DEVELOPMENT OF NOVEL T-SHIRT DESIGNS FOR VENTILATION

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HO Chu Po

DELICATED TO MY FAMILY

ABSTRACT

In today's world, clothing is not only a commodity to meet our basic needs or an object for aesthetic appreciation, but also a portable environment to help us face different external conditions everyday. In order to fulfill such a purpose, a true functional garment is the one that can protect our body from acute changes of external conditions.

In order to strike a balance between work and leisure, sports have become a part of our lifestyle. However, one may not be aware that sports and exercise can sometime bring about certain degree of impairment to our health. For instance, when doing exercise, our body will generate heat, which will eventually result in sweating. If the heat and sweat cannot be efficiently transmitted through our clothing and released to the external environment, the excessive heat not only causes heat stress and affects our performance, in extreme case, it would even lead to tragic death (Sawka and Young, 2000). Since clothing can be a potential obstacle to the heat and moisture transfer (Haghi, 2004; Levine et al 1998; Nielsen et al 1989; Parsons 1993), designers of functional clothing and active sportswear should not only take into consideration the aesthetic requirements, but also try to optimize the thermal comfort of the wearer.

To enhance thermal comfort, ventilation features have been widely applied to clothing systems. Nevertheless, the location and design of the ventilation features have been largely based on trial and error. In this study, the location and designs of ventilation openings in T-shirts are experimentally investigated using the sweating fabric manikin -

Walter. Clothing thermal insulation and moisture vapour resistance of the T-shirts were measured when the manikin simulated walking motion and was at standing posture. The results showed that, the locations and designs of the ventilation panels affected the total thermal insulation and moisture vapour resistance; among the various designs tested, the construction that kept the fabric layer away from the skin surface and openings applied at two vertical side of the T-shirt along the side seams were found to be the most effective in releasing heat and moisture from the body.

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Chapter 1

Introduction

1.1 Background of Research

Comfort is a key factor to be considered in clothing design, since an important function of clothing is to ensure that the heat loss, skin temperature, air movement and humidity at the body surface produce a sensation of comfort (Yee 1988). Among all the comfort factors, thermal comfort, viz. the function of assisting the maintenance of the thermal balance of human body, is primary (Hollies *et al* 1975). Thermal comfort refers to the state of mind of a person's satisfaction to the thermal environment (Fanger 1970). The details of thermal comfort will be discussed in chapter 2.

Clothing generally represents a layer of insulation or a barrier to heat transfer from the skin surface (Gavin 2003). If clothing cannot effectively release the body heat, discomfort will result and in extreme conditions, the wearer may even be in danger. For athletes, heat stress can harmfully affect their sports performance (Ruckman *et al* 2001 and Williamson *et al* 2002). Therefore, it is crucial to optimize clothing design (Ruckman *et al* 1999).

Fabrication has been considered as a key element in functional clothing for thermal comfort. Although some comfort problems can be solved by advanced materials, others have to be solved at the design level. The designer should consider the combination of those materials and where they should be placed creatively (Wilensky 2001).

Some leading sports companies have placed much investment into the development of sportswear for improved comfort; for example, Nike promoted a new two-layer stylish jersey labelled "Cool Motion". This technology constructed a T-shirt with a hydrophobic shell layer, coupled with a high-wicking microfiber inner layer. The inner layer could wick the sweat and moisture vapour quickly to the outer layer for faster evaporation.

In the fashion industry, it is also common that fashion designers work closely with sportswear companies to produce fashionable sportswear. This is known as a kind of crossover, such as Jil Sander collaborating with Puma. Y-3 is another example. Y-3 is a fashionable sportswear clothing line developed by Adidas and a world-class Japanese fashion designer Yohji Yamamoto. We can see a crucially important trend that sportswear/functional wear is adjusted to be more fashionable. The integration of function, aesthetics, fashion and comfort has become a new trend in the 21st century fashion design. The present study is also an example of this new trend.

1.2 Project Objectives

Although there is a great deal of published work on how textile materials can improve clothing thermal comfort, little is reported on the role of the garment design. The present study is focused on the design of novel garment collections for thermal comfort. Function, technology and fashion are considered integrally together. The specific objectives are:

a. To provide a comprehensive and in-depth literature review on how garment design contributes to the thermal comfort of clothing, with specific reference to the development trends of functional sportswear.

b. To explore alternative ways of designing sports T-shirts for optimizing the body ventilation. To achieve this, prototypes were made and evaluated by using a sweating manikin and subjective wearer trials.

c. To develop a novel collection of sports T-shirts that not only incorporate the mechanisms of ventilative cooling, but are also fashionable to wear. To provide guidelines and design briefs for further commercialization of the developments.

1.3 Research Methodology

The research was carried out in the procedure as illustrated in Figure 1.1

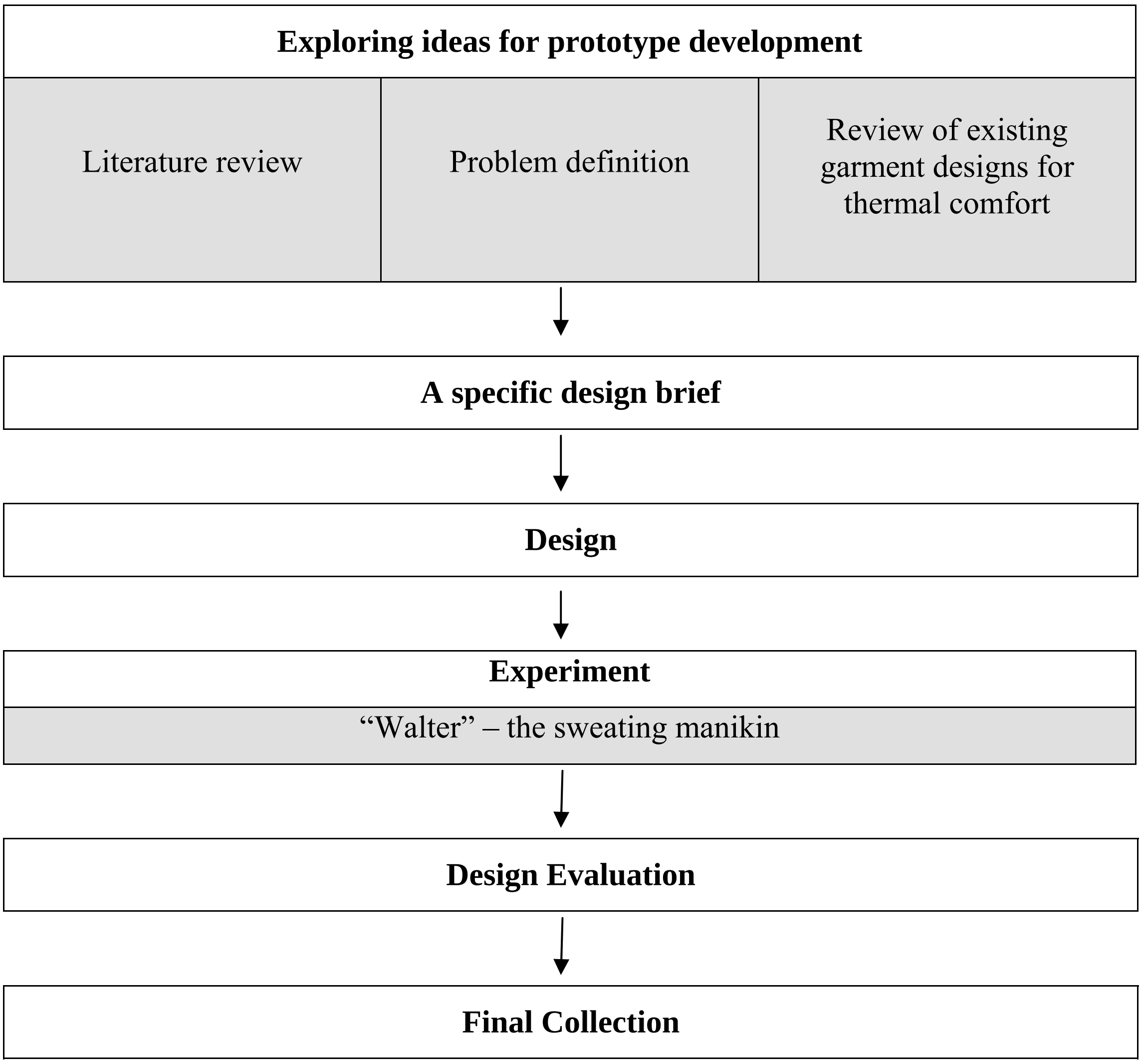


Figure 1.1 Methodology of research

1.3.1 Exploring ideas for prototype development

- Literature Review

A comprehensive review of literature helps to update and integrate relevant information. In this study, relevant literatures on human perspiration, clothing thermal insulation, heat and moisture transfer through clothing and clothing product development are reviewed. It helps to explore creative design ideas for further development.

- Problem definition

In a design process, the requirements or functions should be first defined. This process helps the designer to navigate the routes of design development.

- Review on existing garment designs for thermal comfort. A lot can be learned from the existing garment designs. These include working principles, design details, and fabrication. On this basis, the possibility of further improvement can be explored.

1.3.2 Design brief

By reviewing the relevant literatures, defining the requirements, and studying the existing garment designs, a list of design briefs can be listed for further work.

1.3.3 Design

Short-sleeve men's sport T-shirts will be the control style of the study. T-shirt is a common clothing item for sports (like soccer, tennis, badminton, golf) and for casual exercise (like yoga, gym, cross-training). Due to their popularity and functionality, the present research is focused on the basic sport T-shirts. The design would be only for men.

Plain white T-shirt was part of the U.S. Navy uniform in the First and Second World Wars. In 1913, the U.S. Navy officially adopted the short-sleeved crewneck (i.e. collarless) T-shirt as the underwear for sailors and soldiers, with its main purpose being to cover chest hair (Fresener 1995 and Brunel 2002). Soon afterwards, T-shirts and sports became inseparable because elastic knitted structure can allow free movement. Additionally, people also considered the advantage of the high absorbent material which could wick the sweat from physical exertion. Thus by the 1930s, plain white cotton T-shirts became standard sport clothing at some American universities. Often these universities would affix their names to the T-shirts of their sports teams (Walters *et al* 2001 and Brunel 2002). In the 21st century, the T-shirt is also one of the popular wear items for athletes, and better technology and new design concepts have been developed to improve their functions.

1.3.4 Methods of measuring thermal comfort of clothing

Thermal comfort of clothing and textiles can be evaluated by subjective wearer trials or objective simulation tests, or a combination of the two. In general, objective simulation tests include flat plate methods, cylindrical methods and thermal manikins. However, each test serves different functions so as to test different aspects of the garment.

- Subjective wearer trials

Many researchers use real human subjects to evaluate the thermal comfort of textiles and clothing. This method has been used to assess the effectiveness of pumping effect under various body movements (Holmer *et al*, 1981; Nilsen *et al* 1985; Bakkevig 1995). Although this method has the advantage of allowing direct and simultaneous measurements of heat and moisture transfer of clothing, the measured data tends to be less accurate and consistent.

- Objective measurement

Flat plate and cylindrical methods are widely used to evaluate the thermal and water vapour transmission behaviours of clothing materials or simple clothing ensembles. Since a garment includes more complicated factors like design, shape, cutting, construction, drape, etc, these two methods have limitations in evaluating clothing systems in use. Furthermore, these two methods cannot evaluate thermal and moisture transfer due to the human motion.

To cope with these problems, thermal manikins have therefore been developed to evaluate the thermal comfort of clothing systems. The earliest thermal manikin was developed in the early 1940s by the US army. It was a one-segment copper manikin and could not simulate the sweating and movement of a human being. In recent years, thermal manikins with improved functionality have been developed in many countries. For example, "Coppelius" in Finland (Meinander 1999) and "Walter" in Hong Kong (Fan and Chen 2002, Fan and Qian 2004, Kar *et al* 2007) can simulate "walking motion" and "perspiration" simultaneously.

Figure 1.2 – The sweating thermal manikin – "Walter"

"Walter" is a thermal manikin which can simulate the human perspiration. It is connected with a heat controller and sensors for measuring the temperatures of the skin. Since the manikin is covered with a waterproof but moisture permeable fabric, it can simulate the sweating condition of a human body. It is filled with water to create a soft body similar to a human body. “Walter” is 1.70m tall and its size and configuration are similar to a typical Chinese man. (Fan *et al* 2002).

After evaluating the appropriateness and effectiveness of different testing methods, the thermal manikin (Walter) is considered to be the most suitable method for garment testing because of its accuracy and ability in simulating real use condition.

To evaluate the thermal comfort of the clothing, the core temperature of the manikin was set as 37°C (this is known as the standard core body temperature of a healthy human). During every test, a control piece is produced. This control piece is acted as a common T-shirt without any special design or cutting, and is easily obtained from the market. The data of total thermal insulation and moisture vapour resistance of this control piece will be compared with other T-shirts with special design.

1.3.5 Design evaluation

New designs are continuously evaluated by experimental measurements. The best design in terms of thermal comfort is then chosen for improvement in visual appearance through creative design variations.

1.3.6 Final collection

A final collection is then produced to demonstrate the design concept.

1.4 Project Significance and Value

There are many published works on innovative textile materials for thermal comfort, such as the phase-change materials, fibres with irregular cross-section for improved wicking properties, etc. However, the study on the effect of garment design on thermal comfort is still limited. This study has dual significances by contributing to both academia and industry. Through the present study, an improved understanding of the relationship between thermal comfort and garment design features can be achieved. Furthermore, the novel T-shirts developed in this study have commercial potential.

Chapter 2

Review of clothing thermal comfort

2.1 Introduction

Throughout the day, and across all types of activities (steady or dynamic) and environments, the body constantly regulates itself to maintain a safe, constant body temperature. Therefore, one's body temperature represents a safety balance between heat gain and heat loss (Foss *et al* 1988). Humans must continuously exchange body heat with their environment to maintain their heat balance. Otherwise, too much heat and moisture would cause discomfort to the human. Clothing, as a barrier of heat and moisture transfer, should be able to maintain the heat balance of the wearer.

2.2 Thermal comfort of human body

In the human metabolic process, about 80-90% of the energy is converted to heat and only the residual energy (10-20%) is used by the functional system of the body according to different activities (Fanger 1970). Two physical conditions for general thermal comfort of a human body are:

- Core temperature at 37±0.5°C;

- Skin temperature in the range of 32°C to 35°C, with the skin temperature of the body trunk higher than that of the limbs

The temperature of 37±0.5°C is standard for human physiology. Illness may result in higher or lower temperatures than this standard, leading to discomfort for most humans. In addition, if a human is exposed to extreme climatic conditions for a certain period, it may destabilise the core temperature, resulting in death in some situations. To avoid this danger, many protective garments are developed to maintain a stable body temperature. In hot environments, the garment should ideally be able to release heat from the body, and vice versa in cold environments.

2.3 Clothing, humans and the environment

Comfort is a key factor to be considered in clothing design. Among all the comfort factors, thermal comfort is the primary one (Hollies and Goldman 1975), as an important function of clothing is to provide aids in maintaining the thermal balance of human body and ensure that the heat loss, skin temperature, air movement and humidity at the body surface produce a sensation of comfort (Yee 1988). In general, there are three main elements that affect the thermal comfort of a human body: the condition of the environment; the person himself (physiologically and psychologically); and the clothing (Sweeney and Branson 1990). The condition of the environment includes air temperature, mean radiant temperature, relative air velocity, and water vapour pressure in ambient air. The body exchanges heat with the surrounding environment through radiation, conduction, convection and evaporation.

Humans normally release body heat and moisture periodically during states of sleeping, standing still or moving. Large amounts of sweat and a higher body temperature is the outcome of intensive activity, such as sports and exercises. If heat and moisture are not released effectively from the body, heat stress may occur and the wearer's performance will be negatively affected (Sawka *et al* 2000). If the moisture vapour cannot transfer out from the garment layers, the accumulation of the vapour will lead to the increase of the humidity until the vapour condenses and develops to the liquid form. The undergarment may soak this liquid and the wearer may feel discomfort at this stage. Therefore, contemporary functional garments are designed to improve the heat and moisture transfer from the wearer, no matter the garments are a T-shirt, jacket or protective coat. Of course, thermal comfort may be improved by the use of functional materials such as moisture management fabrics. Nevertheless, garment design, in terms of style, fit and design details, plays a crucial role in achieving the ideal performance of thermal comfort, as clothing is a 3D object.

The heat insulation of a textile material is described by its thermal resistance. This is defined as the temperature difference between the two textile faces divided by the heat flux, and it has units of $Km^2 W^{-1}$. The magnitude of heat flux at a particular point is inversely proportional to the thermal resistance of the material, so that the higher the resistance, the lower the heat loss.

In human science, the unit of thermal insulation is the Clo. The Clo unit of insulation is defined as a mean thermal resistance of 0.155ºC m^2 W^{-1} . One Clo is equivalent to the unit of clothing ensemble of a wearer which allows thermal comfort with a mean skin temperature of 33ºC (92ºF) while sitting in a ventilated room with air movement not in excess of 0.1m/s, temperature of 70°F (about 21°C) and relative humidity of less than 50% (Gagge *et al* 1941 and Ukponmwan 1993).

2.4 The mechanism of heat and moisture transfer through clothing

In the study of clothing comfort, heat loss from the body through the clothing to the environment can be classified in two ways: dry heat loss (through conduction, convection and radiation) and evaporative heat loss.

2.4.1 Dry heat transfer through clothing

Conduction

Conduction is a process of heat transfer of kinetic energy between molecules of objects in direct contact. The greater the temperature difference, the larger the heat transfer by conduction from warmer to cooler objects (Rhoades *et al* 1996). According to Fourier's Law, the rate of heat conduction, L_{cond} can be calculated as:

$$L_{cond} = \frac{-k \cdot A \cdot dT}{dl}$$

where, k is thermal conductivity, A is the surface area, dT is the temperature difference, and dl is the thickness that the thermal energy passes through

Although different fibres conduct heat differently, the difference is not significant in clothing. A piece of fabric that is woven or knitted will trap a large quantity of air. This trapped air has a substantially lower thermal conductivity than the fibre itself. Thus the conductivity of the fabric is largely dependent on the amount of still air trapped inside (Hatch 1993).

Convection

Convection is the transfer of heat from one area to another through the fluid medium, which can be either in gaseous or liquid form. The total amount of heat lost by convection is related to the speed and temperature of the air flow over the surface of skin (Foss *et al* 1998). Clothing can increase the total body insulation through the insulative properties of trapped air layers and fabrics (Pascoe *et al* 1994). The energy of convectional exchange can be expressed as

$$L_{conv} = h \cdot A \cdot (T_s - T_a)$$

L_{conv} is regarded as heat loss by convection, h is heat transfer coefficient, A is surface area, T_s is the body skin temperature, T_a is the ambient temperature.

Radiation

Radiation is heat transfer through electromagnetic radiation between two objects that are not in contact. It travels at the speed of light and requires no medium of propagation, and thus two objects are not required to be touching each other. Normally the degree of radiative heat transfer is dependent on the radiation penetration depth and the thickness of the fabric layer. Also, the greater the temperature difference, the larger the heat transfer from the warmer to the cooler object (Farnworth 1983). The radiative heat transfer from the body surface to the environment is:

$$L_{radi} = \varepsilon \cdot \sigma \cdot A \cdot (T_s^4 - T_a^4)$$

where, L_{radi} is heat loss by radiation, ε, is thermal emissivity and is ≤1;

σ is Stephan-Boltzman constant, σ =5.67 x 10-8 W/m^{2}K^4, T_s is body surface temperature; T_a is the ambient temperature.

Normally, radiation, conduction and convection are classified as dry heat transfer as they are determined by the temperature difference between the skin surface and the environment. The total dry heat transfer through clothing can be described by:

$$L_t = \frac{A \cdot (T_s - T_a)}{R_t}$$

L_t is total dry heat transfer through clothing by radiation, conduction and convection; A is surface area; T_s is the skin temperature and T_a is the ambient temperature; R_t is the total thermal resistance of the clothing and the layer of air outside the clothing surface and it is generally expressed in °Cm^2 /W (ISO unit).

Normal dry heat transfer mechanisms of conduction and radiation are, however, not sufficient to cool the body temperature of a clothed man during high activity levels. Under these conditions, sweat evaporation is the most effective way to release body heat (Weiner 1970). Ventilation becomes a stronger mechanism of heat loss once air convection is forced. It can thus act as another key element to enhance the exchange process between the clothing microclimate (include sweat and vapour) and ambient environment.

2.4.2 Evaporative heat transfer through clothing

Moisture is produced by the body in the form of perspiration, in both insensible and sensible ways. Insensible perspiration evaporates within the skin layers and is emitted as moisture vapour, while sensible perspiration is liquid perspiration, and sweat is a common media for that (Collier 1999). During exercise, heat production may be 20 times higher than at rest because of extensive body movement. Hence, thermal regulation through sweat evaporation is important for body temperature regulation (Kondo *et al* 1996).

Evaporation

Evaporation is the process of converting water from liquid to gaseous phase. The human body sweats when it is hot. Evaporation through the pores of the skin plays an important role when there is a large amount of heat to be removed. This physical process consumes heat (roughly 0.54 kcal to convert one gram of water into gas). Under normal conditions, evaporation in this form of insensible perspiration takes away approximately 15% of the heat lost from skin (Haghi 2004). Evaporation performs better if the ambient temperature is higher and relative humidity is lower.

The energy of evaporation from skin perspiration can be expressed as:

$$L_e = \frac{A \cdot (p_s - p_a)}{R_e}$$

where, L_e is the heat transfer by evaporation through clothing, A is the surface area; p_s is partial water vapour pressure at skin temperature; p_a is the partial water vapour pressure at ambient temperature; R_e is total resistance to water vapour transfer through clothing and air outside the clothing surface and it is generally expressed in Pam^2 /w (ISO units).

