and accumulation of fluid.
- The third degree burn affects all the layers (epidermis, dermal and subcutaneous layers) and damages the regenerative cells and as a result medical treatment is required for the healing process.

The second degree burn can be determined by using the Stoll criterion and Henriques Burn Integral method. The Stoll criterion is widely used. It uses the sensor placed behind the fabric to record the temporal temperature variation. The intersection point of the plot with the Stoll curve indicates the tolerance time of the fabric as shown in Figure 5 (Udayraj et al., 2016). The Henriques Burn Integral method measures the degree of skin burn in terms of the integral of the chemical rate process using the equation below. The Henriques Burn Integral method can be easily integrated with computers making it easier to predict the burn time for the intensity range and heat flux profiles (Udayraj et al., 2016).

6.2.3. Wound dressing

In the medical field wound dressing is important for the health and regeneration of the wound by keeping the wound area moist while preventing microorganisms from invading the wound. Wound dressings must be able to absorb and transport the exudates away from the wound area in order to promote healing. Wound-dressing air permeability is important as the free movement of oxygen to the wound area promotes healing. Other additional requirements for wound dressings are that they must be biocompatible, biodegradable, antimicrobial and nontoxic. Even though the removal of

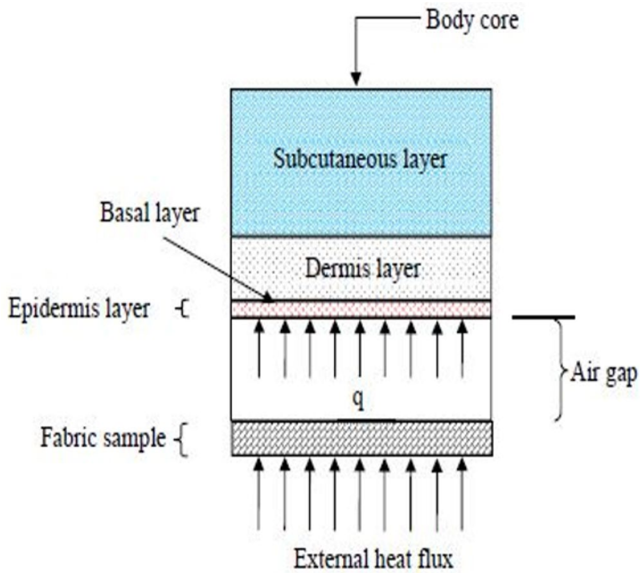

Figure 4. Schematic of heat transfer through fabric, air gap and skin layers (Udayraj et al., 2016).

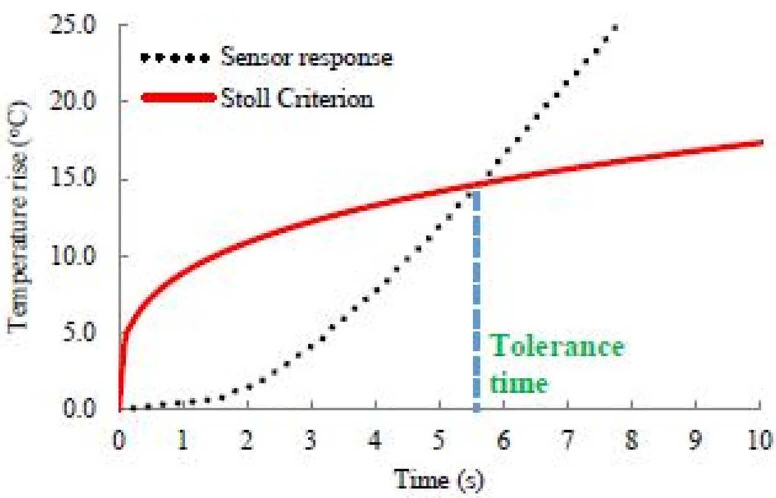

Figure 5. Tolerance time using the Stoll criterion (Udayraj et al., 2016).

moisture promotes wound healing, a complete removal of moisture from the wound area should be avoided as it causes wound dehydration and the fabric will stick to the wound when it dries, so that when it is time to remove wound dressing, it will cause pain and secondary trauma making the wearer feel uncomfortable. Hydrophilic wound dressings are good in absorbing moisture from the wound area but cause the wound to dry and the wound dressing sticks to the wound, so there is a balance that needs to be achieved; the wound area must be kept moist in order to avoid the dehydration of the wound, but excessive moisture accumulation should be avoided as moisture promotes microbial growth. Microbial growth in the wound area can be suppressed by applying antimicrobial agents to the wound dressing or wound area (Baghersad et al., 2018; Cho et al., 2002; Pereira et al., 2013; Singh et al., 2018; Tang et al., 2015).