When a clothed person exercises, the body gets hot and sweats (assuming a relatively hot and dry environment). Dry and evaporative transfer should work together to release body heat and sweat will evaporate to become moisture vapour. Thus the total heat transfer (*L*) should be calculated as

$$L = L_t + L_e = \frac{A \cdot (T_s - T_a)}{R_t} + \frac{A \cdot (p_s - p_a)}{R_e}$$

Heat loss by evaporation through clothing can be divided into three stages. In the first stage, the sweat rate increases and evaporation rate is active. Water vapour gradually accumulates between the skin and fabric layer (this gap is also known as clothing micro-environment). In the second stage, this layer of clothing micro-environment is saturated with water vapour, and at the same time effectiveness of evaporation drops. Then the fabric layer starts to absorb the sweat. In the final stage, evaporation takes place on the fabric surface rather than the skin (Kakitsuba 2004).

As clothing acts as a layer between the skin surface and the environment, apart from the ambient environment, the material/textile will also influence the effectiveness of coupled heat and moisture transfer. If sweat or liquid from the skin cannot evaporate, or be transmitted from skin to the ambient environment through the textile layer, discomfort will result as the body cooling down function will be rendered ineffective by inactive evaporation. Thus the moisture transfer capability of the textile is the dominant factor affecting heat and moisture of the wearer.

2.5 Two key parameters of clothing systems for thermal comfort

Woodcock and other scholars (Spencer-Smith 1976) have pointed out that the thermal function of clothing systems is characterized primarily by the two factors, R_t and R_{et}, representing the total thermal resistance and moisture vapour resistance respectively.

$$R_t = \frac{A \cdot (T_s - T_a)}{L_t} \quad ,$$

$$R_{et} = \frac{A \cdot (p_s - p_a)}{L_e} \quad ,$$

($L_e = L\text{-}L_t$ or $L_t = L\text{-}L_e$)

2.6 Moisture transfer through textiles

The humidity in the clothing microclimate affects sensations of dampness and clamminess experienced by the wearer, both during sweating and cooling down intervals of sweat-generating exercise. The ability of the textile layer to reduce the humidity of skin by transporting moisture vapour to the ambient environment is a critical determining factor for this performance (Prahsarn *et al* 2005). According to Collier *et al* (1999), there are three ways in which water can pass through a textile layer: diffusion, sorption and wicking. Water can also be removed from either the surface of the skin or the surface of a textile fabric by evaporation.

a. Diffusion

Moisture can diffuse through the air spaces between fibres and yarns. Fabric porosity and thickness determines the effectiveness of diffusion. If a fabric is loosely woven or knitted, it provides large pores or space through which water can easily diffuse.

b. Sorption

Sorption includes adsorption, absorption and desorption. Adsorption is the process of taking up water and holding it near the surface. In absorption, molecular moisture diffuses through the materials. Desorption is the release of moisture, either adsorbed or absorbed, from the material.

c. Wicking

Wicking is the transfer of liquid water through the capillary interstices of the yarn. The effectiveness of wicking depends on the wettability of the fibre surface and the structure of the yarn and the fabric.

d. Evaporation

In a similar way to the evaporated heat transfer of clothing, once sweat or moisture of the skin is transferred (by single or combined mechanism of moisture transfer through textile) to the fabric surface, moisture/ sweat will evaporate from the fabric surface if the ambient environment meets specific requirements.

Chapter 3

Review of functional sportswear design for thermal comfort

3.1 Introduction

In order to improve the effectiveness of body heat release and sweat evaporation, some people might keep body nude when they are exercising. However this approach should not be encouraged especially in hot, humid weather because direct and reflected radiation from the sun or artificial lighting can increase heat gain. In this case, a layer of garment can act as a barrier to heat absorption from solar radiation (Foss *et al* 1998 and Gavin 2003). For professional athletes, nude body is not allowed when they are participating in a match. Thus a layer of functional sport clothing is still necessary, especially for outdoor exercise.

A good understanding of existing functional sportswear for thermal comfort serves an important foundation to the creative designs to be developed in the present investigation. In order to realize the existing garment design with function on improving thermal comfort, different design approaches and their recent development should be reviewed.

3.2 Definition of sportswear and sport clothing

Various definitions of "sportswear" and "sport clothing" are prevalent across the world. In U.S., generally sportswear means casual leisure wear or street wear, while in U.K., "sportswear" and "sport clothing" means active and performance clothing that is usually designed and manufactured specifically for sports (Craik 2005 and O'Mahony *et al* 2002).

3.3 Different approaches of functional sportswear design for thermal comfort

When designing a collection of sport clothing, fashion designers do not only consider the style, colour, fabrication and design details; the functionality of item is also an important consideration. Some sport garments are primarily designed for their wind-proof function while the water-resistant function is important for others. However, the first priority for all designs should be easy release of excess heat from the body. Normally, design can solve this problem through three approaches: textile approach and garment design approach, or a combination of the two. Apart from these common approaches, sometimes designers also include special equipment into the garment system. This is known as wearable device approach, although this is not usual for daily use garments and is primarily restricted for special garments such as those for fire fighters and astronauts.

3.3.1 Textile approach

Various factors related to textile materials influence heat and moisture transfer, including fibre types, yarn smoothness, fabric structure and thickness, special finishing process like Gortex® (a type of membrane that provides wind and water protection but still allows water vapour to pass through the fabric from skin); moisture content, water absorption ability, and air permeability. Textile designers can produce suitable fabrics with improved heat and moisture transfer properties by employing technologies, so as to achieve customers' requirements. The role of a sport clothing designer is to choose a suitable fabric that enhances the best performance of heat and moisture transfer, rather than creating such materials. He/she can make use of these materials and place them suitably within the clothing system (Wilensky 2001). Knowledge of the thermal insulation of the textile is essential but not sufficient to evaluate the insulation of a clothing ensemble, as other aspects like garment design, fit, body movements and air velocity will also influence thermal comfort (Nielsen et al 1985).

3.3.1.1 Hydrophilic and hydrophobic properties of the fibre

As discussed above, the higher the ability of the fibre/ fabric to absorb sweat from the wearer, the higher the efficiency of evaporation. Hence moisture uptake action is a vital factor in reducing body temperature. Studies by researchers have focused on investigating the body-cooling effect of hydrophilic and hydrophobic fibre. It was concluded that the hydrophilic properties of fabric or fibre reduce the heat strain during exercise and rest especially when influenced by wind. Although sweat can take up latent heat from the wearer, if sweat is not transported away from the skin surface, discomfort will be generated and heat might be kept within the micro-climate between the skin and fabric layer. Hence the hydrophilic property of the fibre is not only influenced by moisture transfer but also by the heat released by the body. The hydrophilic property of the fibre is directly related to the moisture regain of the fibre/ fabric; in the normal situation, fibre with higher moisture regain could absorb more moisture and heat from the body. Natural fibres like wool and cotton have been shown to have higher ability to absorb large amounts of moisture due to their hygroscopic properties (Kwon *et al* 1998).

Many researchers have indicated that thermal resistance is determined largely by constructional factors, primarily thickness, rather than fibre type (Holcombe *et al* 1988). However, some fibres are more suitable for producing certain types of fabric structure. Cotton and silk can be produced in fine, lightweight weaves and have been traditionally favoured for clothing in hot climates while wool has long been associated with protection in cold weather because it can be used to produce thick and lofty structures with good wind resistance and can therefore be utilized for overcoat garments (Ukponmwan 1993).

3.3.1.2 Fabric structure and thickness

Fabric structure and its thickness influence the effect of heat and moisture transfer. This is because different fabric structures and thicknesses affect the air and moisture permeability, which play a significant role in moisture transfer.

Air has low thermal transmittance. Air entrapped in small spaces experiences low convection and is therefore "still". Generally, more still air in the textile structure can improve the insulation value of the textile and keep the body warm (Louis 1970 and Collier *et al* 1999), and thus entrapped air has been considered a vital factor affecting heat and moisture transfer. Air flow through a fabric occurs when the air pressure is different on the two sides of the fabric. Air permeability is the rate of air flow through the fabric when there is a different air pressure on either surface of the fabric, and it is affected by the fabric porosity. Fabric porosity is the total volume of void space within a specified area of the fabric (Collier *et al* 1999). Apart from the fabric structure, hairy fibre and fabrics also provide a greater surface volume of still air than smooth ones, so providing an insulating barrier to heat and moisture (Grise *et al* 1983).

Fabric thickness, construction (i.e. weaving and knitting particulars), and its bulk density (the mass of fibres in a given volume) have been found to affect the warmth retention of the fabric (Slater 1986). Thicker fabrics have a greater heat-insulation value. The greater the bulk density for a given thickness, the less is its warmth owing to the replacement of air by fibres having greater heat conductivity.

Moisture permeability is one of the key elements affecting the comfort property of the textile. Water evaporated at the skin surface that passes as vapour through a fabric will not clog the fabric's pores and thus there will be continuous movement of air along with heat transference through the fabric. On the other hand, the wearer's comfort is reduced if skin moisture is transported to the surface in the liquid phase by wicking action and it only evaporates on reaching the air layer at the fabric surface. The wearer can also be uncomfortable if the garment permits free access of liquid water in wet weather, so that liquid evaporation or transference is not effective resulting in heat stress. Wearers of fabrics with poor moisture and water absorption will experience greater sweating, and the sweat that is not transported and evaporated will not allow proper release of body heat (Tokura *et al* 1982).

During walking, the air spaces between the fabric layer of a porous clothing system and the skin will change according to the walking speed and rhythm. This movement of fabric will cause air penetration in and out of the clothing system and thus reduce the heat and moisture transfer resistance of the clothing system (Ghali *et al* 2002), depending on the fabric's pore size. Many sport clothing utilise mesh-structure fabric for good ventilation as the pores allow heat transfer from convection or evaporation. However, the amount and size of the pores will influence the thermal and moisture transfer. But other factor like fibre types, fabric thickness, fabric weight and fabric structure may also affect the performance of heat and moisture of a mesh fabric; for example, hairy fibres can block air penetration.

Thermal insulation is primarily determined by fabric structure, especially thickness and its porosity, while the chemical and physical nature of the fibre materials have little influence. Comparing cotton and polyester as an example, research has shown that polyester fibre is inferior in thermal resistance to cotton. However, the thermal resistance of polyester may be improved by lowering the packing factor of fibres in the yarn without changing its chemical nature (Yoon *et al* 1984). Hence, new manufacturing processes can alter the fabric's limitations.

3.3.1.3 Use of single or multiple fabric layer(s) in the garment construction

Apart from fabric structure and its thickness, the numbers of fabric layers also contribute to the thermal value and moisture resistance of the clothing system. Previous sections have noted the importance of still air as a barrier to exchange of warm and cool air between skin surfaces and the environment. The same theory can be applied to clothing systems with more than a single fabric. In general, more layers create additional layers of still air resulting in higher thermal insulation compared to single layer fabrics (Grise *et al* 1982 and Grise *et al* 1983).

As mentioned in the last section, the warmth of the fabric is governed by entrapped air, with thicker fabrics having more room to keep still air within the fibres or the fabric structure itself (Ukponmwan 1993).

In this theory, for a clothed body, the surface area of thermal transfer is increased by total amount depending upon the thickness of the clothing layer (Parsons 1993).

Hence, to design clothing that easily releases body heat and sweat or moisture, thin and single fabric should be listed as the first priority.

3.3.1.4 Special undergarment construction to improve ventilation

For some functional outerwear, it is required to use wind-proof or water proof shell fabrics, which tend to be less permeable to perspiration. To solve this problem, one may use breathable fabrics. Nevertheless, as the breathability of these fabrics are limited, to further improve the release of moisture through the wind-proof or water proof clothing, some designers have developed special construction between fabric layers.

Gioello (1984) developed a ribbed ventilating undergarment (see Figure 3.1) which was worn beneath a non-porous outer garment. In this design, he put a series of parallel raised ribs or cords to form the air channels. The channels would contact the base of the outer garment so that a wider air gap between the channels was formed. By creating a wider gap between the undergarment and the outer garment, the body heat and moisture transferred from the undergarment could be released from this air gap. The inventor further improved this idea later. He applied two layers of ribs or cords together, so as to ensure that the outer garment was separated from the under garment. By using porous material in the under garment touching to the skin, moisture vapour could be more easily transferred to the air channels (Gioello 1996).

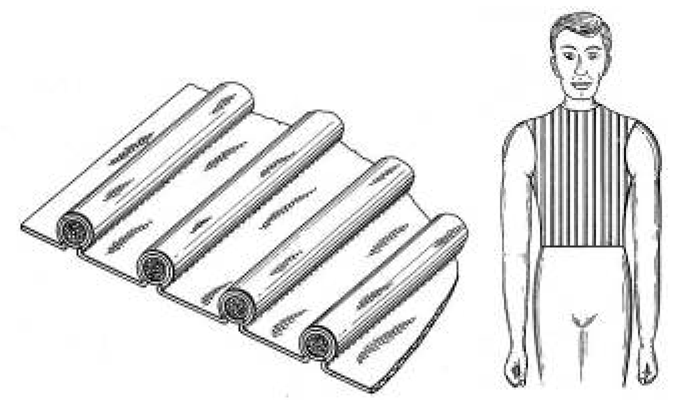


Figure 3.1 - Ribbed ventilating undergarment for protective garments. Source: Gioello 1984

Frim and Michas (1993) invented a cooling vest for the aircrew. This garment contained an inlet and outlet port for a gaseous fluid for the cooling purpose. This cooling vest should be worn under the flight coverall. In this design, the inventor created a bigger air gap inside the vest to improve the circulation of gaseous fluid. The first inner layer was made of a spacer material. The second layer was made of impermeable material with holes. The third layer was made of spacer materials, and inventor constructed it into a wave shape, so that it could increase the air gap by extending the distance between the second and the fourth layer which was made of impermeable materials. In this construction, the second and fourth layers should be fastened together along the edges. As the spacer materials in the middle created a bigger air gap, with the aids of the impermeable materials at both sides, more gaseous fluid could be inputted to this air gap for the cooling effect. Moreover, two impermeable materials could reduce the chance that the gaseous fluid flowed out through the fabric layer, thus the cooling effect could be circulated for a longer period than normal cooling vest.

Moretti (2001) invented a breathable coat which contained several fabric layers between the shell and the lining (see Figure 3.2). The concept of the design was to release moisture vapour from the body, and through an enlarged air gap by the special construction of the material, such moisture vapour could move upward and be accumulated at the shoulder area. The designer then put some holes at the shoulder part of the garment to let that accumulated moisture vapour be released out to the ambient environment. For the construction of the material, the inventor proposed several different means to create the air space within the material. To simplify, the first layer of the material was the lining fabric, in which holes were formed on the fabric structure. Through these holes the moisture vapour could pass to the second layer of the material which was a propping up inter-space created by a sheet of rigid undulated fabric, a pile cloth-like material, or a plurality of small tubes arranged side by side. The moisture vapour would be kept within this air gap, and by the aid of the opening at the shoulder, the warm air could be released to the ambient environment. The third layer was a layer of padding made of hydrophilic fibre such as cotton wool, wool or felt. The function of this padding was to enable the still air to be retained between the fibres for keeping better insulation from outside. Mainly this layer was used to keep the wearer warm. The final layer was the outer shell fabric combined with a membrane for enhancing its protective function to be impermeable to water or storm. This inventor claimed that the special structure could contribute better in air circulation inside the layers, but at the same time it could protect the wearer from cold and rain protection.

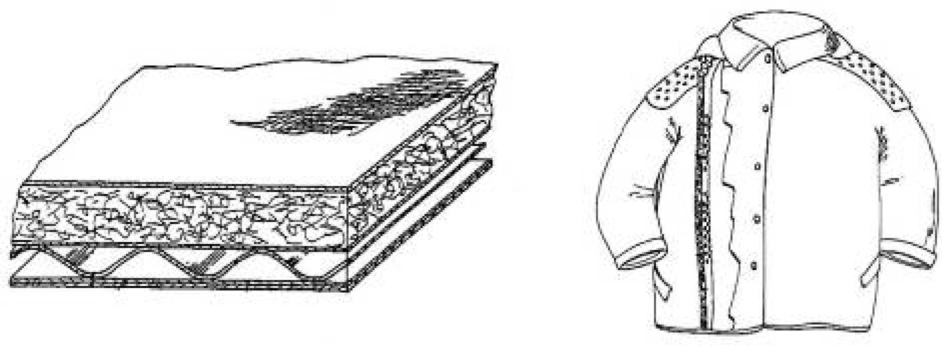


Figure 3.2 - Breathable garment to be worn to improve the comfort of the human body. Source: Moretti 2001

3.3.1.5 Techno textiles

Apart from the physical and mechanical properties of heat and moisture transfer of fibres, yarns and textiles can affect the thermal comfort of the wearer. Some value/function-added textiles are primarily applied in functional-wear and sport clothing in order to improve thermal comfort or even act as a “temperature controller”.

- Moisture Management Fabric

Moisture management fabric is widely applied in sport clothing, high value casual wear and uniforms. The concept of this technology is to have quicker drying rate and provision of efficient movement of moisture away from the skin leading to high breathability. As water vapour can carry heat away from the body by evaporating, absorption of sweat and the transportation through the fabric layer is important to the wear comfort. (Hu *et al* 2005). Coolmax® by INVISTA, Dri-FIT by Nike, and ClimaCool® are examples of this type of moisture management materials.

Nyoni (2003) concluded that the mechanism of moisture management fabric could be divided into five states:

1. Uptake of moisture from the skin surface
2. Removal of moisture away from the skin and transport through the fabric surface
3. Spreading of moisture within the fabric structure
4. Absorption of moisture within suitable fibres: “dynamic” fabrics usually contain an “outer layer” of hydrophilic fibres to absorb and store sweat away from the skin surface.
5. Evaporation of the moisture from the fabric surface.

Inspired by the branching xylem conduits of the plants, woven and knitted plant structured fabrics have been developed in Fan’s group (Fan *et al* 2007, Sarkar *et al* 2007, Chen *et al* 2009) to improve the water transport properties for improved comfort developed.

- Phase change material

By encapsulating paraffin in microcapsules and then incorporating it in either the spinning dope, in insulating foams or in coating paste in the textile materials, Phase change material (PCM) can perform temperature adjustment. When the environmental temperature reaches the PCM melting point, then the physical state of PCM in the fabric will change from solid to liquid along with absorption of heat, and the reverse process will take place if the temperature reaches freezing point of the PCM. In general, PCM fabrics can provide heat absorption/ releasing function to the human body and thus regulate the microclimate of the skin and fabric layer (Ying et al 2004). In conclusion, PCM garments can provide functions of: absorption of surplus body heat; insulation effect by heat emission; and thermo-regulating effect (Shishoo 2002).

This type of phase change material has been used as pre-cool vest invented by the Australian Institute of Sport at the 2004 Athens Olympics. The vests were aimed at reducing the core temperature of the athletes so as to avoid heat stress (Jennifer 2005). Some designers also tried to use the phase change material on protective garments such as fire-resistant cooling suits and cold protective garments, in which PCM is used to assist the wearers in temperature regulation under changing environmental conditions.

3.3.2 Garment design approach

Most of the research investigating thermal and moisture transfer has focused on textile aspects such as fibre contents, yarns, or fabrication. In general, researchers have shown that different fibres, yarns, and textiles could have a huge influence on the heat and moisture transfer of the wearer. They have also suggested that the design such as garment fit, colour and effect of opening should be taken into account for thermal comfort of the wearer. Thus more research needs to focus on garment-related design besides textile aspects.

3.3.2.1 Effect of garment fit

Garment fit has always been considered as one of the elements that influences thermal insulation and evaporative resistance (Fan 1989). Many researchers have studied this aspect. McCullough *et al* (1983) investigated how garment design influences the thermal insulation value of clothing. By comparing tight-fit and relatively loose-fit long trousers, they found that loose-fit trousers provided higher insulation than tight fit trousers (0.34 clo and 0.24 clo respectively). However, the researchers also stated that movement could circulate air inside the trousers and thus increase the convective heat transfer of the loose-fit trousers compared to tight-fitting trousers.

Havenith *et al* (1990) conducted research on the relationship of garment fit and clothing insulation. By testing three clothing ensembles on four male subjects (two wearing loose-fit and two tight–fit clothes) while sitting and walking, and under three wind speed (air speed <0.1m/s; 0.7m/s; and 4.1m/s) conditions. The results showed that tight-fit clothing had 6-31% lower insulation than loose-fit ones. Additionally, the difference was highest during sitting and decreased when wind was present ($p<0.05$).

Chen *et al* (2004) conducted an investigation on the effects of garment fit on thermal insulation and evaporative resistance by using a perspiring fabric manikin (Walter). Three types of jackets (woven poplin, woven denim and knitted fabric) were made in different sizes (five for each style) and tested under no wind and windy conditions (air velocity=2.0±0.5 m/s). The results showed that, under the no wind condition, the thermal insulation increased with the thickness of the air gap when the air gap was small. The rate of increase slowed down once the air gap was thicker. When the air gap exceeded 1 cm (equal to a girth difference of 7.5cm between the garment girth and the body girth), the thermal insulation decreased with the further increase in the air gap. This was because the increased air gap provided more space for natural convection. The similar trend was found in the windy condition, except that the thermal insulation values were smaller and reached the maximum when the air gap was about 0.6cm (a girth difference of 5 cm between the garment and the body). In windy conditions, tight-fitted garments could provide a better performance to keep the wearer warm. The authors concluded that clothing construction and garment fit played a major role in thermal insulation and evaporative resistance compared to fabric properties.

The above research has enhanced our knowledge of how garment fit could affect the heat comfort of the wearer. However some researchers hold different points of view in their investigation. As loose–fit clothing allows bigger space between the body and the material, more airflow is allowed and thus the replacement of warm and cool air should be more active and effective (McArdle *et al*. 2001).

3.3.2.2 Open apertures or vents in garment design

For a clothed person, there will be more or less air entrapped between the clothing layers, or between the skin and fabric layer if he is wearing a garment with only a single layer fabric. As the thermal conductivity of still air is low, solutions should be sought for improving exchange between the inner warmer microclimate and the outside environment, and this is known as air ventilation. One of the most common ways to do this is through open apertures in clothes in order to increase the exchange between the air inside the clothing and the ambient air. Moreover this ventilation will be further increased by the pumping effect of body movement (Mecheels *et al* 1977). Clothing with openings involves two principles of ventilation:

1. Indirect ventilation refers to the exchange of the garment microclimate through the materials itself;
2. Direct ventilation means that the microclimate between garment and ambient air is formed by openings in the garment (Qian 2006).

Direct ventilation, known as forced ventilation, can carry away warm air from the skin and fabric layer and also assist in evaporating sweat and dissipating warm vapour (Watkins 1984).

Open apertures or vents may be designed in garments so as to create ventilative cooling during body motion. Body motion can contribute to the release of body heat and moisture. When people move, the air within the microclimate of the garment can be forced into the ambient environment through the openings of garments or pores in the fabric (Vokac *et al* 1973, Nielsen *et al* 1985, Havenith *et al* 1990, Bouskill *et al* 2002, Haghi 2004). The air space between the skin and the inner fabric layer changes over time, depending on the level of activity and movement. During body movements, air must go in and out as the fabric moves outward and inward towards the skin surface, thus leading to ventilation (Ghaddar *et al* 2003). This ventilation of the microclimate of the clothing can be called "pumping effect" (Olesen *et al* 1982 and Vogt *et al* 1983).

Pumping effect is very crucial for air ventilation and moisture evaporation when the effective opening details and body movement can work in coordination. Even without any motion or movement by the wearer, ventilation can also be caused by natural convection through opening of the garments (Bouskill *et al* 2002).

Every garment contains ventilated openings like cuffs, collars and hem but they may not be strategically placed for a ventilation function by the designer. Another example like eyelets near the underarm can be seen in the market, especially for outerwear. However, the effect of this ventilation opening may not be so obvious if compared with other bigger openings.

Designers tend to use materials with special porous knitted or woven structures so that the body heat and moisture vapour can be released through the pores. For example, Zelano (1944) used lace fabrics and put them into the garment for ventilation purpose (see Figure 3.3). In his design, he put lace as stripe-like openings on various positions of the garment such as the front, back panel, sleeves and trousers. For the suit, the lace was not only put on the shell fabric but also on the lining layer. Lace, in this case, could release the body heat and moisture vapour away because of the porous structure of this fabrication.

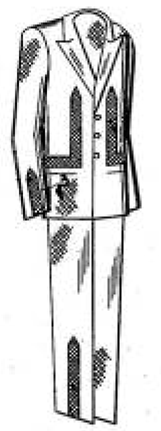


Figure 3.3 - Ventilated clothing. Source: Zelano 1944

Rudman (1998, 2005) developed a ventilated garment system which involved the concept of the air circulation (see Figure 3.4). In this design, he tried to put the vents at the top of the shoulders, two side seams and back. His design concept was to allow ambient air pass into the body skin surface from the mesh panels at the side seams, then convectively moved upward and released out through the mesh panels at the shoulders. This ventilation could help to carry the body heat and moisture vapour out of the microclimate next to body surface. The vents could be fastened using concealed zippers.

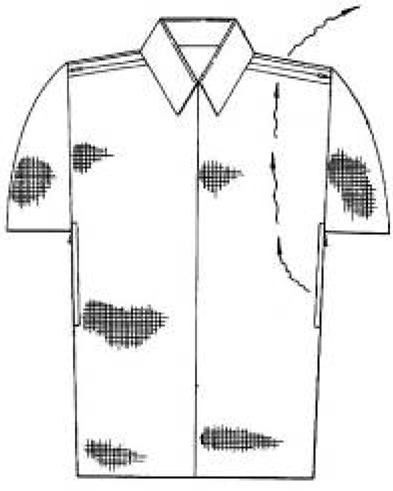


Figure 3.4 - Convectively ventilated garments having protective shield layers.

Source: Rudman 1998 and 2005

Apart from putting flat mesh or other vents on the garment, some designers also invented some three dimensional vents attached on the garment for improving the body ventilation. For example Foster (1988) invented an aperture which looked like a normal pocket with the flap covered (see Figure 3.5). The flap was designed with mesh fabric inserted underneath on the body. In normal cases, this flap was secured to the outer garment just like a regular pocket-closing position. If the wearer needs to have more air ventilation within the garment, he could put the flap in an arched position and fixed by the velcro fastener. The arched shape provided a tunnel over the mesh and the air could come in through the mesh covered by this channel. Sleesen (1988) put a scoop-like airflow design on the jacket which was worn for motor cycling (see Figure 3.6). The inventor put this three dimensional scoop on the shoulders. When the wearer bent down to control the motorcycle, the air could enter from the scoop located at the shoulders, and thus take the body heat and moisture vapour out of the back hem of the jacket.

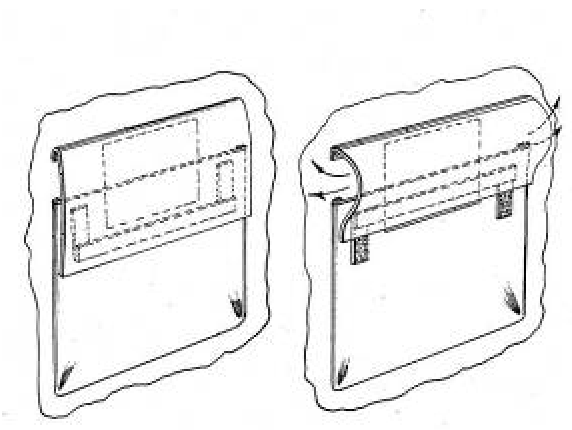


Figure 3.5 - Garment ventilation apertures with cover flap. Source: Foster 1988

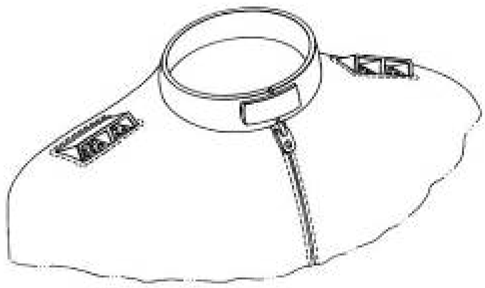


Figure 3.6 - Garment with structural vent. Source: Sleesen 1998

Ruckman *et al* (1998) conducted an investigation on the effectiveness of zip openings (underarm sleeve opening; side seam opening; and both underarm sleeve and side opening; and without opening) of two jackets with a waterproof breathable fabric and a waterproof non-breathable fabric (polyurethane coated). The test was conducted on six subjects walking in a chamber. The authors found that the design of the pit zip openings could contribute to heat loss during exercise period, irrespective of the use of breathable materials.

The location of openings or vents in the garment may be optimized. Ho *et al* (2008) investigated the effect of the location of openings on a T-shirt on the heat and moisture transfer from the wearer. The test was conducted by using a movable thermal manikin-Walter (Fan and Chen 2002, Fan and Qian 2004) in the still air condition, while the manikin was in the standing position and walking motion. The results showed that openings or mesh panels located at the two vertical side panels along the side seams provided the best ventilation effect to the wearer. This is because the air gap between the fabric layer and the body is the largest at two sides of the body trunk. The action of moving arms stretched the side seams of the T-shirt, leading to the fabric layer near to the side seams moving accordingly. Such action strengthened the pumping effect so that the body heat and moisture could be more effectively released through the openings or mesh panels located at the two vertical side panels along the side seams.

Like garment fit, the effects of openings or vented design in the garment may be influenced by the extent of movement of the wearer.

3.3.2.3 Garment design to increase the air circulation between the skin surface and the garment

Garments are normally hung from the shoulders. Due to the natural drape of the fabric and gravity, the garment tends to touch the skin at the chest and the upper part of the back. When doing exercises, the fabrics at these areas may stick to the skin once the wearer sweats. Some advanced materials can absorb or wick away the sweat very quickly, however it does not change the fact that the close contact between the garment and the body at the chest and the upper part of back may block the air ventilation of the body.

To improve air circulation at the body surface, garments are designed to keep a distance from the skin surface. Bengtsson et al (1980) invented a garment for vigorous physical activities in warm environments (see Figure 3.7). The garment comprised of cords and a comparatively open warp knit fabric at the inner surface of the garment. The inventor placed the cords vertically and bound them with the base knit fabric to create a series of plies of vertical air channels. Due to the stiffness and the thickness of the cords, it could increase air movement in those air channels closely adjacent the skin.

Figure 3.7 - Garment for use in vigorous physical activities. Source: Bengtsson, 1980

Moretti (2002) invented a garment in which spacer objects were put under the shoulder areas in order to keep the fabric layer of the garment away from the shoulders. On the construction of the garment, a pair of vents formed by mesh fabrics were created at the top of the shoulder area. This design could create a bigger air space between the garment and the shoulders while the opening of the vented details could help to release accumulated warm air from the shoulders. He applied this design concept into outer garments such as coats and jackets.

Research carried out by Kunz *et al* (2005) tested the effect of heat comfort of a 3D hollow woven structure fabric as a means to improving ventilation underneath ballistic body armour. Although the results found that inserting such woven fabric between the body armour and skin could not alter heat exchange significantly, it suggested that a bigger gap should be formed between a looser-fit ballistic vest and the skin, and ventilation and pumping effect could reduce skin temperature during exercise period.

3.3.2.4 Effect of Colour

Normally darker colours absorb more light rays and add to the radiant heat gain, while lighter colours reflect heat rays (McArdle *et al* 2001). In the outdoors, the influence of light and dark colour results in large differences. Colour effects the emission and absorption of short wavelength radiation (like sunlight, UV), and darker colours absorb more than light colours (Laing *et al* 2002). Clack *et al* (1978) found similar results with black clothing having higher absorption of short wavelength radiation than white clothing (780 Wm-2 and 190 Wm-2 respectively).

3.3.3 Wearable devices approaches

- Air cooling system

During hot weather, people used electric fans to keep the body cool before the invention of air conditioning. The fan system has been adopted in the garment system for specific occasions. Normally these fans are light weight and small enough to be installed on the garment (Walkins 1984). Apart from using fans, some of the air cooling garments use compressors to pump pre-chilled air into a bladder, and then force the air to circulate around the body through tubes, or other engineered openings in the system (Laing *et al* 2002). Figure 3.8 shows an example of the garment using air cooling method to provide ventilation to the body.

Figure 3.8 - Jackets with two fans to ventilate the body. Source: Ming Pao Daily News, Hong Kong (25-7-2004)

- Liquid cooling system

Liquid cooling system requires a fluid reservoir, a circulating pump and connecting hoses which is attached to the garments. The cooled liquid is circulated through the garment and then returned to the reservoir for re-chilling. This circulated mechanism provides lower temperature to the wearer (Laing *et al* 2002 and Walkins 1984). One of the examples of this application is the Liquid Cooling and Ventilation Garment (or LCVG) which is worn by astronauts of NASA (Figure 3.9). The space environment is a vacuum and thus heat cannot be lost through heat conduction. In order to maintain a comfortable core body temperature during extra-vehicular activity, a network of flexible tubes circulates cool water in direct contact with the astronaut's skin.

Figure 3.9 - An astronaut wearing a liquid cooling and ventilation garment. Source: http://www.nasa.gov

<u>- Ice or cold pack system</u>

This system uses ice or a gelled coolant to keep the body part warm. However, the duration of this cooling system is shorter than the air or liquid water-cooled garments, and the ice packs or gelled coolant need longer cooling time for replenishment (Laing *et al* 2002).

Wearing cooling garments during exercise is not practical and also not possible in a formal competition. Normally these kind of garments can only be worn prior to competition and during rest periods, and the mobility of the wearer is also restricted by the equipments (Laing *et al* 2002). Since sports requires different movements, such bulky electronics and extra equipments would be inconvenient to wear.

Most of the above research has concentrated on functional outerwear, protective garments, occasional wear or fabric itself, and limited investigation has been conducted on sport T-shirts. Interesting ideas have been generated such as effect of openings, garment fit and 3D structure fabrics in design concept of functional sport clothing. However, there is a big difference between T-shirts and outerwear, and thus further research should be conducted solely on sport T-shirts as it is one of the most common items of daily life.

3.4 Development trends of functional sportswear by leading sportswear brands

With the application of high-tech materials and design innovation, sport clothing has become high-performance gear rather than just a garment. For athletes, a functional garment is critical as it may affect their physical performance, but for many non-athletes, functional sport clothing has become a fashion statement.

Discomfort is experienced when sweat sticks the skin and the fabric together. Thus different technologies have been invented to circumvent this problem. The amount and rate of sweat production varies by different environments, types of exercises, and body conditions. The primary way of cooling the body temperature is through evaporation of sweat from the skin surface (Walkins 1984). In these conditions, clothing can act as a barrier to thermal insulation, if the design and the fabric cannot help to wick or evaporate sweat away from the skin. To solve this problem, high-wicking or moisture management fabrics have been developed. These two technologies help to keep the skin surface dry by taking away sweat to the ambient environment. Various worldwide brands have developed such technology and applied it to clothing. For example, coolmax® is a well-known performance material that is applied in various active wear. Coolmax®, now a registered trademark of INVISTA for certified performance fabrics, actively moves sweat away from the body to the fabric's outer surface, where it can evaporate quickly. This thermoregulatory effect helps the wearer to stay drier and more comfortable, especially when they are exercising and sweating (http://coolmax.invista.com/active.html).

- Example I: Nike

Nike, Inc. was founded in 1972 and is now recognized as one the world's leading companies selling athletic shoes, apparel and sport equipments. Apart from selling products, this company has also been involved in R&D of new technology.

From the 1990s, Nike focused on combining new fabric technology and design systems. In 1997, "Project Swift" was launched to evaluate the athletic performance by a series of research and product developments (Bradley 2002). This research project was an important event in Nike's history because it helped build up the professional image of the brand.

As moving sweat away from the skin is a primary element to keeping the body cool and comfortable, Nike also invented a high tech fabric called "DRI-Fit". This new technology pulls perspiration away from the skin and spreads the moisture over a wide surface area for quicker evaporation. The fabric was not only widely used for leisure wear such as T-shirts and pants, but also for the authorized team jerseys of professional sport teams of the NBA (National Basketball Association, USA) and FIFA (Fédération Internationale de Football Association or International Federation of Association Football).

In 2002, Nike Inc. invented a new technology called "Cool Motion" and applied it for the 2002 World Cup kit. The concept of this technology was to use a two-layer structure design to enhance thermal comfort by improving the ventilation of the air between the body and the clothing. The inner layer of the uniform was a Dri-FIT fabric, while the outer layer of the uniform was hydrophobic which kept the skin dry even in high humidity environments. Some ventilation panels were designed in the outer layer in order to keep air flowing across the skin (Williamson *et al* 2002 and Bradley 2002).

Apart from Dri-FIT and Cool-Motion, Nike also invented new materials and labelled them as "Nike Sphere React Dry" and "Nike Sphere React Cool" in the year 2002. When the wearer sweats, the material transforms its shape from flat fabric into a three-dimensional structure that reduces the amount of sweat clinging to the body. This reaction allows more airflow across the skin so as to aid in evaporative action. After the sweat has evaporated, the fabric returns to the original flat shape. This new material is mainly used for the shoulders, upper arms and back to reduce the amount of sweat clinging to the body.

With a similar theory, Nike Sphere React Cool increases airflow between the skin and fabric layer. The holes on the material expand when the wearer is sweating, thus allowing more air to circulate over the sweat on the skin ("http://www.funkygrad.com/lifestyle/displayartical.php?artID=wear" and "http:// www.textileinfo.com/en/plan/teijin/index.html"). This change aids in lowering the temperature and the degree of humidity inside the garment.

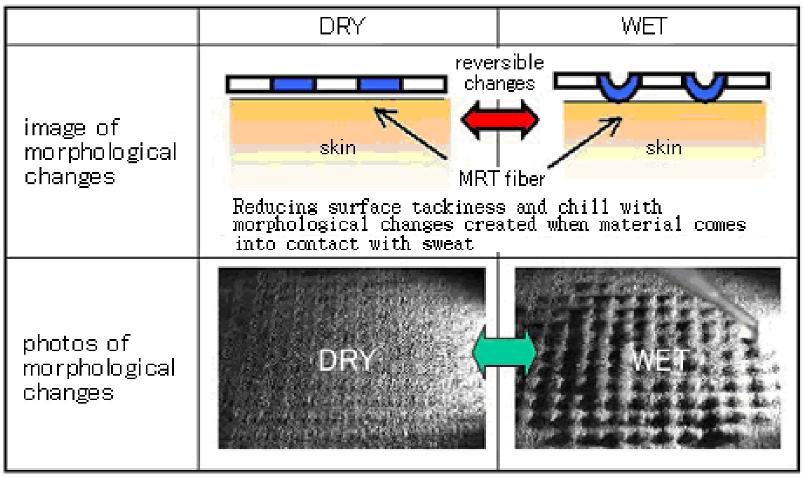


Figure 3.10 – Nike Sphere React Dry

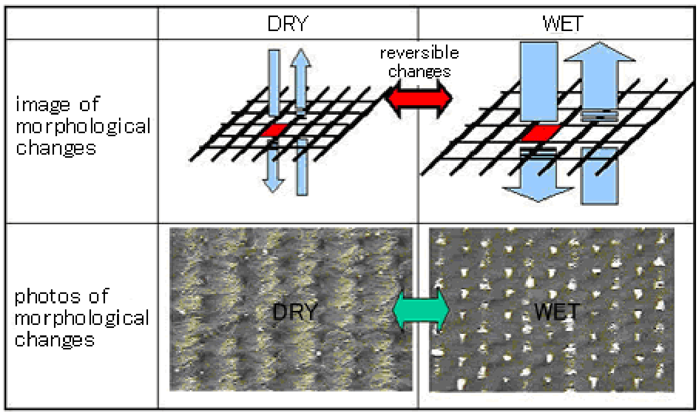


Figure 3.11 – Nike Sphere React Cool

Figure 3.10 and 3.11 – The mechanism of Nike Sphere React Dry and Nike Sphere React Cool allow the airflow over the skin surface. Photos and illustrations from www.textileinfo.com (http://www.textileinfo.com/en/plan/teijin/index.html)

Since 2002, Nike has continuously developed various designs for professional athletics. In 2004, Nike launched a series of new designs, namely "Total 90ZD" (Figure 3.12). Apart from the original ideas of Dri-FIT fabric and ventilation panels to regulate body heat through movement, this design also applies light-weight fabric and new stitch-less method to enhance comfort. Apart from football, Dri-FIT fabrics are widely used in other sportswear lines and even casual wear.

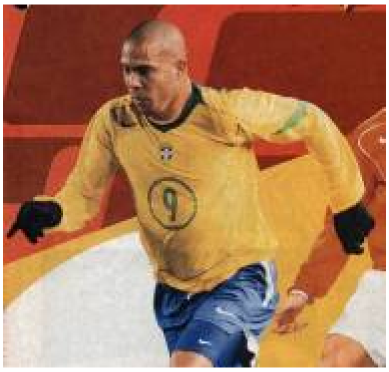


Figure 3.12 - Total 90ZD sport clothing by Nike Inc. Source: Apple Daily News Hong Kong, 18-3-2004

- Example II: Adidas

Adidas was founded in 1949 by Adi Dassler. The company's clothing and shoe designs typically feature three parallel stripes, and this motif is incorporated into the Adidas signature. In a similar way to Nike, Adidas is also involved in development of new technology in sport shoes, apparel and sports gear.

Adidas has diversified its product line into "Sport Heritage" and "Sport Performance". According to the official website of Adidas, "Sport Performance" focuses on providing functional and innovative products in various sport categories (www.adidas.com). ClimaCool® was one of the technologies invented by Adidas (Figure 3.13). The concept of this technology is to help release heat and sweat away from the body through a combination of heat and moisture-dissipating fabrics, ventilation channels and 3D fabrics, allowing air to circulate in the space between the skin and garment. Under this integrated system of technology, Body Flow Mapping has been studied to understand how air flows across the body by placing ventilation channels on different parts of the garments (Tozer 2004). Adidas widely applies this technology to athletic shirts, trousers, and casual wear products.

Figure 3.13 - ClimaCool Design by Adidas, (05 Football: product catalogue of Adidas. 2005)

3.5 Current trend of sportswear fashion

Sport clothing trends are evolving in dual-directions. Achieving functional objectives by using high-performance fabrics or technology through a wide range of research and development is not the sole trend in today's sport clothing. The other key trend is to merge sport clothing and high fashion together. Sport clothing is not only the dominant style of clothing and footwear manufactured and marketed but also an important segment of fashion design. This kind of "sport couture" has played the role of connecting functional sportswear and daily wear high fashion (Craik 2005). Many fashion designers create "de luxe sportswear" collections by using different advanced materials and offering functional features (O'Mahony *et al* 2002).

Various global fashion brands have developed their division lines with the concept of "sport", for example Polo Sport, Armani Sport, Prada Sport, Hugo (Hugo Boss) Sport. These are good examples showing that sport trend is a major development of global fashion brands. They not only take sport as product style, but also as source of expertise in the development of sport fashion (Shishoo 2005).

Among the international fashion brands, Prada is one of the high-end fashion brands that has created fashionable sport clothing. Miuccia Prada, the chief designer of Prada, launched Prada Sport as a division line in 1992. The red little stripe with the brand name became a well known label for fashion conscious people (Figure 3.14). By using different techno textiles, Prada Sport created performance garments with trendy aesthetic effects (Bradley 2002). In comparison, some other fashion brands just use sports as inspiration for design rather than entering functionality into the design concept.

Figure 3.13 - Prada Sport S/S 2002 collection (Prada's catalogue S/S 2002)

After 2000, Adidas tried to work with different international fashion designers to create division lines in the market. Yohji Yamamoto, a famous Paris based Japanese designer, was the first international designer to collaborate with Adidas. In 2003, Y-3, a cross-over brand was launched by Adidas and Yamamoto. The brand Y represents Yamamoto while the 3 is the classic symbol (3-stripes) of Adidas. In this collection, Yamamoto tried to input the 3-strips typical Adidas signature into his “Zen” design (Figure 3.15).