7. Test for heat transfer in clothing

Conventional methods used for measuring moisture, thermal resistance and air permeability require that the fabrics be cut and the test procedure is time consuming. The thickness of the sample and temperature difference between the two surfaces must be known in order to determine the thermal resistance. New measuring devices like the Thermoscope are not limited by those shortcomings as they are required to touch only one surface (Dolezal et al., 2019).

The thermal properties of yarns and fabrics are influenced by their structure, fabric thickness, surface treatment, level of the heat source, air held within the fabric, external air movement and moisture content within clothing.

Fabric thermal resistance is highly dependent on the fabric thickness. The greater the thickness of the fabric the higher is its thermal resistance and this is attributed to the air trapped inside the fabric which serves as an insulation layer between skin and the outside environment (Lenfeldova et al., 2016; Slater, 1977; Zhang et al., 2021).

7.1. Manikins

Expressing the transfer of heat and moisture from the body surface through fabrics is a complex process when the thermal and moisture-transfer processes are constantly changing. The microclimate that exists between the skin surface and inside of the fabric surface enables a build-up of heat and moisture. To simulate the transfer from the skin surface, sweating manikins as shown in Figure 6 are used (Wang et al., 2014); their aim is to mimic human physiological responses and the tests also take into consideration the movement of limbs, clothing and contact of the skin and clothing. The total surface area of the manikin can be measured and the heat and moisture loss of the different sites of the manikin can be observed and measured. The air movement, sweating and temperature can be regulated and the signals are transferred to enable computer modelling of the transmission. In general, manikin tests are more expensive than conventional bench-top tests and they also require more time to set up (Lim et al., 2015; Su et al., 2019; Wang et al., 2014; Zhang et al., 2021) but unlike the bench-top tests, the manikin tests allow for the observation of ignition, burning and shrinkage during and after burning of protective clothing (Su et al., 2019; Xu et al., 2019).

For firefighters' protective clothing there are three types of tests that can be conducted to simulate the firefighting environment, namely the routine, hazardous and emergency (Su et al., 2019).

- The routine test uses the ASTM F2731-11: Standard Test Method for Measuring the Transmitted and Stored Energy of Firefighter Protective Clothing Systems, to evaluate fabric thermal protection.
- The hazardous test uses the ASTM F2702-13: Standard Test Method for Radiant Heat Performance of Flame Resistant Clothing Materials with Burn Injury Prediction, to evaluate fabric thermal protection against radiant heat source.

Figure 6. Manikins used for modular body mapping T-shirts (Wang et al., 2014).

- The emergency test uses the ASTM F2703-13: Standard Test Method for Unsteady-State Heat Transfer Evaluation of Flame Resistant Materials for Clothing with Burn Injury Prediction, to evaluate fabric thermal protection against both convective and radiative heat sources.

The ASTM F1930: Standard Test Method for Evaluation of Flame Resistant Clothing for Protection Against Fire Simulations Using an Instrumented Manikin and ISO 13506 -2017 Protective Clothing Against Heat and Flame Parts 1 and 2 are widely used for full-scale manikins exposed to flame. Full-scale manikins have heat flux sensors on their surfaces to measure the transfer of heat through the fabric. The manikin is exposed to a heat flux of 84 kw/m^2 for 20 seconds generated by propane burners. Based on the data generated at various locations of the manikin the degree of burn can be predicted. Several types of manikin are available (Udayraj et al., 2016):

- *Tennessee Eastman Manikin*: The manikin is made of polyester/fibreglass and then coated with epoxy resin that can withstand heat flux. It has 80 heat flux sensors which measure the temporal variation in thermocouple temperature to obtain the temperature on the three-skin layer model and first, second and third degree burn.
- *Minnesota Women Manikin*: The manikin is made of polyester and fibreglass. It is coated with a mixture of asbestos, plaster of Paris and cement. It has 44 heat flux sensors that measure the temperature to obtain temperature in the three-skin layer model and second degree burn.
- *University of Alberta's Manikin*: The manikin is exposed to 84kw/m^2 heat flux provided by 12 propane burners that surround it. It has 110 heat flux sensors that measure heat transfer.
- *Donghua Flame Manikin*: It has many body parts connected by flexible joints. Its 12 burners are arranged in such a way that mimic real fire conditions. It has 135 heat flux sensors that measure heat transfer.
- *Thermo-man and Pyro-man*: There are 122 heat flux sensors on the surface of the manikin which are connected to the computer.