Figure 3.15 - Y-3 menswear collection S/S 2008 (www.men.style.com)

Apart from Yohji Yamamoto, Adidas has continuously cooperated with British designer Stella McCartney since 2004. After about 2 years of development, a new product line was launched in A/W 2005 (Figure 3.16). According to the official website of Adidas, this collection was aimed at creating a high-end athletic wear with a credible focus on sport performance (www.adidas.com). The product categories of this new division line included tennis, running, gym and swim. Apart from the style-conscious approach, this collection also adapted sweat wicking technology for its high performance function.

Figure 3.16 - Adidas by Stella McCartney (www.adidas.com)

3.6 Conclusions

Consumers not only need functionality in the garment, but also prefer to “look good” and “trendy”. Although wearing a garment made of a thin mesh fabric with big pores may be a good way of releasing heat and moisture, it is not feasible from the aesthetic point of view. To strike a balance between aesthetics and function, the present study is aimed at creating fashionable design with scientific evidence.

Chapter 4

Design brief

4.1 Regional difference of temperature and sweating of human body

The rate of sweating varies from one location of the body to another. When increasing exercise intensity, the degree of increase in sweat rate in different body locations varies (Kondo 1998 and Buono 2000). Regional sweating differences of various body parts like chest, back, forearm, thigh and calf have been investigated by many researchers. Like sweating, body temperature also varies in different body parts.

The last chapter mentioned the importance of ventilation panels or openings on the garment for heat transfer from the skin surface to the outside environment. As a 3D body, the contact area of the skin and the fabric layers is different in different locations, which causes variation of air space between the skin and fabric layers. Ueda *et al* (2006) carried out research to investigate the influence of clothing ventilation on the humidity of clothing microclimates in the chest, back, and upper arm areas. Their data reflected that clothing microclimate volumes affected ventilation, and the thickness of air layers influenced air currents in clothing microclimates, thus causing regional differences in clothing ventilation. Their results showed that the air permeability of fabric was not the dominant factor contributing to heat transfer from the wearer, but instead the effectiveness of clothing ventilation of various body regions was more significant.

4.2 Style

A range of short-sleeved T-shirts will be designed and produced for experiment. The reasons and details have been discussed in chapter one.

4.3 Air ventilation and pumping effect

As discussed in the previous chapter, wind is an important factor which modifies the thermal insulation value and also the warmth of the clothing fabric (Zhang 2002). Research has shown that wind can quickly carry away the warm air within the clothing micro-climate and also evaporate liquid sweat and dissipate warm vapour (Watkins 1984). Ventilation details of the garment can force the air exchange process. In order to maximize the pumping effect, these ventilation details can be strategically placed on garments by designers. Through creativity, different details can be applied in order to increase pumping effect. Putting zips is a good example for achieving this aim. Thus the challenge faced by designers is creating new design details to increase pumping effect, and how to apply them to garments. For this kind of functional wear, the position and the application of ventilation panels is the key design detail, and thus clothing ventilation should be measured in different body regions (Ueda *et al* 2006). For a basic sport T-shirt, zipper openings may not be appropriate because of the heavy weight of the zip and also as it may cause friction against skin when it is opened. In this case mesh fabric is preferable as the initial media to act as a ventilation panel. Other effective ventilation details will be designed in this study.

4.4 Fit

As discussed in the previous chapter, garment fit also contributes to the change of thermal insulation and evaporative resistance. Furthermore, limited research has been conducted for pure cotton sport T-shirt under a systematic approach such as keeping the same materials and size for all garment samples. Hence further experiments need to be carried out to investigate the knowledge of this field.

4.5 Fabric use

Due to limited resources, high-tech and functional fabric such as fast sweat-wicking and phase change materials will not be used in the early stages of development. In order to standardize the testing, 100% cotton jerseys will be used as basic material, and polyester mesh fabric will be used only for essential functions. Thus the outcome of the study will be focused on the “engineering design” of the garment instead of utilizing any special smart fabric to achieve the aims. However, the best performance of thermal comfort can be achieved if an effective engineering design co-operates with smart textiles such as moisture management or high-wicking fabrics.

Chapter 5

Effects of opening designs in T-shirts on thermal comfort

5.1 Introduction

To enhance the thermal comfort of functional clothing, ventilation features have been widely applied to a clothing system (Ruckman et al 1998). For example, the use of mesh fabrics are nowadays very common in sportswear, because the open construction of the mesh fabric is believed to be highly beneficial for releasing heat and moisture away from the body. However, exactly how effective the ventilative features are and how the locations of openings affect heat and moisture transfer from the human body to the environment have not been systematically investigated and are not well understood.

In this chapter, a range of plain jersey T-shirts having varying opening designs were therefore produced and tested on the sweating fabric manikin-Walter so as to investigate the effects of the type and positions of openings on the thermal comfort properties of the T-shirts.

5.2 Method

5.2.1 T-shirt samples of different designs

Two categories of T-shirts, “Mesh style” (6 pieces) and “Opening style” (3 pieces), were designed and produced for evaluation. An additional basic T-shirt (without any mesh or opening design) was also made as a control sample. The size of all T-shirts was kept the same. In order to standardize the designs for comparison, the area of mesh fabric or opening for each garment sample (except the control garment) was kept the same at 310 cm^2 in total. Apart from the panels made of the mesh fabric, other parts of the garments were made of typical 100% cotton, fine gauge single jersey fabric (153g/m^2). The mesh fabric was made of 100% polyester and the weight was 66.3g/m^2. The size of holes per cm^2 of the mesh fabric was approximately 0.38cm^2 (See figure 5.1). For the opening style, a certain area of the T-shirt was cut off and an empty rectangle was created. To avoid excessive distortion of the empty rectangle due to fabric draping and gravity, thin polyester tapes (0.6 cm width) were attached to hold the shape (See the photos of the samples). Besides, as the head of the manikin-“Walter” was connected with wires and water pipes, all T-shirts were put on using an open-ended nylon zipper either at the front or back without affecting the placement of mesh fabric or opening. The photos and specifications for these T-shirts are shown in Table 5.1.

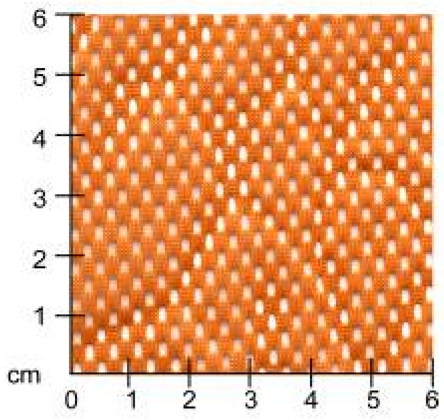


Figure 5.1 – Structure of the mesh fabric

Code of T-shirts	Photo	Weight (g)	Description
F-STD		137.2	Control piece. A basic T-shirt without mesh fabric or opening design
M-CFH		136.1	Mesh style. Mesh area was placed across the front chest horizontally.
M-CFV		138	Mesh style. Mesh area was placed at the centre front.
M-CBH		137.8	Mesh style. Mesh area was placed across the back horizontally.

M-CBV		139.2	Mesh style. Mesh area was placed at the centre back.
M-SS		138.7	Mesh style. Two vertical side mesh panels were placed along the side seams. The total area of mesh was 310cm² (equally 155 cm² x 2)
M-U		137.4	Mesh style. Mesh areas were placed at the armhole area. The total area of mesh was 310cm² (equally 155 cm² x 2)
O-CF		139.1	Opening style. Opening was placed across the front chest.
O-CB		137.5	Opening style. Opening was placed across the back.
O-SS		133.8	Opening style. Openings were placed on both sides. The total area of mesh was 310cm² (equally 155 cm² x 2)

Table 5.1 - Details of T-shirts design in experiments

5.2.2 Measurement method

In order to study the relationship between different T-shirts designs and their thermal comfort properties, "Walter" was used for testing. The experiment was conducted in a climatic chamber of 20.0 ± 0.5º C and 65.0 ± 2% RH with an air velocity of 0.5 ± 0.3 m/s. The core temperature of the manikin was set as 37º C. In order to simulate the real situation of daily life, tests were conducted for all garments under both "standing" posture and "walking" motion. In the simulated "walking" mode, the arms and legs of the manikin were pushed and pulled with an equivalent walking speed of 1.04 km/hour. For all the tests of varying T-shirt samples, the same pair of short trousers (made of 100% cotton) was put on the manikin. Each T-shirt was tested for three times and a mean value out of the three tests was taken. In order to avoid the presence of dust and oil that would possibly affect the testing results, the T-shirts were washed once before testing. As discussed in previous chapter, clothing thermal insulation (R_t) and moisture vapour resistance (R_{et}) were calculated to evaluate the level of thermal comfort affected by different T-shirt designs.

5.3 Results and Discussion

5.3.1 Total thermal insulation in "walking" mode and "standing" mode

The experimental results are listed in Table 5.2 and plotted in Figure 5.2 and 5.3. The coefficients of variation of repeated tests are generally less than 5.0%. The T-shirts with lower R_t values are preferred because it indicates that they have higher ability to release body heat through the garment. In "standing" mode, all T-shirts recorded lower R_t value than the control piece (F-STD) except the style M-U which did not show any significant difference from the control piece. In the category of "opening" style, O-CB, O-CF, and O-SS were found to have 2.1% ($t(4) = 1.107$, $p = 0.33$), 3.4% ($t(4) = 1.936$, $p = 0.125$) and 4.1% ($t(4) = 5.601$, $p = 0.045$) lower thermal insulation than the control piece (F-STD), respectively. Only O-SS was significant difference. For the mesh style, M-SS was measured to have the lowest thermal insulation among all the "mesh" style designs. It was 3.4% lower than that of the control piece, however the t-test showed that there were no significant difference ($t(4) = 2.402$, $p = 0.074$). It was the same value as the O-CF style. Apart from M-SS, M-CFH had 2.1% lower thermal insulation than the control piece and other designs, however, had less than 2.0% reduction in total thermal insulation.

T-shirts code		Walking mode Mean	Walking mode SD	Standing mode Mean	Standing mode SD
F-STD	R_t	0.14	0.003	0.146	0.002
	R_{et}	16.379	0.341	19.34	0.284
M-CFH	R_t	0.153	0.003	0.143	0.002
	R_{et}	15.094	0.587	18.079	0.36
M-CFV	R_t	0.141	0.005	0.145	0.004
	R_{et}	15.771	0.45	19.022	0.402
M-CBH	R_t	0.147	0.006	0.145	0.004
	R_{et}	15.655	0.546	18.866	0.316
M-CBV	R_t	0.151	0.006	0.144	0.004
	R_{et}	16.293	0.419	19.12	0.314
M-SS	R_t	0.13	0.004	0.141	0.003
	R_{et}	15.848	0.207	18.492	0.241
M-U	R_t	0.137	0.005	0.146	0.004
	R_{et}	15.527	0.405	18.458	0.26
O-CF	R_t	0.133	0.003	0.141	0.004
	R_{et}	15.834	0.199	18.157	0.364
O-CB	R_t	0.13	0.003	0.143	0.003
	R_{et}	15.716	0.237	18.565	0.284
O-SS	R_t	0.123	0.005	0.14	0.003
	R_{et}	15.478	0.388	17.91	0.339

Table 5.2 - Clothing thermal insulation and moisture vapor resistance of different T-shirts

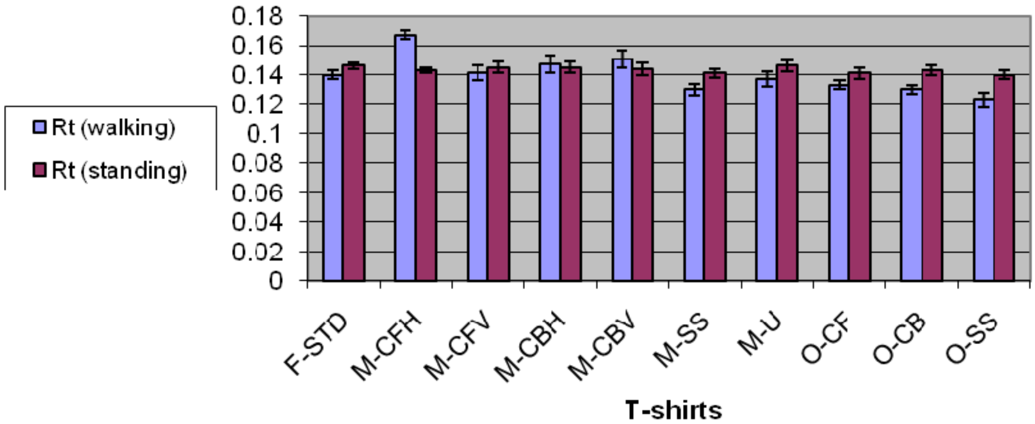


Figure 5.2 – Clothing thermal insulation of different T-shirts under "walking" mode and "standing" mode

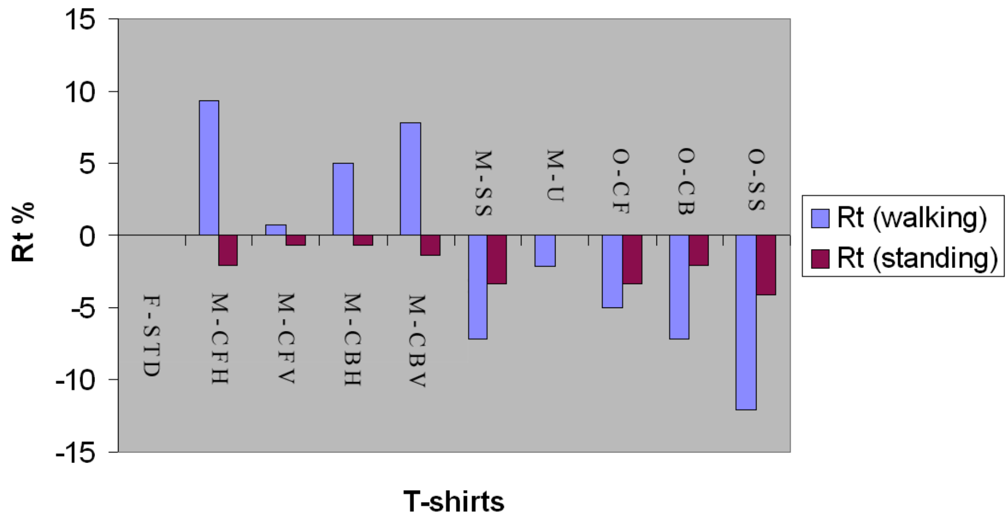


Figure 5.3 –Differences between the T-shirts samples and the control piece in terms of clothing thermal insulation under "walking" mode and "standing" mode.

In "walking" mode, O-SS had much lower R_t value than the control piece, with a reduction of 12.1% (t (4) = 5.05, p = 0.007). For comparison, the thermal insulation of M-SS and O-CB were both 7.1% (M-SS: t (4) = 3.464, p = 0.026; O-CB: t (4) = 4.082, p = 0.015) lower than that of the control piece, and that of O-CF was about 5.0% (t (4) = 8.165, p = 0.001). However, other mesh styles (M-CFV, M-CBH, M-CBV, M-CFH) were found to have a higher R_t value than the control piece. It means that placing mesh fabrics at the centre back or centre front either vertically or horizontally did not help to release more dry heat under the "walking" mode. This is surprising, and perhaps is because the presence of mesh fabrics at these locations did not increase "pumping" effect as the mesh fabrics tended to lay on the manikin's skin surface due to garment draping.

From the measurements under "standing" and "walking" mode, it becomes clear that O-SS was the best one in releasing dry heat from the body, and the "pumping" effect in O-SS was also the most effective. By observation, this can be understood as the manikin's arms were moving forward and backward when simulating "walking", air movement between the arms and body sides were created, and this could also increase the air exchange from the side openings or small holes of the mesh fabric to the ambient environment. This principle is also supported by the fact that the M-U style was measured to have lower R_t value than the control piece under the "walking" mode (about 2.1% reduction), but the reduction was not present under the "standing" mode (It was measured to have the same value as the control piece). In general, the opening styles had higher ability in releasing dry heat from the body.

5.3.2 Moisture vapour resistance

The experimental results are listed in Table 5.2 and plotted in Figure 5.4 and 5.5. Under both "walking" and "standing" mode, all T-shirts were measured to have a lower R_{et} value than the F-STD. In general, mesh fabric or openings applied in the T-shirts could help to transfer the moisture out into the environment. By comparing the R_{et} value under "walking" and "standing" modes, M-CFH and O-SS had more than a 5% (M-CFH: standing: $t(4) = 4.763$, $p = 0.009$; walking: $t(4) = 3.279$, $p = 0.031$) (O-SS: standing: $t(4) = 5.601$, $p = 0.005$; walking: $t(4) = 3.021$, $p = 0.039$) reduction in comparison with the F-STD, they were significantly difference. M-U style also achieved an over 5% reduction under "walking" mode and almost a 5% ($t(4) = 2.787$, $p = 0.049$) reduction in "standing" mode ($t(4) = 3.488$, $p = 0.025$). Comparatively, M-CBV was not so effective in improving moisture transmission with only 0.5% and 1.1% reduction of total moisture vapour resistance under "standing" and "walking" mode respectively.

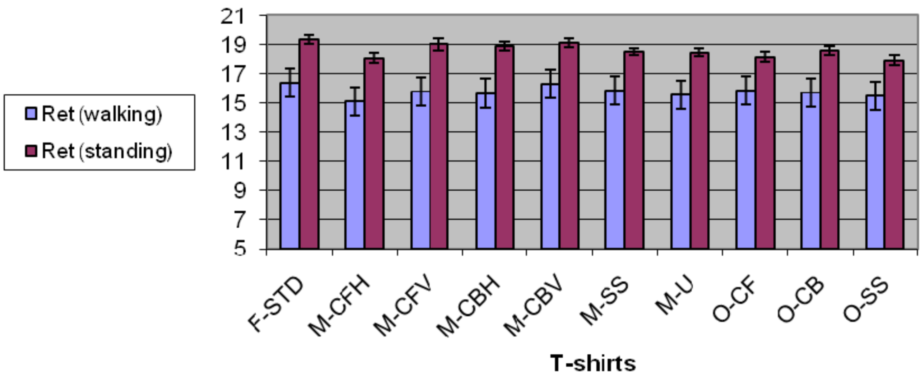


Figure 5.4 – Total moisture vapour resistance of different T-shirts under "walking" mode and "standing" mode

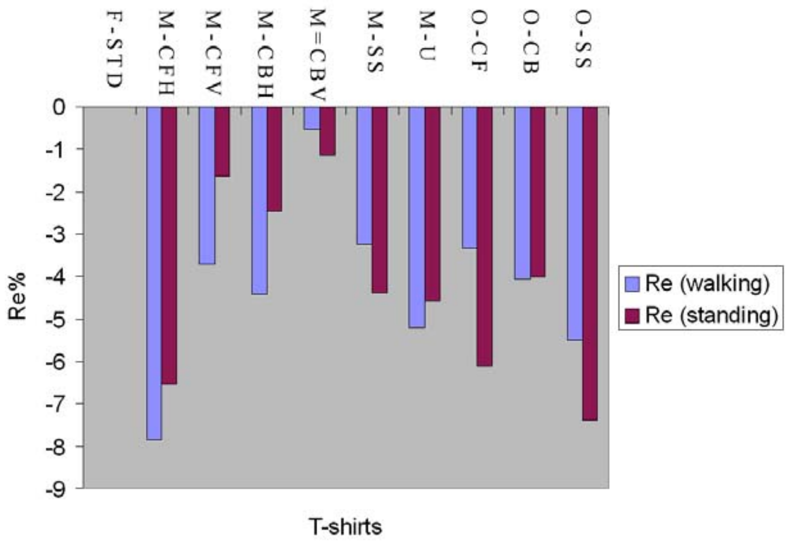


Figure 5.5 - Differences between the T-shirts samples and the control piece in terms of total moisture vapour resistance under “walking” mode and “standing” mode.

5.3.3 General performance of opening style and mesh style

When the similar styles of opening designs and mesh designs (i.e., O-SS versus M-SS, O-CF versus M-CF, and O-CB versus M-CB) were put into a direct comparison, the results indicated that the “opening” styles were better than the “mesh” styles in terms of releasing body heat to the environment. Since the T-shirts for experiments were in a normal fit, there is space between the T-shirts and the skin surface in certain parts of the body. As illustrated by Figure 5.6, when a T-shirt was worn by the manikin properly, the air gap between the fabric layer and the body is the largest in both sides. If the air stayed still, the air gap would contribute towards thermal insulation and moisture vapor resistance so as to make the wearer felt warmer and wetter. However, the air in the air gap tends to move even under “standing” mode because of natural convection. The air movement increases under “walking” mode, which helps to release the warm and wet air out. This is the reason why the opening or mesh applied at two vertical side panels along the side seams were among the best in cooling. The study clearly showed that body movement contributed to the air exchange between the microclimate around the body and the ambient environment. For sportswear, ventilation panels placed near the two sides of body trunk is ideal for cooling, provided the air outside the body was relatively cool and dry.

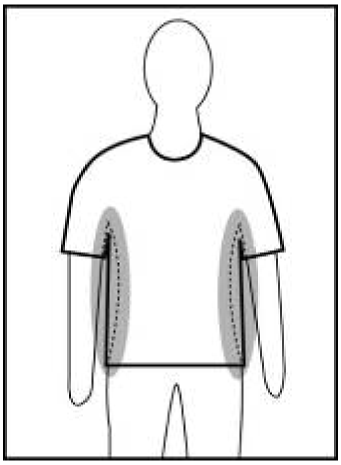


Figure 5.6 – Air gap was formed in areas along the side seams

5.4 Conclusions

From this research it is shown that the clothing design can contribute to the thermal comfort, and that the provision of ventilation at appropriate positions in the T-shirts could be the key factor. In terms of overall performance, the design of putting openings at the two vertical side panels along the side seams of T-shirt was found to be ideal for ventilative cooling and thermal comfort.