- *26-segment Newton-type Sweating Manikin*: It measures temperature at different sites of the manikin such as stomach, shoulders, chest and arms. The apparatus has four modes; the temperature, power, thermoregulatory and comfort mode. The manikin sweating and temperature levels are adjusted and the computer is used to model thermoregulation (Wang et al., 2014).

It is still helpful to be able to take a measure of fabric thermal conductivity prior to progressing to working with a manikin, and there are three different methods that can be used:

- the two-plate method,
- the cooling method and
- the constant temperature method.

In the two-plate method, a fabric is placed between the two metal plates and the temperature difference is calculated. In order to determine the thermal conductivity and thermal resistance of a fabric, the heat flow rate per unit area (heat flux) must be known. Even though the heat flux is known, it is difficult to measure it in one direction as the flow is in all the directions. The two-plate method is further subdivided into two methods. The first one uses referencing where a reference sample with a known resistance is used and the tested fabric sample is then compared with it. The other method removes the amount of heat loss that does not pass through the fabric.

7.1.1. Thermal resistance

Thermal resistance expresses the ability of the fabric to act as a thermal barrier. It is the ratio of the temperature differences to the heat flow per unit area.

$$\text{Thermal resistance } R = \frac{\Delta T}{Q / A} \quad (1)$$

where *ΔT* is the temperature difference, *Q* is the heat flow, *A* is the surface area.

When the thickness of fabric is taken into consideration, the fabric thermal resistance can be calculated using the ratio of fabric thickness to the fabric effective thermal conductivity:

$$R = \frac{h}{K_{eff}} \quad (2)$$

where *h* is fabric thickness, K_{eff} is effective thermal conductivity of the material (Siddiqui & Sun, 2018; Zhang et al., 2021).

The influence of fabric thickness on the fabric thermal resistance is attributed to an increase in fabric volume. Because of an increase in fabric thickness, there is an increased amount of air in the fabric pores and its thermal resistance will increase than that of a thinner fabric. However, if the fabric air permeability is too high, its thermal resistance can decrease due to increased removal of heated air. Coarser yarns produce fabrics with less permeability due to increased inter-yarn air spaces and decreased inter-yarn air spaces. Highly-twisted yarns produce fabrics with high permeability as the fabric structure is less dense (Gidik et al., 2016).

The Togmeter hot plate instrument measures fabric thermal resistance. The temperature of the different plates is recorded and the fabric thermal resistance is calculated using the relation:

$$R_f = \left(\frac{(T_2 - T_3)}{(T_1 - T_2)}\right) * R_S - R_C \quad (3)$$

where R_f is fabric thermal resistance, R_c is the thermal resistance of contact and R_s is the thermal resistance of reference fabric, T_1 is temperature of the hot plate, T_2 is temperature between the lower surface of the tested fabric and the top of the reference fabric and T_3 is temperature between the upper surface of the tested fabric and the top of metal plate (Siddiqui & Sun, 2018).

The clothing and the air inside serves as a barrier against heat transfer and acts as thermal insulation. Clothing and surface air layer thermal insulation can be calculated using the relation:

$$R_t = \frac{A_s (T_s - T_a)}{H_s - H_p - H_e} \quad (4)$$

where R_t is the total clothing and surface air layer thermal resistance, A_s is total surface area of the body, T_s is the skin temperature, T_a is the environment temperature, H_s is the heat generated by heaters, H_p is the heat generated by the pump, H_e is the evaporative heat lost due to evaporation.

H_e is calculated using the relation:

$$\text{He} = Q\lambda \quad (5)$$

where Q is perspiration rate or water loss per unit time and λ is water evaporation heat at the skin temperature.

When the influence of the total moisture vapour resistance is taken into consideration the resistance of clothing and the surface air layer can be calculated using the relation:

$$R_{et} = \frac{A_s (P_s - RH_a Pa)}{H_e} - R_{es} \quad (6)$$

where R_{et} is total moisture vapour resistance, P_s is saturated water vapour pressure at the skin temperature, RH_a is relative humidity of the surrounding environment in a fraction, Pa is saturated water vapour pressure in the surrounding environment, R_{es} is moisture vapour resistance of the skin (Ho et al., 2008).