Chapter 6

The effect of added fullness and ventilation holes in T-shirt design on thermal comfort

6.1 Introduction

Garment fit is considered as one of the most important elements that influence thermal comfort (Fan 1989). Many researchers have studied this factor. McCullough *et al* (1983) compared the thermal insulation value of tight-fitting and loose-fitting long trousers and found that loose-fitting trousers had higher insulation than tight fitting trousers when standing still and under no wind condition. They, however, stated that, during body motion or under windy conditions, movement could result in air circulation inside the trousers and thus greater increase of convective heat transfer in the loose-fitting trousers than that in tight-fitting ones.

Havenith *et al* (1990) conducted research on the effect of garment fit on clothing insulation. Testing of three clothing ensembles on four male subjects (two wearing loose-fitting and two tight-fitting clothing) while sitting and walking, and under three wind speed conditions (air speed: <0.1, 0.7 and 4.1m/s), showed that tight-fitting clothing had 6-31% lower insulation than loose-fitting one. Moreover, the difference was greater during sitting, but reduced when wind was present.

Chen *et al* (2004) investigated the effect of garment fit on thermal insulation and evaporative resistance by using a perspiring fabric manikin (Walter). Three types of jackets (woven poplin, woven denim and knitted fabric) were made in various sizes (five for each style) and tested under no wind and a windy condition (air velocity = 2.0±0.5 m/s). The results showed that under no wind condition, thermal insulation increased with the thickness of the air gap when the air gap was small. The rate of increase slowed down once the air gap was larger. Once the air gap exceeded 1 cm, the thermal insulation decreased with further increase in the air gap. This was because an increased air gap provided more space for natural convection. A similar trend was found under windy conditions, except that the thermal insulation values were smaller and reached a maximum when the air gap was about 0.6cm. Tight-fitting garments provided better performance in retaining warmth under windy conditions.

From the above mentioned investigations, it can be learned that a larger air gap between the garment and the body skin surface can result in a reduction in thermal insulation and moisture vapour resistance, when the wearer is in motion or under windy conditions. Greater air gap between the garment and body surface can therefore promote thermal comfort by enhanced convective heat loss to compensate the increased body heat generation by body motion. One can increase the air gap by wearing more loose-fitting garments, however with conventional sizing method, larger sizes will only increase the air gap at the side of the body and no air gap is added at the chest and back area where ventilation is most required, as garments hang on the shoulder and are normally in touch with the chest and back of the body. This makes wearing loose-fitting garments less efficient in ventilative cooling. In order to add air gap at the chest and back area and to improve ventilative cooling, this present study experimented special T-shirt designs with added fullness and ventilation holes, and investigated their effectiveness in terms of thermal insulation and moisture vapour resistance using the sweating fabric manikin-Walter.

6.2 Garment samples

All T-shirt samples are made of the same 100% cotton plain single jersey fabric of 153g/m^2 in weight. T-shirts in a conventional pattern design and a special pattern design with added fullness were used to produce in various sizes of T-shirts for comparative tests. “Add fullness” is a cutting technique for adding extra fabric drape and fullness in desired areas, which has been used to make flared skirts and flared sleeves (Bray 1986, Stanley 1995, Armstrong 2000).

For the conventional design, four T-shirts were made in sizes S, M, L, and XL, which was graded in a conventional sizing system to enlarge the armholes and two side seams (See Figure 6.1). As the effect of size was the main focus on this experiment, no alternation was made on the neckline, shoulder width and body length. Air gap was mainly created at the areas near to the side seams only. For the special design with added fullness (See Figure 6.1(B)), the T-shirts were designed to have a larger hemline girth than the chest girth and evenly increased girth from the chest to the hemline by spreading the pattern, while keeping the measurement of neckline unchanged. In doing so, the pattern was divided into two sections as shown in Figure

6.1, the location of the top point at the neckline was remained unchanged, the angle of the neckline curve was altered, but the length of the neckline was the same as that of the conventional design.

With the conventional pattern design, the fullness of the fabric tends to drape and accumulate in the area near the side seams (See the illustration in Figure 6.2(A)). However, with the special design of added fullness, the fullness of the fabric would be accumulated at the front and back of the body. Due to gravity, the fabric is stretched downwards, resulting in a pulled neckline which creates a triangle-like drape in the front and the back (see Figure 6.2(B)). As a result, when the T-shirt with the special design of added fullness is worn, air gaps in the front and back of the body are created.

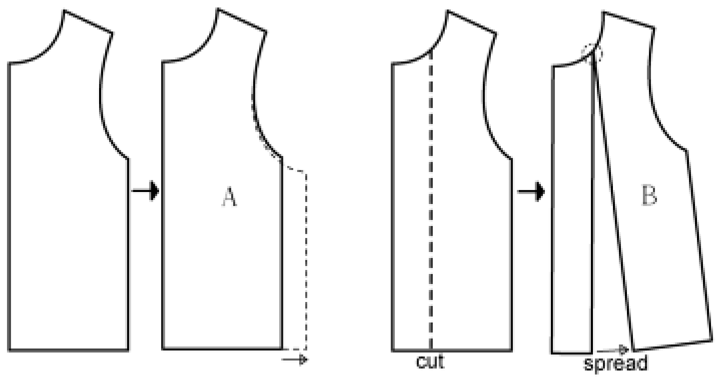


Figure 6.1 – Comparison of conventional pattern design (A) and a special design with added fullness (B).

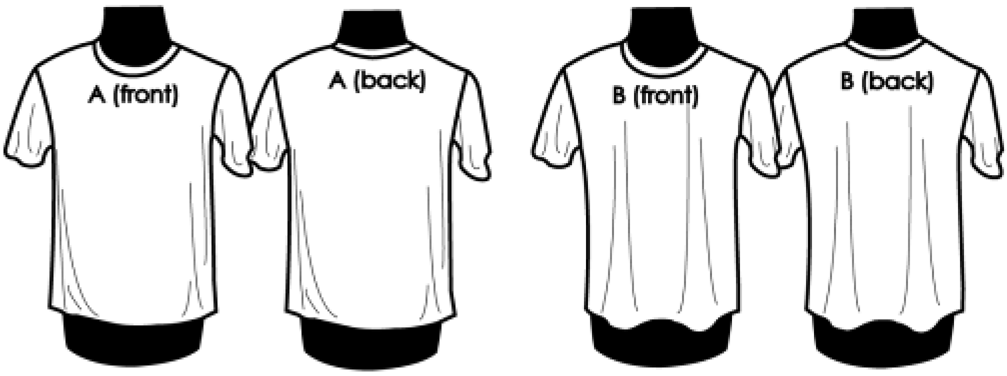


Figure 6.2 – Drape appearance (front and back view) of T-shirts in conventional pattern design (A), in the special pattern of added fullness (B).

Two T-shirts in the special pattern of added fullness (F-1 & F-2) were made. F-1 has no holes in the front and back pieces. T-shirt F-2 was in the same size and pattern design as those of T-shirt F-1, but small holes were cut in the front and the back pieces by a laser beam. The holes were in an oval shape with a horizontal width of 2 cm and vertical length of 1 cm. Totally, there were 36 evenly distributed holes (18 in the front and 18 in the back panel).

The measurements of the T-shirts as defined by Figure 6.3 and 6.4 are listed in Table 6.1. For the T-shirts in the conventional design (S, M, L and XL), an extra 5cm was added to the chest width and hemline, as the size is increased from S to M, from M to L and from L to XL. The T-shirts in the special design with added fullness (F1 & F2) were designed to have the same chest girth as that of the conventional design in L Size and the same hemline girth as that of the conventional design in XL. Figure 6.5

and Figure 6.6 show the photo images of a T-shirt in the special design with added fullness and holes (F-2) and a T-shirt in the conventional design (XL), respectively.

The T-shirts were tested in terms of thermal insulation and moisture vapour resistance by using fabric thermal manikin "Walter". The dimensions of the thermal manikin "Walter" are listed in Table 6.2. As can be seen, the half chest girth of manikin was 47.5cm, the same as that of size S T-shirt in conventional design. Therefore, S size T-shirt was tight fit to the thermal manikin without any size allowance, which made no air space at the chest during testing.

T-shirt measurements (in cm)							
T-shirt	Chest width	Neck width	Hem width	Shoulder width	Body length	Armhole	Sleeve length
	(E-F)	(A-B)	(G-H)	(C-D)	(J-K)	(D-L)	(D-M)
S	47.5	18	47.5	47.5	61	17	17
M	52.5		52.5			19.5	
L	57.5		57.5			22	
XL	62.5		62.5			25	
F-1	57.5		62.5			25	
F-2	57.5		62.5			25	

Table 6.1 – Measurements of the T-shirts (in cm)

Measurement	cm
Height	172
Neck circumference	45
Across shoulders	46
Half chest	47.5
Arm circumference	26.5
Half natural waist	45
Natural waist length	40

Table 6.2 – Measurements of the thermal manikin “Walter” (upper body)

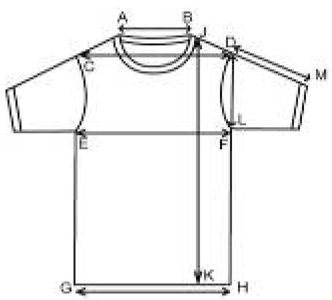


Figure 6.3 – Shape and measurements of T-shirts in conventional design (S, M, L and XL)

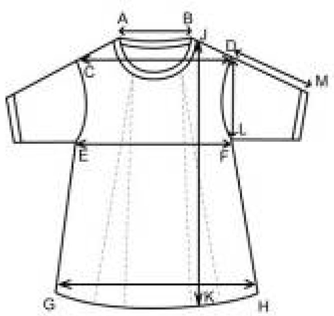


Figure 6.4 – Shape and measurements of T-shirts (F-1 and F-2)

Figure 6.5 – The photo images of the T-shirt in the special design with holes (F-2) (Left: front view; middle: side view; right: back view)

Figure 6.6 – The photo images of the T-shirts in conventional design in XL size (Left: front view; middle: side view; right: back view)

6.3 Testing using the thermal manikin-Walter

The tests were conducted in a climate controlled chamber at the temperature of 20.0 ± 0.5º C and 65.0 ± 2% RH under a no wind condition (air velocity of 0.5 ± 0.3 m/s) and a windy condition (air velocity of 1.5 ± 0.5 m/s). The core temperature of the manikin was set at 37º C. In order to simulate the real life situation, tests were conducted for all garments under both “standing” posture and “walking” motion. In the simulated “walking” mode, the arms and legs of the manikin were pushed and pulled with an equivalent walking speed of 1.04 km/hour. For all the tests of varying T-shirt designs, the same pair of short trousers (made of 100% cotton single jersey) was put on the manikin in order to keep consistency during testing. Each T-shirt was tested for three times and a mean value out of the three tests was taken. In order to avoid the presence of dust and oil that would possibly affect the testing results, the T-shirts were washed once before testing. As discussed in the previous chapter, clothing thermal insulation (R_t) and moisture vapour resistance (R_{et}) were calculated to evaluate the level of thermal comfort affected by different T-shirt designs.

6.4 Results and Discussion

The results are listed in Tables 6.3 and 6.4, and are plotted in Figures 6.7, 6.8, 6.9 and 6.10. The coefficients of variation of repeated tests were less than 5.0%. The T-shirts with lower R_t values are preferred as this indicates greater ability to release body heat through the garment. Also, lower value of moisture vapour resistance (R_{et}) signifies that the T-shirt could release the body moisture vapour into the ambient environment more efficiently.

To evaluate the significance of the differences of the six T-shirts in terms of thermal insulation and moisture vapour resistance values, one-way ANOVA was conducted. To compare the differences between two types of pattern designs, independent t-test was carried out. Two-way ANONA was also conducted to determine the interaction of the effects of pattern design, air velocity and body motion on the thermal insulation and moisture vapour resistance.

		Standing (no wind)		Walking (no wind)	
		Mean	S.D.	Mean	S.D.
S	R_t	0.141	0.004	0.138	0.005
	R_{et}	18.757	0.216	15.931	0.473
M	R_t	0.146	0.002	0.14	0.003
	R_{et}	19.091	0.378	16.379	0.341
L	R_t	0.148	0.004	0.142	0.004
	R_{et}	19.34	0.284	16.663	0.456
XL	R_t	0.149	0.003	0.144	0.002
	R_{et}	19.851	0.348	16.862	0.289
F-1	R_t	0.149	0.005	0.142	0.002
	R_{et}	19.885	0.257	16.472	0.369
F-2	R_t	0.145	0.002	0.134	0.002
	R_{et}	18.98	0.33	16.002	0.314

Table 6.3 – Clothing thermal insulation and moisture vapour resistance of different T-shirts under NO WIND condition

		Standing (windy)		Walking (windy)	
		Mean	S.D.	Mean	S.D.
S	R_t	0.067	0.001	0.065	0.001
	R_{et}	7.462	0.091	6.615	0.149
M	R_t	0.067	0.001	0.066	0.003
	R_{et}	7.818	0.281	6.794	0.187
L	R_t	0.068	0.001	0.065	0.002
	R_{et}	7.819	0.111	6.769	0.132
XL	R_t	0.067	0.001	0.065	0.002
	R_{et}	7.897	0.045	6.788	0.162
F-1	R_t	0.065	0.001	0.062	0.002
	R_{et}	7.252	0.112	6.479	0.145
F-2	R_t	0.063	0.001	0.06	0.002
	R_{et}	6.897	0.193	6.077	0.13

Table 6.4 – Clothing thermal insulation and moisture vapour resistance of different T-shirt under WINDY condition

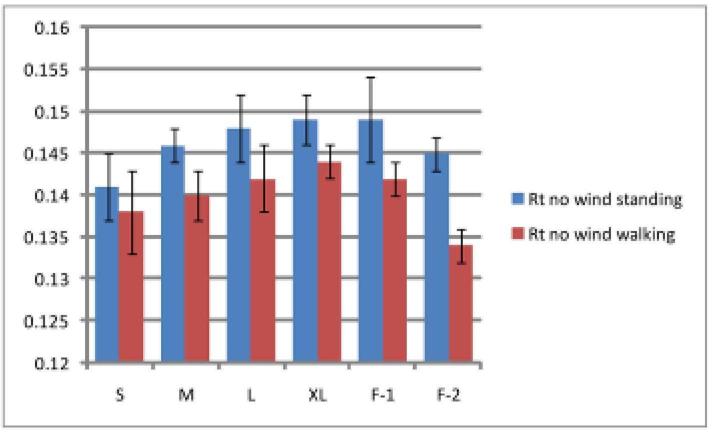


Figure 6.7 - Total thermal insulation in no wind condition

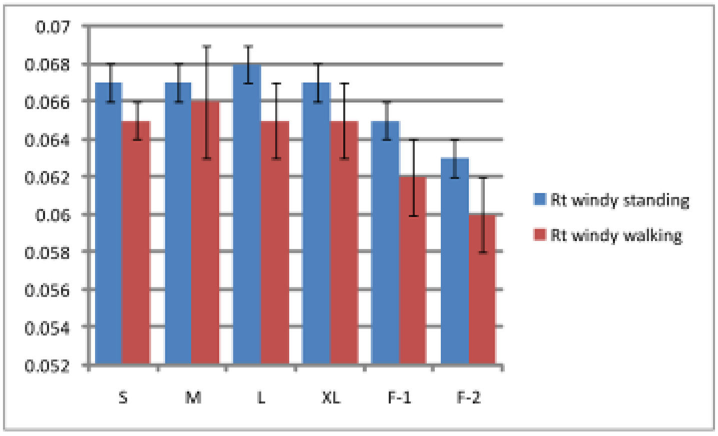


Figure 6.8 - Total thermal insulation in windy condition

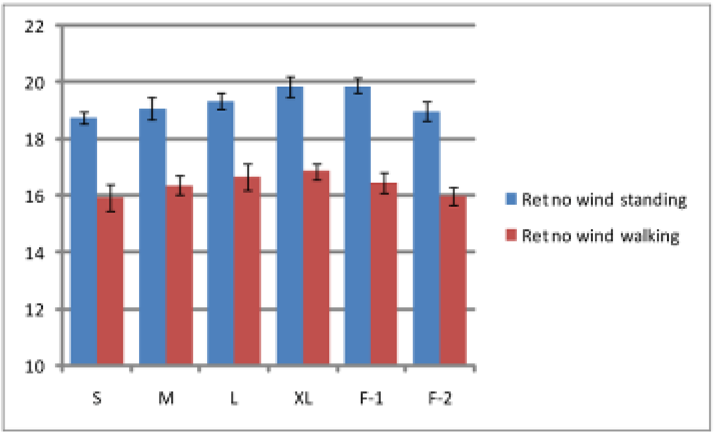


Figure 6.9 – Total moisture vapour resistance under no wind condition

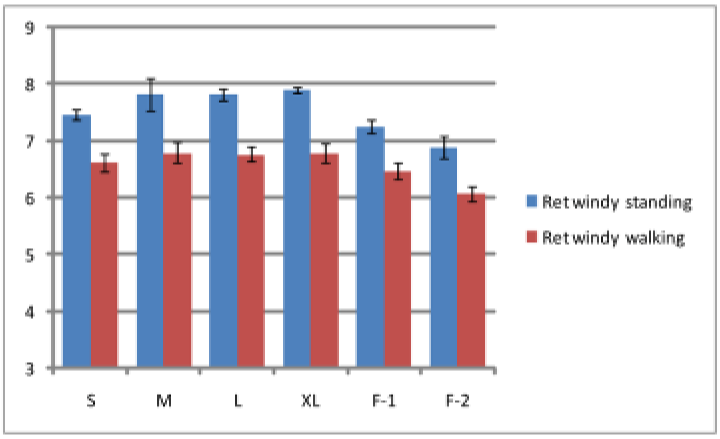


Figure 6.10 – Total moisture vapour resistance under windy condition

6.4.1 Thermal Insulation

No wind condition

As can be seen from Figure 6.7, there is a general tendency for the thermal insulation (R_t) value to gradually increase with the increasing size of the T-shirts under no wind condition, no matter it was standing still or in walking motion. Under the standing mode with no wind, the mean values of R_t for Size XL, L and M is +5.67%, +4.97% and +3.55% greater than that of the Size S, respectively. The differences were statistically significant at the 92.5% significance level ($F (3, 8) = 3.378$, $p = 0.075$). On the other hand, under the walking mode with no wind, the mean values of R_t for Size XL, L and M is +1.45%, +2.9% and +4.38% greater than that of Size S, respectively. Under such condition, the increase in terms of R_t for Size XL compared to Size S was less than that for M, opposite to the trend found under no wind and standing condition. However, the differences between these four T-shirts were not statistically significant under the walking mode with no wind ($F (3, 8) = 1.606$, $p = 0.263$).

As F-1 was designed to have the same chest measurement as L and the same hem measurement as XL, comparison of F-1 with Size L and XL of conventional design was carried out. Under the no wind and standing condition, F-1 had almost the same R_t value (0.149) as XL and L of the conventional design (Based on the independent t-test, the difference of F-1 to L and XL was not significant ($t (4) = 0.271$, $p = 0.8$; $t (4) = 3.275$, $p = 1$, respectively). However, the R_t value for F-1 was approximately +2.05% and +5.67% higher than that of M and S, respectively. In other words, the T-shirt with the special design of added fullness did not have any advantage in reducing the total thermal insulation, although more air space had been created in the front and the back. When small openings were placed in the F-2 T-shirt, slightly lower R_t values were found in comparison with all the T-shirts except for the S size of the convention design. In comparison with F-1, the F-2 design was -2.68% lower in terms of R_t, however this difference was also not significant statistically (t (4) = 1.287, p = 0.268). This can be explained as follows. When the manikin was standing still without any movement, no air circulation was generated and the increased air space in the front and the back panel in F-1 could have trapped more still warm air, thus resulting in higher thermal insulation than the T-shirts with conventional design. Although the apertures had been applied in the case of F-2, the trapped warm air was not able to be released from the small openings through natural convection.

Under no wind and walking condition, F-1 recorded the same R_t value as that of Size L (0.142), but slightly lower than that of XL (0.144 or -1.39% less), but difference was not statistically significant (t (4) = 0.316, p = 0.768; t (4) = 1.225, p = 0.288 respectively). The benefit of F-1 design was therefore limited. However, F-2 recorded the lowest R_t value, which was -5.63% (in comparison with F-1 and L), -6.9% (in comparison with XL), -4.29% (in comparison with M) and -2.9% (to S). The difference was significant when compare to F-1 (t (4) = 4.899, p = 0.008), XL (t (4) = 6.124, p = 0.004), L (4) = 3.479, p = 0.025), M (t (4) = 2.882, p = 0.045), except for S (t (4) = 1.287, p = 0.268). From the graph, it can be seen that thermal insulation increased with the size. It shows that although the arms and legs of the manikin were moving during simulated “walking” motion, such movement was not strong enough to ventilate the warm and moist air from the increased microclimate of larger sizes. However, the apertures of F-2 could allow more air exchange, although it was still not significantly different from Size S of conventional design in terms of R_t value. If the motion of the manikin was faster, the cooling advantage of F-2 would be more significant.

Windy condition

Under the windy condition, the R_t value was reduced for all T-shirts in comparison with those under no wind condition due to forced convection. Although there were some differences between T-shirts of conventional design, the result was not significantly different in standing ($F(3, 8) = 0.143$, $p = 0.931$) and walking ($F(3, 8) = 0.418$, $p = 0.745$). Comparing the two types of designs (conventional design and the special design with added fullness), the t-test showed that the differences under both standing ($t(13) = 6.501$, $p = 0.000$) and walking conditions ($t(13) = 2.729$, $p = 0.017$) were significant. Consequently, the means of R_t value of F-1 under the standing and windy condition was 3% less than that of S and the R_t value of F-1 under the walking and windy condition was 4.6% less than that of S. The reduction R_t for F-2 was even greater than that of F-1, being 6% less than of S under the standing and windy condition ($t(4) = 6.261$, $p = 0.003$) and 7.7% under walking and windy condition ($t(4) = 3.153$, $p = 0.034$). It can therefore be concluded that, under windy conditions, the T-shirts with the special design of added fullness reduce thermal insulation relative to T-shirts with conventional cutting. Apertures in F-2 T-shirt further enhance convective heat transfer in walking and windy conditions.

6.4.2 Moisture Vapour Resistance

No wind condition

Under no wind and standing condition, larger size T-shirts in conventional design tend to have higher moisture vapour resistance (See Figure 6.9) due to the increased still air layer. This difference was significant ($F(3,8) = 6.514$, $p = 0.015$). Comparing the T-shirts of the special design (F-1 and F-2) with those in the conventional design, F-1's moisture vapour resistance was greater than all T-shirts in conventional design, and F-2's moisture vapour resistance was almost the same as Size M's. This indicates that F-1 design tends to increase the moisture vapour resistance relative to T-shirts in conventional design under no wind condition. However, the difference was not significant ($t(4) = 2.465$, $p = 0.069$; $t(4) = 0.136$, $p = 0.898$, respectively). In walking mode, although F-1 design had lower R_{et} value than Size L and XL in conventional design, the difference was also not significant ($t(4) = 0.564$, $p = 0.603$; $t(4) = 1.225$, $p = 0.288$, respectively). Between F-1 and F-2, the difference was also not significant ($t(4) = 1.68$, $p = 0.168$).

Windy condition

As can be seen from Figure 6.10, under windy conditions, the T-shirt in Size S still had the lowest R_{et} value among all the T-shirts in conventional design. However, both F-1 and F-2 had lower moisture vapour resistance than that of Size S. In the standing posture, F-1 and F-2's moisture vapour resistance was 2.8% ($t(4) = 2.521$, $p = 0.065$) and 7.57% ($t(4) = 4.586$, $p = 0.01$) lower compared to that of S, respectively. Under this condition, F-2 had significant difference in comparison with S in terms of moisture vapour resistance. The similar trend was found under a walking and windy condition, with F-1 and F-2 recorded lower R_{et} values than that of S by 2.1% ($t(4) = 1.133$, $p = 0.321$) and 8.1% ($t(4) = 4.712$, $p = 0.009$), respectively. In windy conditions, F-2 design had significantly lower R_t and R_{et} values than that in the T-shirt S.

6.4.3 Observation of the relationship between add fullness cutting method and wind

In walking motion, F-1 performed slightly better possibly as the moving arms of the thermal manikin increased air circulation between the T-shirt and the body. Observation of the T-shirts during the experiment suggested that the forward and backward movement of the arms stretched the fabric, thus pulling the "added fullness" areas and pressing the warm air out into the ambient environment, but this movement of garment drape was still subtle if no wind was blowing onto the manikin. When wind was blown in the chamber, movement of the garment drape was even more significant. Although the air velocity was theoretically unchanged, the actual velocity changed with time. An anemometer placed 50 cm in front of the manikin showed the fluctuation of air velocity between 1 and 2m/s. This fluctuation added the movement of garment drape, especially for the T-shirts of the special design with added fullness (F-1 and F-2). During the experiment, it could be observed that the form of the drape of F-1 and F-2 changed constantly, which helped the exchange of the warmer and more humid air in the clothing microclimate with the colder and drier air in the ambient environment (see Figure 6.11). This is the main reason that F-1and

F-2 had much better cooling efficiency in windy condition than that in a no wind condition.

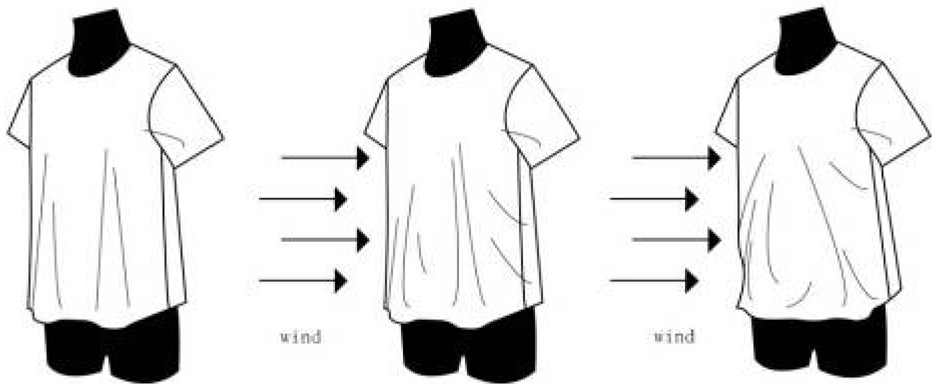


Figure 6.11 – The distortion of the natural drape by wind

6.4.4 Interaction between pattern design, wind and body motion

In comparison of F-1 (the special pattern design with added fullness) and the conventional pattern design (viz. S, M, L, XL), there was significant difference in the windy condition, but not in no wind condition. The t-test showed that there were no significant differences in thermal insulation and moisture vapour resistance in no wind conditions, no matter under "walking" motion (R_t: t (13) = 0.516, p = 0.615; R_{et}: t (13) = 0.043, p = 0.967) or standing posture (R_t: t (13) = 1.051, p = 0.312; R_{et}: t (13) 2.077, p = 0.058). However, in windy conditions, the difference became significant in both walking (R_t: t (13) = 2.729, p = 0.017, R_{et}: t (13) = 2.814, p = 0.015) and standing postures (R_t: t (13) = 6.501, p = 0.000; R_{et} t (13) = 3.677, p = 0.03). The same trend was found when comparing F-2 (the special pattern design with added fullness with ventilation apertures) and those in conventional pattern design. The ventilation apertures in F-2 design further contributed the cooling in windy conditions.

Two-way ANOVA was carried to determine the interaction of different pattern design, windy conditions, and body motion. It was found that the independent effect of pattern design, wind or body motion on R_t and R_{et} was significant ($p< 0.000$). The interaction between wind and body motion and the interaction between pattern design and wind were also significant ($p = 0.002$ and $p=0.028$, respectively). However, the results showed that there was no significant interaction between pattern design and body motion, giving $F=1.369$, $p = 0.262$ for R_t and $F = 0.417$, $p = 0.661$ for R_{et}. It means that similar effects of pattern design exist under standing still and “walking” motion, and similar effects of body motion exist for two types of pattern designs.

6.5. Conclusions

From this study, it can be concluded that, increasing the looseness in fitting by wearing larger sizes of T-shirts of conventional pattern design cannot improve ventilative cooling under standing still and no wind condition, as the thermal insulation and moisture vapour resistance increase with increasing garment size under such conditions. The ventilative cooling efficiency of loose fitting T-shirts in conventional pattern designs is limited even under walking motion and windy conditions, as extra air gaps are only created at the side body and the T-shirts are still in contact to the upper front and upper back of the body, where ventilative cooling are most needed. The study showed that adding fullness in the T-shirt design to create the “flared” drape can significantly reduce the T-shirt’s thermal insulation and moisture vapour resistance under walking or windy conditions, hence improving the ventilative cooling. The cooling efficiency can be further enhanced by creating small apertures in the pattern design with added fullness. This is because, with the special pattern design air gaps are created at the upper front and upper back of the body, and the form of the air gaps or microclimate changes constantly as a result of body motion and natural fluctuation of air velocity.

Chapter 7

Development of the ventilative T-shirts (I): the initial prototypes

7.1 Introduction

Based on the past literature and the test results discussed in Chapters 5 and 6, development ideas of T-shirts are inspired. The design process takes several stages. During each phase of development, prototypes were made and tests were conducted to evaluate the effectiveness for further improvement. This chapter reports on the initial prototypes and their tests results.

7.2 Inspiration from the testing results reported in Chapters 5 and 6

- Increase air space by propping up garment from the skin

Increasing air space between the skin and the fabric layer could improve ventilation if the air gap was not still. Cutting the garment to add fabric fullness was one of the methods utilized to increase the air space; however, this method might not be appropriate if we want to keep the form and the shape of the T-shirt to be simple. Additionally, a strong wind might press the drape against the skin surface, thus eliminating the air space. In order to keep the distance between the T-shirt fabric and the skin surface by a subtle approach, an object could be placed underneath the garment to keep the garment propped away from the body. In this regard, the object needs to be light weight and air permeable; otherwise it would not reduce the thermal insulation and moisture vapour resistance but instead have adverse effects. Hence, a spacer material (Figures 7.1 & 7.2) was selected to be placed between the fabric layer and the skin surface. The original thickness of the mesh fabric was approximately 0.75cm. In order to make the propping up effect more pronounced, two plies of spacer materials bound together (for a thickness of approximately 1.5cm) was designed.

Figure 7.1 - Spacer material used

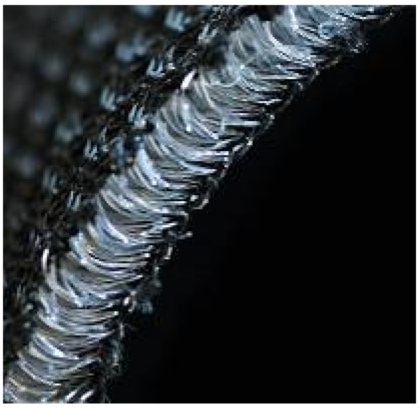


Figure 7.2 - Picture of the spacer material. Source: www. Healthcoat.co.uk

When a normal garment was worn properly by the wearer, the garment should lie down on the shoulders and the fabric should drop downwards, following the contour lines of the body. This results in the fabric closely touching the shoulders, chest and the upper back, so that when the wearer starts sweating, the fabric sticks to these areas, thus making the wearer uncomfortable because of the stickiness of the fabric layer. The spacer blocks were placed under the shoulders, the chest and the upper back areas so that the fabric layers are kept away from the body skin surface in these areas. Compared to the flat fabric layer, the contact area from the spacer material was far smaller so that the discomfort from stickiness of the fabric layer should be reduced theoretically. Moreover, as the spacer material propped up the fabric layer, the air space between the T-shirt and the skin surface increased, resulting in increased air circulation for the air exchange between the inner microclimate and external environment.

- Placement of ventilation panels

The previous testing results proved that the placement of ventilation panels could highly contribute to air circulation so that body heat and moisture vapour could be transferred out. To improve the ventilation especially in the area of shoulders, chest and upper back because of the drapery of the T-shirt fabric, mesh fabric panels were put in this area for releasing body heat. Due to the wide knitted and porous structure of the mesh fabric, air exchange could be activated inside and outside the air space. With the aid of spacer objects, the fabric is kept a certain distance away from the skin, thus improving air ventilation.

7.3 Design trial

The experiment reported in Chapter 5 showed that the vented details put across the chest and along the side panels could enhance ventilation. In order to examine the effectiveness of this design concept when the garment is propped up, a series of designs with different placements of mesh panels together with or without a spacer material for propping up were produced for testing. Since warm air rises up, the mesh panels should be placed around the shoulder areas so that the warm air within the air space was not stationary and it could be released from the porous surface. To compare the effectiveness of the new design concept, two groups of T-shirts were tested, namely:

Group 1

- T-shirts with mesh panels applied, without any spacer material placed under the garment. This group of T-shirt was treated as a normal T-shirt, since it could be obtained from the market.

Group 2

- T-shirts with mesh panels and a spacer material. This group of T-shirts incorporated the new design concept.

There were totally four styles tested:

Style 1: Basic short sleeve T-shirt (Figures 7.3 and 7.4) without mesh panels and no spacer objects placed under the garment. This T-shirt was used as a control piece in the tests.

Figure 7.3 - Front view of Style 1

Figure 7.4 - Back view of Style 1

Style 2: Basic short sleeve T-shirt with mesh panels on chest, shoulders and upper back. No spacer objects used in this style (Figures 7.5, 7.6 and 7.7).

Figure 7.5 - Front view of Style 2

Figure 7.6 - Front view of Style 2

Figure 7.7 - Side view of Style 2

Style 3: The same design as Style 2, with the addition of spacer materials placed underneath the shoulders, chest and upper back. The propping effect was applied in this style. (Figures 7.8, 7.9, 7.10 and 7.11)

Figure 7.8 - Front view of Style 3　　Figure 7.9 - Back view of Style 3

Figure 7.10 - Close-up of shoulder area of Style 3

Figure 7.11 - Close-up of spacer objects

Style 4: The same style as Style 3, with the mesh panels and spacer objects placed in the same position. Additionally, the two vertical mesh panels were added in this design to test its effectiveness with spacer objects added. (Figures 7.12, 7.13 and 7.14)

Figure 7.12 - Front view of Style 4 Figure 7.13 - Back view of Style 4

Figure 7.14 - Inside-out view of Style 4

7.4 Fabrication

For the first prototype development, a basic fabric was preferred as it is common in the market. 100% cotton fine gauge jersey (200g/m²) was used as the material since cotton jersey is one of the typical materials for T-shirts available in the market. Further testing was done with other materials for comparison. The mesh fabric was made of 100% polyester and the weight was 66.3g/m². The size of holes per cm^2 of the mesh fabric was approximately 0.38. This mesh fabric was the same as the T-shirt used in the test discussed in Chapter 5. The size of all T-shirts was the same and the measurements are listed in Table 7.1.

Garment part	Measurement (in cm)
Neck width	19 cm
Chest width	52 cm
Hem width	52 cm
Shoulder width	50 cm
Armhole length	23 cm
Sleeve length	23 cm
Body length (from high point shoulder)	66 cm

Table 7.1 – Measurement of T-shirt

7.5 Measurement method

In order to test the functionality of the propping up effect, the test was conducted under no wind and windy conditions. In this preliminary test, Walter remained in standing posture only. The experiment was conducted in a climatic chamber at 20.0 ± 0.5 ºC and 65.0 ± 2% RH with an air velocity of 0.5 ± 0.3 m/s (no wind condition) and 2 ± 0.3 m/s (windy condition). The core temperature of the manikin was set at 37 ºC. For all the tests with varying T-shirt samples, the same pair of short trousers (made of 100% cotton) was put on the manikin. As discussed in the previous chapter, clothing thermal insulation (R_t) and moisture vapour resistance (R_{et}) were calculated to evaluate the level of thermal comfort that was affected by different T-shirt design styles. To evaluate the significance of the differences of the T-shirts in terms of thermal insulation and moisture vapour resistance values, independent t-test was carried out.

7.6 Results and Discussion

The results are listed in Table 7.2 and plotted in Figures 7.15, 7.16, 7.17 and 7.18. The coefficients of variation of repeated tests were generally less than 5.0%.

		No Wind		Windy	
T-shirt code		Mean	SD	Mean	SD
Style 1	R_t	0.119	0.004	0.0705	0.001
	R_{et}	19.63	0.782	9.204	0.288
Style 2	R_t	0.117	0.004	0.0692	0.002
	R_{et}	18.511	0.643	8.671	0.367
Style 3	R_t	0.114	0.003	0.0674	0.002
	R_{et}	18.264	0.474	8.217	0.351
Style 4	R_t	0.113	0.004	0.0656	0.001
	R_{et}	18.247	0.545	7.775	0.241

Table 7.2 – Testing results (R_t and R_e) for T-shirt styles 1- 4
*SD : Standard Deviation
*R_t : Total Thermal Insulation (°Cm^2/W)
*R_e : Total Moisture Vapour Resistance (P_am^2/W)

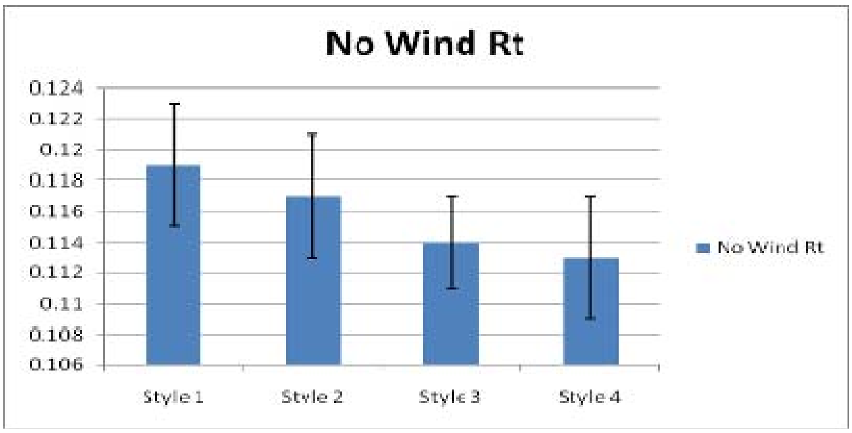


Figure 7.15 – R_t under no wind condition

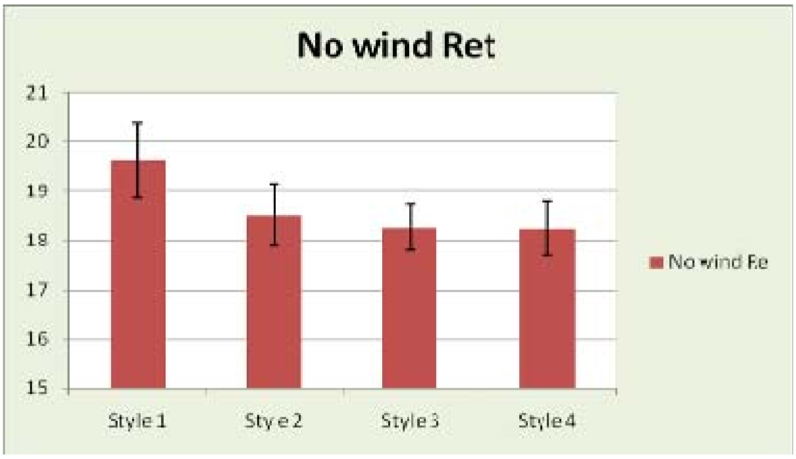


Figure 7.16 – R_{et} under no wind condition

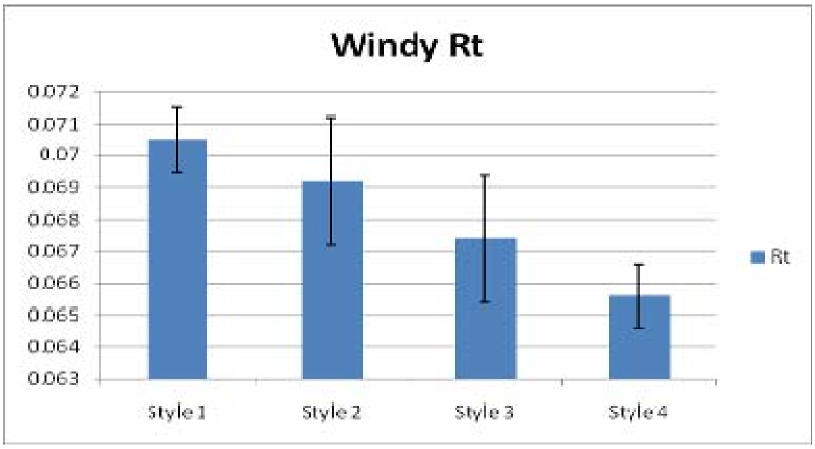


Figure 7.17 – R_t under windy condition

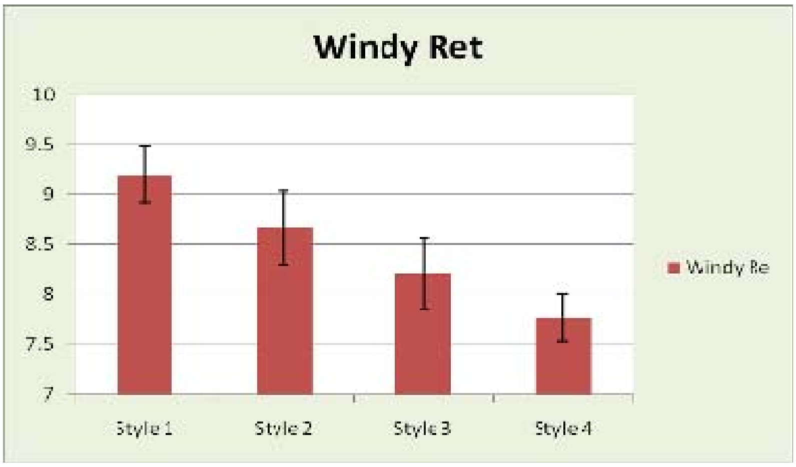


Figure 7.18 – R_{et} under windy condition

The improvement (in percentages) of R_t and R_{et} for styles 1-4 are listed in Tables 7.3 and 7.4. As the basic T-shirt (Style 1) was the control piece, the improvement of each T-shirt should be compared with the results for Style 1.

	Improvement under no wind condition	
	R_t	R_{et}
Style 1	0%	0%
Style 2	0.00%	-5.70%
Style 3	-2.56%	-6.96%
Style 4	-3.42%	-7.05%

Table 7.3 – The improvement (in %) of R_t and R_{et} for all T-shirts under no wind condition

	Improvement under windy condition	
	R_t	R_{et}
Style 1	0%	0%
Style 2	-1.84%	-5.79%
Style 3	-4.40%	-10.73%
Style 4	-6.95%	-15.53%

Table 7.4 – The improvement (in %) of R_t and R_{et} for all T-shirts under windy condition

7.7 Conclusions from the testing results

In the no wind condition, Style 2 T-shirt had a certain reduction in R_{et} (-5.7%) relative to style 1 (control piece), however the t-test showed that there was no significant difference ($t(4) = 1.914$, $p = 0.128$). This implies that putting mesh panels solely on the T-shirt could contribute to a limited amount of heat and moisture transfer. By placing spacer objects underneath the chest, shoulders and upper back area of style 3, the condition improved with a 2.56% reduction in R_t and 6.96% reduction in R_{et}, however, the results of the t-test showed that there were no significant difference (Rt: t (4) = 1.732, p = 0.158,: Ret: t (4) = 2.587, p = 0.061). The results for style 4 T-shirt were similar to style 3 although mesh fabrics placed along two vertical side panels could further improve the ventilation. Compared with the control piece, this style resulted in a reduced R_t by 3.42% and R_{et} by 7.05%, again the results of the t-test showed that there were no significant differences (Rt: t (4) = 1.837, p = 0.14; Ret: t (4) = 2.513, p = 0.066).