For the ensemble total thermal resistance and evaporative resistance the following relations can be used:

$$R_t = R_{cl} \frac{1}{f_{cl}.(h_c - h_r)} = R_{cl} + \frac{1}{f_{cl}}.R_a \quad (7)$$

$$R_{et} = R_{ecl} + \frac{1}{f_{cl}.h_e} = R_{ecl} + \frac{1}{f_{cl}}.R_{ea} \quad (8)$$

where R_{cl} is the ensemble intrinsic thermal resistance in m^2 °C W^{-1}, f_{cl} is the clothing area factor, the dimensionless ratio of the clothing surface to body surface area, R_a is the thermal resistance of the boundary air layer in m^2 °C W^{-1}, R_{ecl} is the ensemble intrinsic evaporative resistance in m^2 Pa W^{-1}, h_e is the evaporative heat transfer coefficient in W m^{-2} Pa^{-1} and R_{ea} is the evaporative resistance of the boundary air layer in m^2 Pa W^{-1}. R_a and R_{ea} are the values measured on nude manikins (Xu et al., 2019).

The equation below calculates the thermal resistance of a wet fabric and it incorporates water thermal conductivity. Wet fabric thermal resistance for a fabric with an area of 1 m^2 can be calculated using the relation:

$$\lambda_{\mathrm{RES}} = \varepsilon\, \lambda_{\mathrm{T}} + (1-)\, \lambda_{\mathrm{W}} \quad (9)$$

where surface porosity, λ_T fabric thermal conductivity, λ_W water thermal conductivity (Hes & Loghin, 2009; Slavinec et al., 2016).

The combined rate of radiative heat loss and convective heat loss in can be calculated using:

$$RC = \frac{T_s - T_o}{R_t} \quad (10)$$

RC is the combined rate of radiative heat loss and convective heat loss in W m^{-2}; T_s is the skin temperature °C; T_o is the operative temperature °C; R_t is the ensemble total thermal resistance in m^2 °C W^{-1} or clo (1 clo = 0.155 m^2 °C W^{-1}) which is resistance to heat transfer by conduction, convection and radiation. R_t describes the effect of clothing on the heat transfer from the skin to the outside environment.

7.1.2. Thermal conductivity

The thermal conductivity of fabrics plays an important role in the transfer of heat to and from the body and as such influences the comfort of the wearer. At high and low temperatures, the fabric acts as a barrier the effectiveness of which depends on its thermal conductivity and thermal resistance. In high-temperature environments, the fabric's thermal insulation also acts as a protection against the outside environment. Thermal conductivity expresses how readily the material transfers heat. Thermal conductivity of textile structures ranges from 0.01–0.033 W/m/K. The thermal conductivity of air is about 0.026 W/m/K while that of water is about 0.6 W/m/K (Slavinec et al., 2016).

Thermal conductivity is calculated using the relation (Behera & Hari, 2010):

$$\lambda = \frac{\Delta T}{P} \quad (11)$$

where λ is thermal conductivity (K m^2/W), ΔT is temperature difference and P is heat flux density.

Heat flux through the surface of the material is:

$$P = -\lambda S \Delta \quad (12)$$

where λ is material thermal conductivity, *S* is surface, Δ *T* is temperature difference between the surfaces of the materials.

If the heat is transferred through a material thickness in one direction it is calculated using the relation:

$$P = -\lambda.S\frac{\Delta T}{d} \quad (13)$$

where *d* is the material thickness.

Thermal conductivity can also be calculated using the relation below where influence of the thickness of the fabric is taken into consideration:

$$K = \frac{WD}{\Delta T} \quad (14)$$

where *W* is the heat loss (W/cm^2), *D* is the thickness of specimen (cm), and *ΔT* is the temperature difference (°C).

The KES-F7 Thermo-Lab-II Instrument uses the two-plate method to measure fabric thermal conductivity (Siddiqui & Sun, 2018). It has heaters which are insulated so that heat passes only through the tested fabric. The tested fabric is placed on a cold plate and a controlled hot plate is placed over the tested fabric. The effective thermal conductivity of the fabric can be calculated by using the following equation:

$$K_{\mathrm{eff}} = \frac{W*h}{A*\Delta T} \quad (15)$$

where *W* is the heat loss (mW or W), *h* is the fabric thickness (cm), *A* is the area of the hot heat plate (cm^2) and *ΔT* is the temperature difference across the fabric (°C).