Under windy conditions, putting mesh panels alone on the T-shirt reduced R_t by 1.84% and R_{et} by 5.79% in comparison with the control piece, the differences were no significant (Rt: t (4) = 1.007, p = 0.371; Ret: t (4) = 1.979, p = 0.119). Style 3 improved the results even further, with 4.4% reduction in R_t (t (4) = 2.401, p = 0.074) and 10.73% in R_{et} (t (4) = 3.765, p = 0.02). The difference was significant in reducing moisture vapour resistance but not in total thermal resistance. Style 4 had the best performance in heat and moisture transfer among all the T-shirts. It reduced R_t and R_{et} by 6.95% and 15.53% compared to the control piece. The t-test results were significantly differences (Rt: t (4) = 6.001, p =0.004; Ret: t (4) = 6.591, p = 0.003). Comparing the two T-shirts with spacer objects for propping up the fabric layer away from the skin, the one with mesh panels on the two side seams performed better than the one without, as it resulted in approximately 3% reduction in R_t and 4.8% in R_{et}.

7.8 Further development ideas

The tests proved two things. The first was that, keeping the T-shirt layer away from the skin surface and circulation in the air space improved the ventilation of the garment. This was because the body heat and moisture vapour could flow within the sufficient air gap between the body skin surface and the fabric layer, and they were released out to the ambient environment through the porous surface of the mesh vented panels.

The second design concept was the importance of the placement of the vented panels at the two side seams. In chapter 5, it was shown that sufficient space at the two side seams could contribute to the heat and moisture transfer especially with pumping effect. The test was conducted under a no wind condition with body motion. It is therefore believed that body motion coupled with vented panels at the two sides promote the pumping effect. The present tests were carried out under a windy condition. Like body motion, wind can force the cool air to enter into the microclimate next to the body through the vents, and as a result, air circulation occurred around the body and this was further enhanced as it was no longer blocked by the fabric layer sticking to the skin surface. In the normal circumstances, the warm body heat and moisture vapour rise up and are accumulated in the chest (similar to the F-1 style in the testing of chapter 6), shoulders and upper back area. Placing a mesh fabric with propping up effect could circumvent the accumulation of warm and wet air because the space between the fabric and body skin surface was large enough for ambient wind to go into and to carry body heat and moisture vapour away through the mesh fabric. The two vertical side panels acted as two big channels for ambient wind to enter. Wind could make the body cooler and drier when it is in contact with the warm and wet body. Such warm body heat would travel up and be released from the shoulder area. This is called a "chimney effect", which provided inspiration for further development.

Further improvement is necessary so that the spacer object will not scratch the skin surface. Additionally, the construction of the spacer object should be modified so that it can be more easily attached to the T-shirt. Moreover, the spacer objects should be lightweight, and have appropriate thickness to keep the fabric layer sufficiently away from the skin surface. Besides, when the garment is worn, the spacer object should not collapse under the weight of the T-shirt.

Apart from the construction of the garment and the spacer object, the design style should also be more trendy and fashionable.

Chapter 8

Development of the ventilative T-shirt (II): the second prototypes

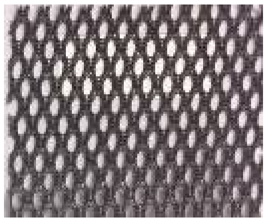
8.1 Introduction

Following the experience of developing the first prototype reported in Chapter 7, the design concept had been proved to strengthen the ventilation of T-shirt, and this concept should be further developed and improved. This chapter focuses on the design of the spacer object and its placement on the T-shirt. Moreover, in order to further improve the chimney effect, some variations of the T-shirt design were made for comparison.

8.2 Design of the second prototype

8.2.1 Fabrication

As the function of the T-shirt is for sports, the fabrication should be stretchable for easy movement. For the tests, the fabrication remained as the same fine gauge jersey but the fibre content was changed to 95% cotton 5% spandex. Spandex is a kind of elastic fibre that can give greater stretch-ability. The weight of the base fabric was 220 g/m^2 (please see fabric swatch 8.1). Open knitted mesh fabric was once more used as vented details, and its weight was 65.45g/m^2 (please see fabric swatch 8.2).

 Fabric swatch 8.1	 Fabric swatch 8.2

8.2.2 Development of spacer object

The spacer object in Chapter 6 was formed by binding two layers of spacer blocks in order to maintain a certain thickness; however, there were two main problems that occurred during the test. The first one concerned air and water permeability. The spacer material for the T-shirt reported in Chapter 6 was constructed with a porous structure, but the middle layer was formed by the intersection of many filament fibres. When the two layers are bound together, the double layers of the filament fibre could keep still air between the spaces among each filament yarn. This could even increase the thermal insulation and the moisture vapour resistance by deferring heat and moisture transfer (see Figure 8.1). To solve this problem, an air channel needed to be created in the spacer object. Therefore special constructions of spacer objects were designed for the T-shirt.

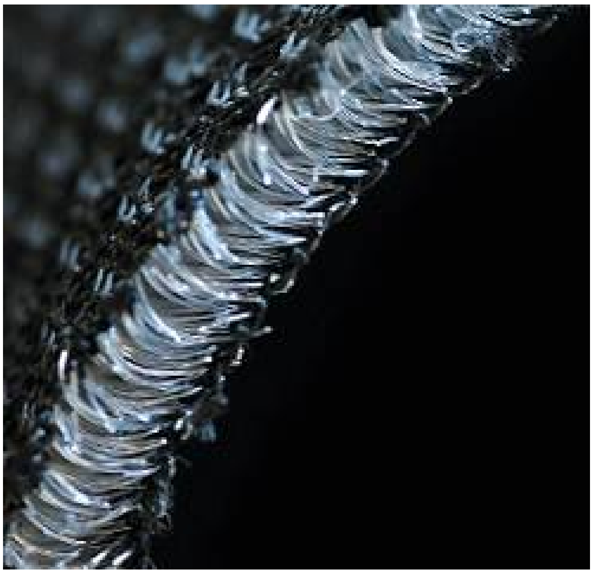


Figure 8.1 – Small spaces between the filament yarns could keep still air

(Source: www.healthcoat.co.uk)

8.2.3 Construction of the new spacer objects

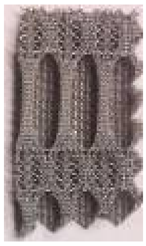
To conclude, the new design of the spacer object should:

1. Hold the T-shirt away from the skin without collapsing.
2. Not be too heavy.
3. Allow air flow within the construction of the spacer objects.

4. Not defer the heat and moisture transfer, as suggested by the literature review. This suggests that the spacer object should not be too thick, and it should provide a certain distance between the T-shirt and the body skin surface.

5. Be smooth in surface so that it does not scratch when it contacts the skin surface.

In order to fulfil the requirements 1, 2 and 4, the choice of the spacer material should strike a balance between stiffness, weight and smoothness. A spacer material with stiff fibre could support the weight of the T-shirt, but it may be too heavy and at the same time scratchy (see fabric swatch 8.3). On the other hand, a smoother material might be too loose and it might collapse, so that it might not be easy to prop up the T-shirt. Some spacer materials have porous surface on the right side, but not on the wrong side (see fabric swatches 8.4 and 8.5). This kind of spacer material is also not suitable for our purposes because the wrong side could block the air penetration leading to increased thermal insulation. In order to strike a balance between these considerations, one type of spacer material (see fabric swatch 8.6) was finally chosen for further development.

 Fabric swatch 8.3	 Fabric swatch 8.4
 Fabric swatch 8.5	 Fabric swatch 8.6

The initial idea was to construct the object like a shoulder pad, although the material would be the spacer material instead of cotton. This construction could fulfil requirement 1, but if many plies of spacer material are put together (Figure 8.2), it might be too heavy for the wearer. Furthermore, the thickness of the material could increase thermal insulation by reducing air flow, although the material was fabricated with porous material. Therefore this method was not adopted.

Figure 8.2 – Spacer shoulder pad. (Left: inner construction; right: the T-shirt)

To cope with the problem of the lack of air flow within the spacer object, a “U-shaped wave” (see Figures 8.3 and 8.4) shape was chosen to solve the problem. In this construction, wider space was created between the layers of the spacer materials so that theoretically it would not keep still air inside the spacer material, thus increasing the flow of air penetration in, which would contribute to the transfer of heat and moisture from the skin.

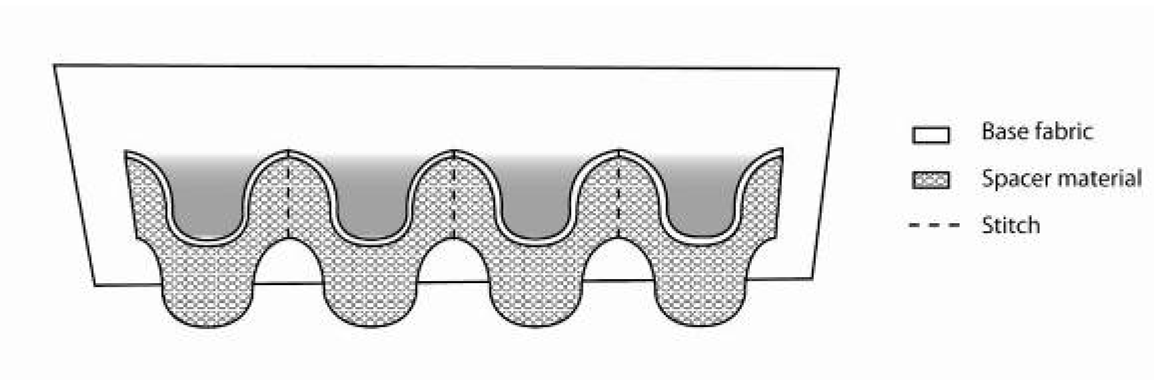


Figure 8.3 - The design of “wave” construction of the spacer material

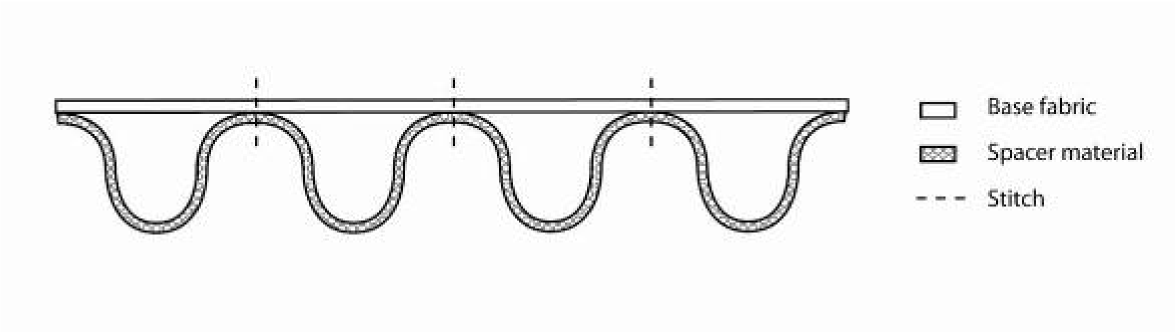


Figure 8.4 - Side view of the "wave" construction of the spacer material

But there were two main problems that occurred once this design was made. The first problem was the collapse of the wave under weight. Although the spacer material used for the experiment was ideal in its stiffness, it could not hold the shape of the wave once the T-shirt was put on the body without distortion (see Figure 8.5). This suggested that when the wave design material is put on the body, gravity and the weight of the T-shirt press the wave downwards. This results in reduced distance between the garment and the skin surface i.e. reduced space and air circulation. Thus, the special construction had to be further developed to minimize the amount of collapsing.

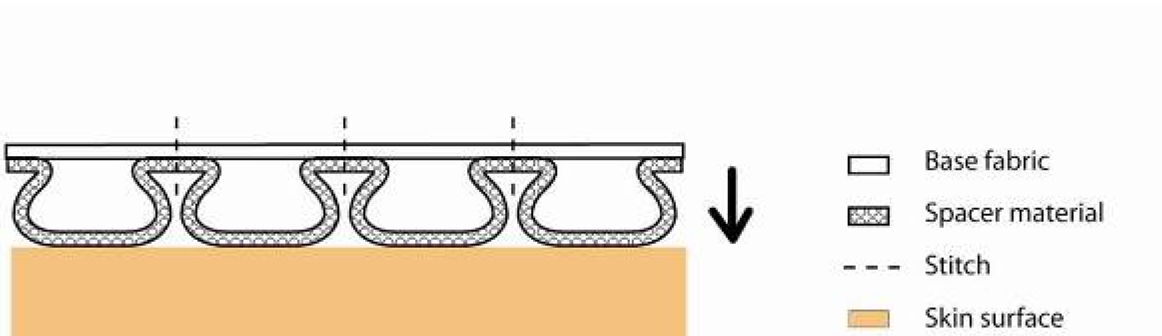


Figure 8.5 - Collapse of the wave under the pressure of gravity and the T-shirt

The second problem was the bending of the spacer material, i.e. it tends to be flattened (see Figure 8.6 and 8.7), making it difficult to control the wave shape of the spacer material.

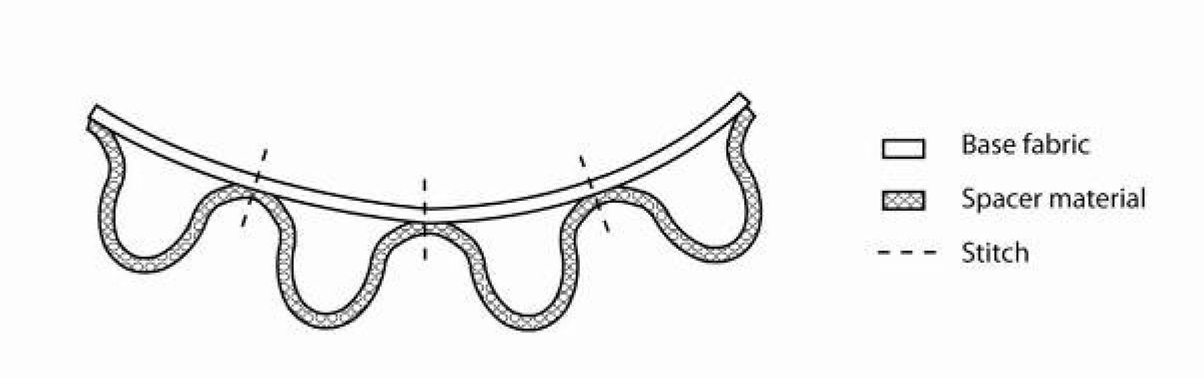


Figure 8.6 - Bending of the spacer material towards the cotton jersey

Figure 8.7 - Photos of the spacer object with bending effect

In order to hold the shape of the wave without distortion or bending, loops were formed continuously so as to reduce the space between each individual "u-shaped wave" (see Figure 8.7). To solve the bending problem, a piece of flat spacer material was placed between the loops and T-shirt fabric to provide a stronger base. In addition, stitches “B” (see Figure 8.9) were placed so as to gather the loops together and stitch A was used to attach the loops and T-shirt fabric together. These two stitches eliminated the recovery ability of the spacer loops, so that the problem of bending was solved. Additionally, the stitch gathering the sides of each U-shaped wave together made them strong enough to support the weight of the garment, so that it was able to keep the desirable distance between the shell fabric and the body skin surface with minimum distortion (see Figure 8.10). Because of the limit of the sewing machine, stitch “B” was done by hand.

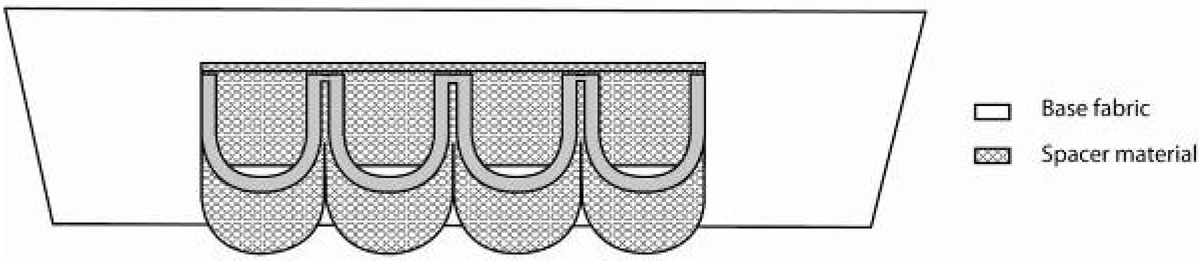


Figure 8.8 - Design of the continuous loops of spacer material

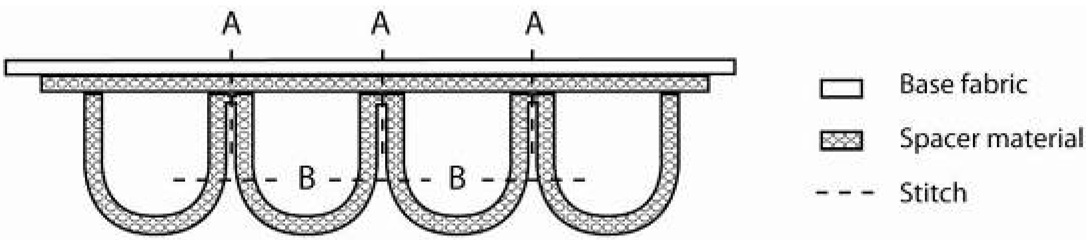


Figure 8.9 - Side view of the spacer loops

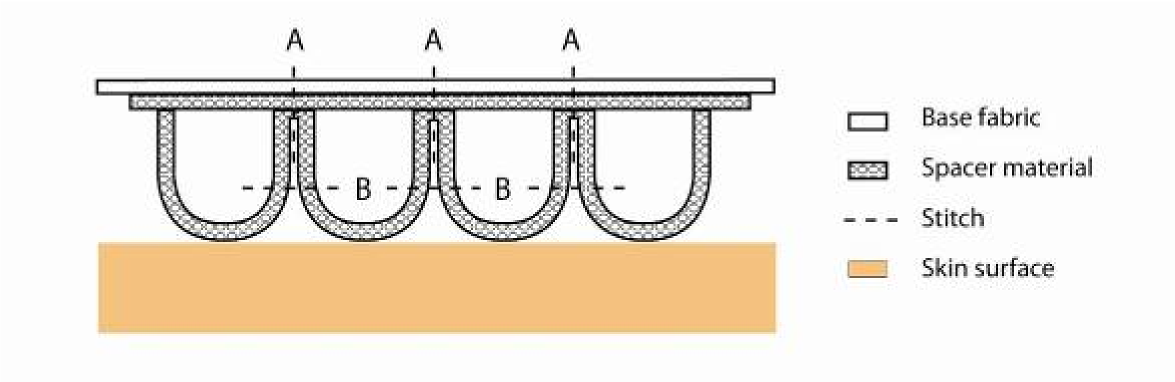


Figure 8.10 - Side view of the spacer loops contacting the skin surface

8.2.4 Design and styles

According to the initial evaluation of the tests outlined in Chapter 7, the propping up effect using spacer objects could increase air flow within the micro-climate between the T-shirt and the body skin surface. In order to further test the design concept using the new spacer loops, several T-shirts were made to evaluate the reduction in thermal insulation and moisture vapour resistance. Mesh panels were used in the new design as before, to act as a vented detail for achieving the chimney effect or ventilation. The designs were divided into two groups: with and without spacer loops located underneath the shoulders. Each group of design comprised five styles, with different placement of mesh panels. All T-shirts were constructed of the same size (see Table 8.1).

Garment part	Measurement (in cm)
Neck width	20 cm
Chest width	55 cm
Hem width	55 cm
Shoulder width	52 cm
Armhole width	23 cm
Sleeve length	23 cm
Body length (from high point shoulder)	68 cm

Table 8.1 – Size of the T-shirt with spacer loops

<u>Group 1 – Design without spacer loops put underneath the shoulders</u>

NM (No Mesh): No mesh (a typical T-shirt without any special design that served as the **control piece** for the whole test) (see Figures 8.11 & 8.12)

Figure 8.11 – front view

Figure 8.12- back view

MS (Mesh on Shoulders): mesh panels on shoulders (see Figures 8.13 & 8.14)

Figure 8.13- front view Figure 8.14 – back view

MSC (Mesh on Shoulders and Chest): mesh panels on shoulders and across chest (see Figures 8.15 & 8.16)

Figure 8.15 – front view Figure 8.16 – back view

MSS (Mesh on shoulders and Side panels): mesh panels on shoulders and two vertical side panels near the side seams (see Figures 8.17 & 8.18)


Figure 8.17 – front view Figure 8.18 – back view

MO (Mesh all Open): mesh panels on shoulders, across chest and two vertical side panels near the front side seams (see Figures 8.19 & 8.20)


Figure 8.19 – front view Figure 8.20 – back view

Group II – Design with spacer loops located underneath the shoulders

NM (No Mesh): no mesh panels on the T-shirt (see Figures 8.21 & 8.22)

Figure 8.21- front view Figure 8.22 – back view

MS (Mesh on Shoulders): mesh panels on shoulders (see Figures 8.23 & 8.24)

Figure 8.23 – front view Figure 8.24 – back view

MSC (Mesh on Shoulders and Chest): mesh panels on shoulders and across the chest (see Figures 8.25 & 8.26)

Figure 8.25 – front view Figure 8.26 – back view

MSS (Mesh on shoulders and Side panels): mesh panels on shoulders and two vertical side panels near the side seams (see Figures 8.27 & 8.28)

Figure 8.27 – front view Figure 8.28 – back view

MO (Mesh all Open), mesh panels on shoulders, across chest and two vertical side panels near the side seams (see Figures 8.29 & 8.30)

Figure 8.29 – front view   Figure 8.30 – back view

The inside-out view of the T-shirts with spacer loops placed underneath the shoulders are shown in Figures 8.31 & 8.32

Figure 8.31 - Inside-out of T-shirt with spacer loops placed underneath the shoulders (front)

Figure 8.32 - Inside-out of T-shirt with spacer loops placed underneath the shoulders (back)

8.3 Measurement method

In order to test the functionality of the chimney/pumping/ventilation effect, the test was conducted under no wind and windy conditions with Walter at standing posture and under simulated "walking" motion (walking speed of 1.24 km/h). The experiment was conducted in a climatic chamber of 20.0 ± 0.5ºC and 65.0 ± 2% RH with an air velocity of 0.5 ± 0.3 m/s (no wind condition) and 2.0 ± 0.3 m/s (windy condition). The core temperature of the manikin was set at 37ºC. For all tests with the various T-shirt samples, the same pair of short trousers (made of 100% cotton) was placed on the manikin. As discussed in a previous chapter, total thermal insulation (R_t) and moisture vapour resistance (R_{et}) were calculated to evaluate the effect of the different T-shirt designs. To evaluate the significance of the differences of the T-shirts in terms of thermal insulation and moisture vapour resistance values, independent t-test was carried out.