Jia et al., 2019 used the relation to calculate the effective thermal conductivity:

$$k = \varepsilon_l k_l + \left(\varepsilon_a - \varepsilon_f\right) k_f \quad (16)$$

where k_l is thermal conductivities of the water, k_f thermal conductivities of the fibre, εa is volume fractions of water vapour, εl is volume fractions of water, εa is volume fractions of fabric.

The Alambeta Instrument can be used to measure the fabric thermal properties such as thermal conductivity, thermal resistance and thermal absorptivity. It measures the amount of heat that passes through the fabric with a certain thickness. The heat flow is measured due to the differences in the temperatures between the measuring head and bottom plate when the measuring head is in contact with the fabric. It is also capable of measuring the thermal properties of a wet fabric provided the moisture in the sample is kept constant. When moisture levels increase, the thermal conductivity and thermal absorptivity also increase. However, an increase in moisture levels will cause a decrease in thermal resistance. The Alambeta allows testing of the samples without destroying them (Hes et al., 2018; Hes & Loghin, 2009).

Thermal conductivity can also be measured by using the *Cooling Method* (Siddiqui & Sun, 2018) or the *Constant Temperature Method* whereby the fabric sample covers a hot body and the energy required to keep the temperature difference constant between the fabric and the air in the chamber is calculated (Siddiqui & Sun, 2018).

When a fabric contacts the skin, the transient heat is transferred. The fabric's warm/cool feeling can be measured by thermal absorptivity and maximum heat flux. Fabric thermal absorptivity *b* measures heat flow level when a fabric is in contact with the skin for a very short period. Heat capacity, fabric thermal conduct and the area between the skin and fabric determines the warm cool feeling. Fabrics with smooth surfaces possess high thermal absorptivity and heat flux due to larger surface area of contact between the skin and fabric than fabrics with rough surfaces. High thermal absorptivity and heat flux causes a cool feeling while low thermal absorptivity and heat flux causes a warm feeling. The amount of heat that penetrates a fabric when the temperature increases rapidly can measured using the thermal absorptivity using the relation:

$$b = \sqrt{\lambda.\rho c} \tag{17}$$

where b thermal absorptivity; λ is thermal conductivity; ρ is fabric density and *c* is specific heat capacity of fabrics. The units for thermal absorptivity is $Ws^{1/2}/m/K$ (Mishra & Militky, 2019).

$$b = (\lambda.\rho_c)^{1/2}. \tag{18}$$

where ρ_c is thermal capacity

Heat flow q passing through the fabric can be determined using the relation:

$$q = \frac{b(t_1 - t_2)}{\pi\tau^{1/2}} \tag{19}$$

where t_1 is constant temperature between the skin and fabric, t_2 initial temperature τ is heat contact time. The higher the fabric thermal absorptivity, the higher the cooling feeling.

7.2. Test for moisture transfer in clothing

Moisture transfer in clothing is a complex process as it involves the wearer's psychological and physiological relations to the clothing properties and the weather also influences how people sweat. Conventional bench-top tests and manikins cannot be the only methods used as they do not take into account the combined effects of wearers' psychological and physiological reactions. To account for both together, clothing moisture comfort can be assessed by subjective methods (Cho et al., 2002; Tang et al., 2015).

Recently manikins have been adopted to simulate conditions that take into consideration the human body shape. Electrical sensors measure the movement of moisture in different directions of the fabrics. The fabric is placed between the two sensors. Since a dry fabric has a high electrical resistance, the introduction of moisture lowers its electrical resistance and this is recorded by the computer. Change in electrical resistance corresponds with the movement of moisture between the two surfaces (Ozdil et al., 2009; Tang et al., 2017).

Some of the methods that are used to determine transfer of moisture are the wicking, moisture content and regain, moisture absorption capacity, absorbency of the fabric, wettability, fabric saturation, water vapour transmission fabric saturation and subjective wetness sensation assessment.

7.2.1. Wicking test

In a wicking test, a fabric is suspended or placed vertically or horizontally in a beaker containing distilled water. The rise of water through the fabric is recorded at various intervals. Wicking is influenced by pore size and its distribution and surface tension. The main movement of liquid in yarns and fabrics is due to capillary action (Patnaik et al., 2006; Priyalatha & Raja, 2018; Sampath et al., 2011). Wicking occurs inside the fabric or yarn rather on its surface as the liquid travels from one void to the next with the inner part of the fabric or yarn displaying high wicking rate due to increased capillary force attributed to smaller pores in the inner part of the fabric or yarn. When two yarns are packed parallel to each other, whether liquid can wick from one yarn to the other depends on whether the liquid can move from the inner region of the yarn to the outer region (Beckham et al., 1997; Patnaik et al., 2006).

- Horizontal wicking: The fabric is placed horizontally and water is transferred into the sample from below. This minimises the influence of gravity. The supply of water from below is considered to imitate the transport of moisture from the skin surface to the clothing. The sample is enclosed in an airtight environment to prevent evaporation of water from the fabric and the spread of water is captured by the camera mounted at the top of the apparatus (Tang et al., 2015).
- Vertical wicking test: The fabric sample is suspended vertically with its lower end in the liquid, and the height reached by the liquid is recorded at regular time intervals. The wicking rate, which is the speed at which water reaches a particular height, is expressed in mm/s (Tang et al., 2015).

When liquid, fabric materials and atmospheric pressure are kept constant, the only factor that influences the capillary height is the capillary radius. The capillary pressure can be determined by using the relation:

$$p = \frac{2YCOS\theta}{R_c} \qquad (20)$$

where p is the magnitude of capillary pressure, Y is the surface tension, θ is the contact angle at the liquid-fibre-air interface and R_c is the capillary radius formed in the fibrous structure (Kumar et al., 2015).

Changing the capillary radius changes the contact angle and interfacial speed. Migration of fibres in the path of liquid obstruct the flow. One percent of Procion Blue MR dye solution can be added to the liquid to improve readability without affecting the surface tension and viscosity of the liquid (Kumar et al., 2015).

7.2.2. Moisture content and regain

When a fabric is exposed to moisture, it continues to absorb moisture until it reaches equilibrium where the amount of moisture it absorbs is equal to the amount of moisture that is being lost due to the evaporation. Moisture content and regain can be measured using the gravimetric method whereby the weight of the sample is weighed, then dried, and weighed again. Bedek et al. (2011) reported that fabrics with high moisture absorption exhibit high regain values. The moisture content or regain values for a fabric can be calculated using the relations:

$$\text{Moisture content} = \frac{\textit{mass of absorbed water in a fabric}}{\textit{mass of undried fabric}} \times 100 \tag{21}$$

$$\text{Moisture regain} = \frac{\textit{mass of absorbed water in a fabric}}{\textit{mass of dry fabric}} \times 100 \tag{22}$$

Determination of moisture regain requires that samples must be dried in special containers containing drying agents at room temperature otherwise the fabrics will absorb moisture from the surroundings. Drying of samples is time-consuming as it can take weeks to dry them fully. Achieving dryness in an oven is not a perfect option as the relative humidity in the oven is not zero. There is always moisture that still remains in the sample which is called residual regain. In practice the samples are dried in heated ovens at about 110 °C. Since heat is being used to remove moisture, other substances in the fabrics such as oil and waxes which are not intended to be removed can also be removed as well making the loss of moisture appear higher than it should be. One way to overcome this is by allowing the sample to absorb moisture, weigh it and dry it again. When moisture is being removed heat is also being removed at the same time (Morton & Hearle, 1993, 2008).

7.2.3. Water absorption capacity

A fabric sample with a square shape is cut and soaked in water. Once it is saturated, it is removed and hung vertically until there is no water dripping from it. The water absorption capacity of the fabric is measured as the weight of water per unit area of fabric area; it is expressed in g/m^2 (Tang et al., 2015).

7.2.4. Absorbency of the fabric

A drop of water is released from a fixed height and the time it takes for it to be completely absorbed by the fabric is taken as the absorbency of the fabric. The absorbency shows the ability of the liquid to spread outward on the surface of the fabric. Fibres, fabric and finishing properties influence the absorbency of the fabric. Fabrics that have high wettability absorb water faster than those with low wettability (Kumar et al., 2015; Tang et al., 2015). Fabrics made of fibres which possess high moisture absorption may not necessarily be good for the removal of moisture as they tend to have low evaporation rates and it takes a much longer time for them to dry (Priyalatha & Raja, 2018).

7.2.5. Wettability

A drop of distilled water is released from a height and the time it takes to completely wet the top and bottom surfaces of the fabric is recorded and is called wetting. Fabrics with a large wetting radius dry faster. The spread of water in the fabric indicates the movement of moisture in all directions of the fabric at the same time (Sampath et al., 2011).

7.2.6. Fabric saturation

Drops of distilled water are dropped on the fabric until the fabric cannot absorb more water. When the saturation point is reached the water starts falling from the fabric. The time it takes to reach the saturation point is recorded (Sampath et al., 2011).

7.2.7. Water vapour transmission

Water vapour transmission is the transfer of mass of water vapour through a unit area of a fabric. Evaporation is considered as the main mechanism by which the heat is removed from the body. Moisture vapour transmission can be determined by measuring the height of water in the container covered by the fabric or by weighing the container as shown in Figure 7 (Zhu et al., 2013). Water-vapour transmission can be tested by the desiccant and water methods. In the desiccant method, a fabric sample is placed and sealed on the mouth of a dish containing the desiccant. A sample is placed in a controlled atmosphere and weighed periodically to find out the amount of water vapour that has been transferred and absorbed in the desiccant. Greater amounts of still air between the inside of the fabric and water layer reduce the transmission rate. Water permeability of the fabric is the difference in the weight lost and can be expressed as a $g/m^2/day$ (Huang & Qian, 2007; Russell, 2007; Sampath et al., 2011).

The water vapour permeability tester (WVP) is used to test fabrics for water vapour transmission. WVP tester does not measure the heat generated or absorbed when the fabric is in contact with water. Because of the high thermal conductivity of water, the presence of moisture in clothing makes the wearer feel uncomfortable. High thermal conductivity of wet fabrics is due to the replacement of air in the fabrics with water. Air acts as a thermal insulator. With higher amounts of water in the fabric, the fabric thermal conductivity approaches that of water (Slavinec et al., 2016).

Water vapour transmission can be determined by Eqs. (23) and (24):

$$Q = \frac{1}{R} \times \Delta c \times D \times At \tag{23}$$

where Q is the amount of water vapour in g, *R* (a function of pores/openness) is the resistance by the fabric, *D* is the diffusion coefficient, Δc is difference in vapour concentration, *A* is area in cm^2 and *t* is time in s (Kumar et al., 2015).

The loss of water through the fabric which is moisture vapour permeability can be calculated using the relation:

$$WVP = \frac{24 \times M}{At} \mathrm{g/m2/day} \tag{24}$$

where *A* = internal area of the fabric (m^2), *t* = time of testing in 24 hours.

7.2.8. Subjective wetness sensation assessment

In general subjective methods are preferred to describe comfort even though it is prone to error due to its inherent biases as different individuals have different responses. In order to minimise the biases of the subjective methods, the sample size is increased, however this increases the time and cost of conducting the tests. Mechano- and thermo-receptors in humans are considered to be responsible for the wetness sensation, with pressure, moisture evaporation, thermal conductance and stickiness of material playing an important role for the stimulation of sensation. Although different sites of the body can be used to assess clothing quality, the fingers are preferred as they contain more sensors per centimetre than other sites of the body. Other sites of the body contain hairs which make them to be too sensitive to tingling sensation than the hairless fingers (Cho et al., 2002; Tang et al., 2015).

7.2.9. Moisture management tester

The moisture management tester measures the electrical resistance of the face and back sides of the fabric. A fixed drop of water is released from a height and the spread of the droplet is recorded. The fabric is placed between two sensors one at the top and the other below. The liquid is introduced at the top of the fabric. The two sensors are connected to the computer to record changes in the sensors (Kumar et al., 2015; Tang et al., 2015).

7.2.10. Magnetic resonance imaging (MRI)

Magnetic resonance imaging (MRI) are widely used in the medical field to generate images and have now been used in the textile field to measure pores in selected parts of the fabric that is of interest. The technique produces 1, 2 or 3-D images of the water in the pores. The MRI technique is very fast and capable of measuring the distribution of water within the fabric and of simultaneously producing images in real time. The movement of moisture and its distribution as well as the drying of the fabric can be observed in real time without destroying the fabric. The fabric specimen is simply prepared by completely wetting it then capturing the MRI images (Beckham et al., 1997; Mazela et al., 2014).

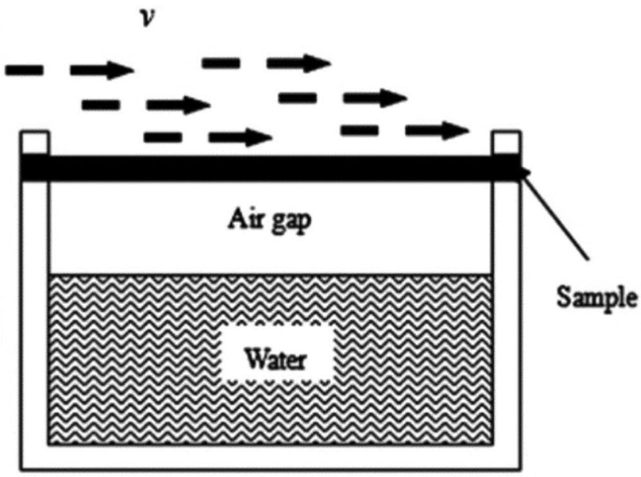

Figure 7. Schematic of water vapour transmission (Zhu et al., 2013).

7.2.11. Sweating guarded hot plate

A fabric and membrane samples are placed on a metal plate with a constant temperature of 35 °C and water from the cylinder is released. The air temperature and humidity are kept at 35 °C and 40%. The resistance is influenced by temperature, vapour pressure, air and fabric area. This simulates the transfer of heat or moisture from the body through the fabric. This method is time consuming as it can take up to 60 minutes to test each sample (Huang & Qian, 2007).

7.3. Test for air transfer in clothing

7.3.1. Air permeability and pore size

Air permeability of textile fabrics is calculated by measuring the flow rate under a constant pressure (Song, 2011). Fabric pores size measurement is important as it affects air permeability. Fabrics with large pore size have higher air permeability than those with small pores as smaller pores decrease the amount of air that can pass through the pores. In order to calculate the fabric pore size, the capillary flow porometry bubble point test method is used along with other methods. A fabric is wetted with a wetting liquid such as the Galwick which has a known surface tension. The pressure is raised to displace the liquid from the fabric pores. Larger pores size have low differential air pressure and will show bubbles first than smaller pores size which will require high differential air pressure (Park & Shin, 2011). The pressure required to form the first bubbles is used to calculate the fabric pore diameter using the relation:

$$d = C\frac{t}{p} \tag{25}$$

where d is pore size diameter, t is surface tension of Galwick (dynes/cm), p is the differential pressure and C is constant. Fabric pore size can also be calculated using the relation:

$$d = \frac{46\sigma * 10^6}{p} \tag{26}$$

where d is the pore diameter (mm); σ is the surface tension (N/m) of the liquid and the contact angle between the liquid and the pore wall is assumed to be zero; p is the capillary pressure (equivalent to the applied pressure) in Pa (Russell, 2007).

In order to determine fabric air permeability and air resistance the following relations are used:

Air permeability q is determined from the relation:

$$q = \frac{Q}{A} \times 167 \tag{27}$$

where Q is the rate of air flow (cm^3/min.), A is the area of specimen (cm^2), and 167 is the conversion constant.

Fabric air flow resistance can be calculated using the relation:

$$\mathrm{R} = \frac{\Delta P}{Q} \tag{28}$$

where ΔP is the pressure difference across the test sample (Pa), Q is the rate of air flow (cm^3/min.)

When the influence of fabric thickness is taken into consideration, the specific air flow resistance can be calculated using the relation (Antonio, 2011):

$$R_s = \frac{S.\Delta P}{Q.d} \tag{29}$$

d (m) is the thickness of the sample, S is the cross-section area of the sample (m^2).

8. Conclusion

The transmission of moisture, heat and air is important for the wearer's comfort. Rapid transmission through the fabric improves the wearer's comfort but must be compromised in the case of particular types of protective clothing, such as those used by firefighters. Fabric, yarn, and fibre properties such as fabric structure, pore size, fibre type, weave type, yarn twist, air permeability and the surrounding environmental condition all exert their own particular influence on heat, moisture and air transfer through a fabric. The clothing acts as a barrier, it restricts transfer and when moisture and heat accumulate the wearer feels uncomfortable. When air penetrates a fabric, the sweat on the surface of the skin evaporates and the body temperature drops. Blending of lipophilic and hydrophilic fibres to make a fabric with an open structure improves the transfer of moisture.

Different body parts sweat differently, so the body-mapping approach can be used to design clothing that maximise the local transfer of sweat, heat and air of the different body parts. Protective clothing like firefighters clothing usually have low transmission of moisture, heat and air and as a result they are less comfortable to wear as their primary function is to provide protection, not comfort. Moisture can be transported by absorption or wicking through the fabrics while heat is transferred by conduction, convection and radiation. Bench top tests and manikins are used to evaluate the transmission of heat, moisture and air through the fabrics. Manikin tests are considered to be more advanced as they take into consideration the human body shapes. When using manikins, transmission at various sites of the body can be monitored and measured.

Acknowledgement

This work is based on the research supported in part by the National Research Foundation of South Africa (grant-specific unique reference numbers (UID) 104840. Authors also acknowledged several sources for granting permission to re-use some of the figures in this paper.

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