8.4 Results and discussion

The results are listed in Tables 8.2 and 8.3 for no wind and windy conditions, respectively. The coefficients of variation for repeated tests were less than 5%. T-shirts with lower R_t and R_{et} values are preferred because they indicate that the design had a greater ability to release body heat and moisture vapour out to the ambient environment.

			Standing (no wind)		Walking (no wind)	
			Mean	S.D.	Mean	S.D.
Group 1	NM	R_t	0.126	0.006	0.116	0.003
		R_{et}	20.85	0.45	18.51	0.3
	MS	R_t	0.122	0.005	0.113	0.004
		R_{et}	18.82	0.65	17.643	0.37
	MSC	R_t	0.121	0.005	0.115	0.003
		R_{et}	18.72	0.55	17.301	0.45
	MSS	R_t	0.119	0.005	0.113	0.004
		R_{et}	18.85	0.47	17.5	0.47
	MO	R_t	0.12	0.005	0.114	0.002
		R_{et}	18.77	0.44	17.439	0.13
Group 2	NM	R_t	0.126	0.005	0.116	0.003
		R_{et}	20.42	0.5	18.354	0.37
	MS	R_t	0.123	0.004	0.116	0.003
		R_{et}	18.02	0.5	17.632	0.55
	MSC	R_t	0.121	0.004	0.114	0.004
		R_{et}	18.21	0.29	17.341	0.21
	MSS	R_t	0.12	0.005	0.113	0.002
		R_{et}	18.51	0.46	17.284	0.53
	MO	R_t	0.12	0.003	0.112	0.002
		R_{et}	18.17	0.54	17.282	0.42

Table 8.2 - R_t and R_{et} values of all designs under no wind condition

			Standing (windy)		Walking (windy)	
			Mean	S.D.	Mean	S.D.
Group 1	NM	R_t	0.067	0.001	0.063	0.001
		R_{et}	7.52	0.23	7.57	0.23
	MS	R_t	0.064	0.001	0.061	0.003
		R_{et}	7.35	0.13	6.861	0.33
	MSC	R_t	0.062	0.01	0.059	0.002
		R_{et}	6.52	0.2	6.902	0.28
	MSS	R_t	0.062	0.001	0.059	0.001
		R_{et}	6.48	0.13	6.646	0.23
	MO	R_t	0.061	0.001	0.059	0.001
		R_{et}	6.4	0.24	6.309	0.14
Group 2	NM	R_t	0.063	0.002	0.063	0.002
		R_{et}	7.52	0.1	7.115	0.05
	MS	R_t	0.062	0.001	0.062	0.001
		R_{et}	7.36	0.15	6.8	0.07
	MSC	R_t	0.06	0.001	0.059	0.001
		R_{et}	6.42	0.22	6.199	0.25
	MSS	R_t	0.06	0.001	0.058	0.001
		R_{et}	6.32	0.2	6.152	0.22
	MO	R_t	0.06	0.001	0.058	0.001
		R_{et}	5.9	0.14	5.845	0.17

Table 8.3 - R_t and R_{et} values of all designs under windy condition

8.4.1 Thermal insulation under no wind condition

Figure 8.33 compares the total thermal insulation (R_t) for all designs in Group 1 and Group 2 for standing and walking postures under a no wind condition. Table 8.4 shows the percentage change for each garment. As mentioned earlier, the basic T-shirts (NM) of Group 1 was the control piece for comparison.

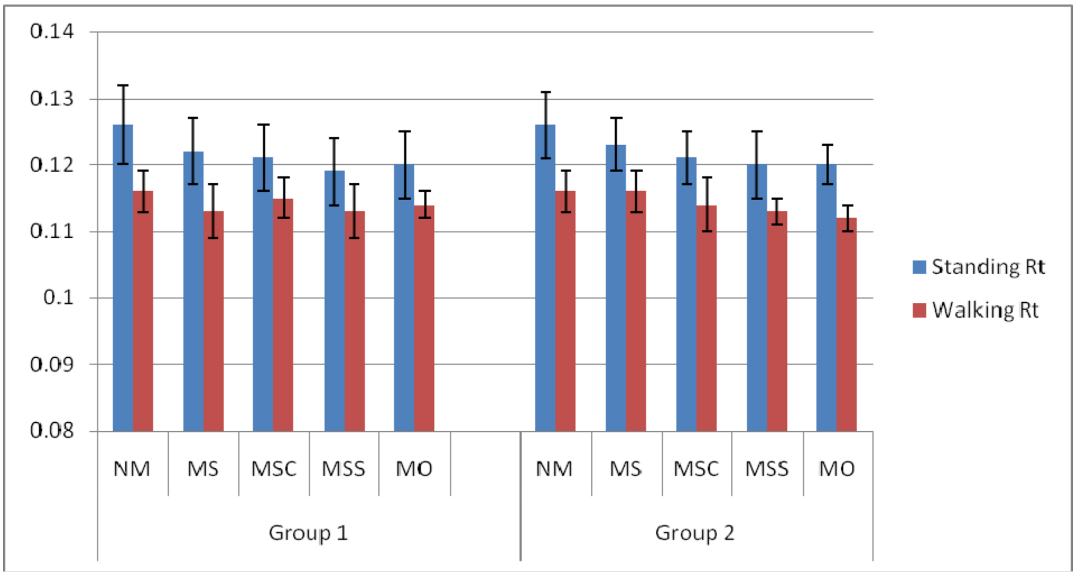


Figure 8.33 - Comparison of the total thermal insulation for all T-shirts for standing and walking postures under no wind condition

	Group 1					Group 2				
	NM	MS	MSC	MSS	MO	NM	MS	MSC	MSS	MO
Standing Rt (%)	0%	-3.17%	-3.97%	-5.56%	-4.76%	0%	-2.38%	-3.97%	-4.76%	-4.76%
Walking Rt (%)	0%	-2.59%	-0.86%	-2.59%	-1.72%	0%	0%	-1.72%	-2.59%	-3.45%

Table 8.4 Percentage change in total thermal insulation for all T-shirts for standing and walking postures during no wind condition

From the testing results, it can be seen that the new designs could not significantly reduce the thermal insulation of the garment under a no wind condition. In a standing posture, MSC ($t(4) = 1.201$, $p = 0.296$), MSS ($t(4) = 1.331$, $p = 0.254$) and MO ($t(4) = 1.549$, $p = 0.196$) of Group 2 (with spacer loops) design reduced by about 4% thermal insulation compared to the control piece. In a walking posture, MSS and MO of Group 2 design achieved the best performance in reducing thermal insulation; although, the percentage change was only 2.59% ($t(4) = 1.441$, $p = 0.223$) and 3.45% ($t(4) = 1.922$, $p = 0.127$), respectively. The findings indicate that placing spacer loops continuously underneath the shoulders could not significantly reduce the thermal insulation, irrespective of standing or walking postures while there was no wind.

8.4.2 Thermal insulation under windy condition

Figure 8.34 shows the comparison of the total thermal insulation (R_t) for all designs in Group 1 and Group 2 for standing and walking postures under a windy condition. Table 8.5 shows the percentage change for each garment compared with the control piece (NM of Group 1).

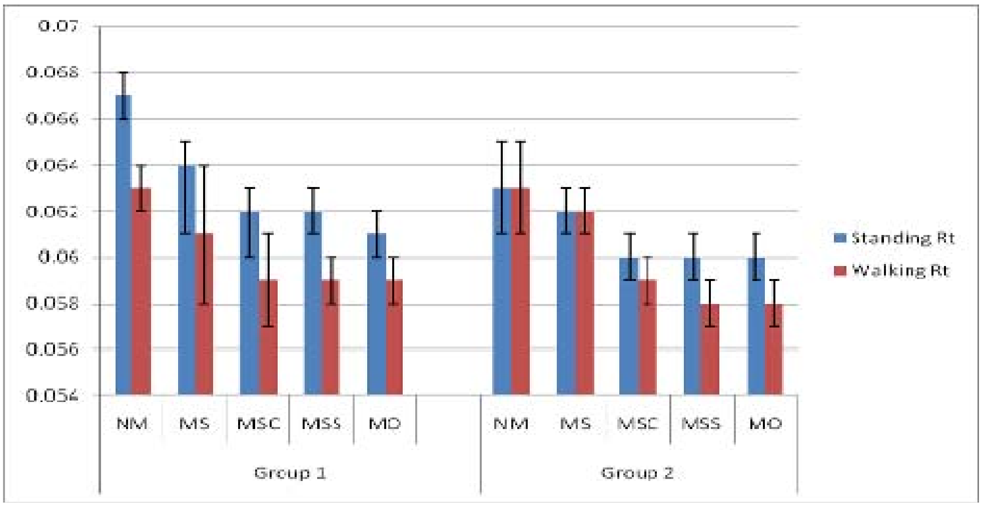


Figure 8.34 - Comparison of the total thermal insulation for all T-shirts for standing and walking postures under windy condition

	Group 1					Group 2				
	NM	MS	MSC	MSS	MO	NM	MS	MSC	MSS	MO
Standing Rt (%)	0%	-4.48%	-7.46%	-7.46%	-8.96%	-5.97%	-7.46%	-10.45%	-10.45%	-10.45%
Walking Rt (%)	0%	-3.17%	-6.35%	-6.35%	-6.35%	0%	-1.59%	-6.35%	-7.94%	-7.94%

Table 8.5 Percentage change in total thermal insulation for all T-shirts for standing and walking postures under windy condition

From the results, it appears that generally T-shirts in Group 2 performed better with lower thermal insulation compared to the designs in Group 1 under a windy condition. In a standing mode, MSC ($t(4) = 80573$, $p = 0.001$), MSS and MO designs of Group 2 recorded more than a 10% reduction in thermal insulation compared to the control piece, although comparing them to the same styles in Group 1, the difference is less (approximately 1.5% to 3%).

In a walking mode, T-shirts in Group 2 could not reduce much thermal insulation in comparison with the T-shirts in Group 1. The designs MSC, MSS and MO of Group 2 could reduce thermal insulation by 6.35% ($t(4) = 4.899$, $p = 0.008$), 7.94% ($t(4) = 6.124$, $p = 0.004$) and 7.94% ($t(4) = 6.124$, $p = 0.004$), respectively, relative to the control piece. However the same designs in Group 1 also produced a 6.35% reduction in thermal insulation compared with the control piece.

The results for thermal insulation in the two postures during no wind and windy conditions show that although the new designs of Group 2 could reduce certain thermal insulation compared to the control piece, the performance was not that remarkable if it is compared with the designs of Group 1. Hence, the new design used in Group 2 did not achieve so much reduction in thermal insulation in comparison with Group 1.

8.4.3 Moisture vapour resistance under no wind condition

Figure 8.35 shows the comparison of the moisture vapour resistance (R_{et}) of all designs in Group 1 and Group 2 for standing and walking postures under a no wind condition. Table 8.6 shows the percentage change of each garment compared with the control piece (NM of Group 1).

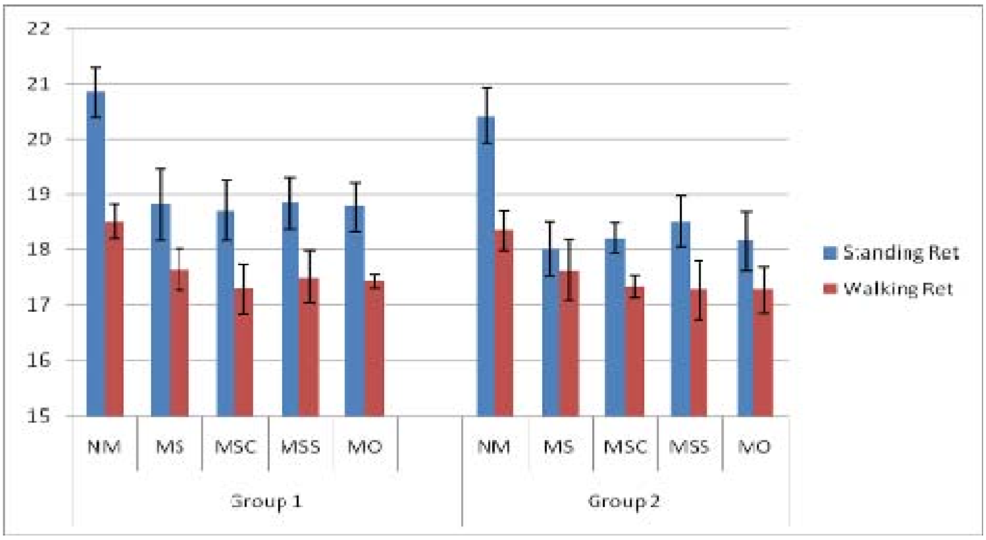


Figure 8.35 - Comparison of the moisture vapour resistance for all T-shirts for standing and walking postures under no wind condition

	Group 1					Group 2				
	NM	MS	MSC	MSS	MO	NM	MS	MSC	MSS	MO
Standing Ret	0%	-9.74%	-10.22%	-9.59%	-9.98%	-2.06%	-13.57%	-12.66%	-11.22%	-12.85%
Walking Ret	0%	-4.68%	-6.53%	-5.46%	-5.79%	-0.84%	-4.74%	-6.32%	-6.62%	-6.63%

Table 8.6 - Percentage of moisture vapour resistance for all T-shirts for standing and walking postures under no wind condition

Under a no wind condition and standing posture, designs of Group 2 including MS (t (4) = 7.287, p = 0.002), MSC (t (4) = 8.541, p = 0.001), MSS (t (4) = 6.298, p = 0.003) and MO (t (4) = 6.604, p = 0.003) significantly reduced moisture vapour resistant relative to the control piece by about 11% to 13%. In comparison, the designs of Group 1 reduced moisture vapour resistant by nearly 10% compared to the control piece. This means that the open mesh panels alone on the T-shirt already reduced certain moisture vapour resistance, and placing additional spacer loops underneath the shoulders had only a minor contribution (the difference was 1% to 3% approximately) if compared with the designs of Group 1. In a walking posture, all T-shirts recorded lower R_{et} than the control piece, and thus the designs of Group 2 did not have a significant advantage over the designs of Group 1.

8.4.4 Moisture vapour resistance under windy condition

The recorded values for the moisture vapour resistance (R_{et}) for all designs under a windy condition are plotted in Figure 8.36 and the percentage change values are listed in Table 8.7.

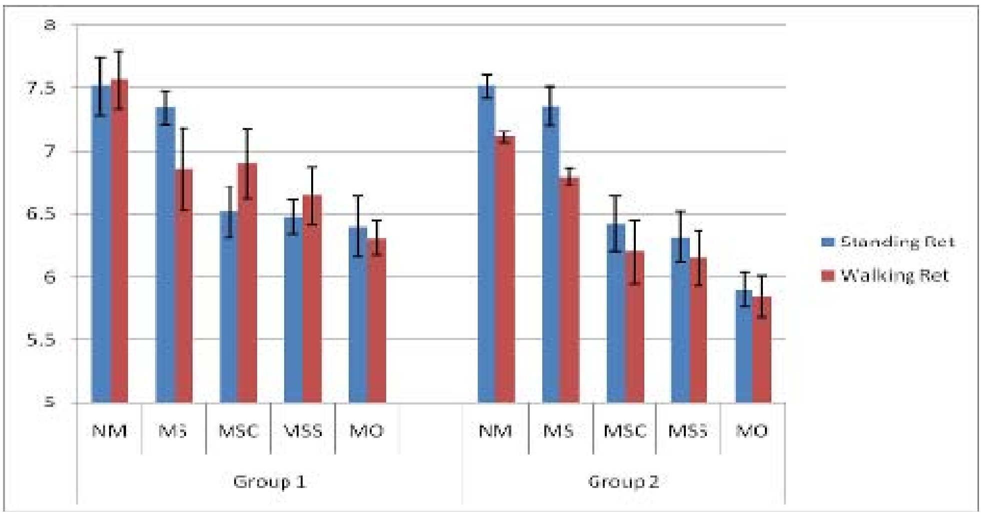


Figure 8.36 - Comparison of the moisture vapour resistance for all T-shirts for standing and walking postures under windy condition

	Group 1					Group 2				
	NM	MS	MSC	MSS	MO	NM	MS	MSC	MSS	MO
Standing Ret	0%	-2.26%	-13.30%	-13.83%	-14.89%	0%	-2.13%	-14.63%	-15.96%	-21.54%
Walking Ret	0%	-9.37%	-8.82%	-12.21%	-16.66%	-6.01%	-10.17%	-18.11%	-18.73%	-22.79%

Table 8.7 Percentage of moisture vapour resistance for all T-shirts for standing and walking postures under windy condition

For standing postures, the designs of MSC, MSS and MO of Group 1 and Group 2 recorded over 10% lower moisture vapour resistance than the control piece. Among these, MO of Group 2 performed the best with reduced R_{et} by 21.54% ($t(4) = 5.836$, $p = 0.004$) relative to the control piece. The data also showed that for a standing posture under windy conditions, an open mesh on the shoulders was not as effective in releasing moisture vapour out, irrespective of the presence of spacer loops. This suggests that the convection or chimney effect was not as effective for this design, unlike other designs with mesh panels placed across the chest, or two front vertical side panels near the side seams, even when both of them were kept open. It can be seen from Table 8.7 that when the mesh is placed on the shoulders only, the test recorded approximately 2% lower R_{et} than the control piece ($t(4) = 1.009$, $p = 0.37$). Once the mesh panels of other body parts were open, the percentage of reduction could be increased from approximately 2% to 13-14%, the differences were significant (MSC: $t(4) = 5.986$, $p = 0.004$; MSS: $t(4) = 6.818$, $p = 0.002$; MO: $t(4) = 5.836$, $p = 0.004$). This indicates that vented design placed on the shoulders solely could not activate the chimney effect, although the vapour moisture would still be released from the porous fabric. However, if other mesh panels were opened at the same time, the ventilation effect would be more remarkable. This shows that dry air could enter the T-shirt through these mesh panels, and carry away the moisture vapour by natural convection.

In a walking posture, again the MO design of Group 2 recorded the lowest R_{et} value compared to the others, a value of 22.79% ($t(4) = 10.447$, $p = 0.000$) lower than the control piece, and 6.13% ($t(4) = 3.649$, $p = 0.022$) lower than the same design style "MO" in Group 1 (-16.66%). MSC and MSS of Group 2 recorded 18.11% ($t(4) = 6.99$, $p = 0.002$) and 18.73% ($t(4) = 7.717$, $p = 0.002$) lower values for R_{et}, respectively. Body motion thus contributed to a further reduction in moisture vapour resistance.

8.5 Conclusions

The experiment showed that the T-shirts with newly designed spacer objects could reduce both total thermal insulation and moisture vapour resistance relative to a normal T-shirt (NM of Group 1, the control piece). Additionally, the performance in reducing moisture vapour resistance was more remarkable than that for thermal insulation. As the T-shirt is a simple garment not intended for thermal protection, its thermal insulation is less important than its moisture vapour resistance with respect to thermal comfort.

As mentioned previously, applied mesh or other vented panels on the shoulders by themselves were not the best solution in contributing to the reduction of total thermal insulation and moisture vapour resistance. Rather, they should be combined with other vented panels located at other body parts in order to activate the chimney effect for better convection and ventilation.

Two chains of spacer material were applied in the shoulder part only in this new design. This design might defer the effectiveness of heat and moisture transfer because the chains of spacer loops only prop up the shoulder part of the T-shirt rather than keeping the whole garment away from the skin. The fabric layer at the lower torso part would still stick to the skin surface. Hence, a better design needed to be created for further development.

Chapter 9

Development of the ventilative T-shirt (III): the third prototypes

9.1 Introduction

From the study conducted in Chapter 8, the new design did not contribute too much for ventilation, the result was different from the one reported in Chapter 7. Hence, the design development should be continuously studied. The construction and the position of the spacer loops should be the prior one to be developed. Furthermore, to ensure that this new design is able to be applied on other fabrication with better air and moisture vapour permeability, moisture management materials should be used.

9.2 Shortcomings of the second prototypes reported in Chapter 8

9.2.1The placement of spacer blocks

Although a chain of continuous spacer loops placed underneath the shoulder area of the T-shirt reduced thermal insulation and moisture vapour resistance, the propping up effect was not applied to other body parts, where it might deter air circulation around the whole body. For example, chest, and the whole lower body truck were still sticking with the T-shirt fabric because the natural drape of the fabric layer tended to be lay down backwards. In addition, no special cutting was applied to the T-shirt shape. When wind blew, the wind pressure "pushed" the fabric against the chest and stomach area, thus minimizing the chimney effect due to a reduced inner air layer between the T-shirt and the skin surface. A new design concept was created to prop up the T-shirt around the whole body, instead of just propping up the shoulder parts of the garment, so as to achieve air circulation around the body.

9.2.2 Construction of the spacer blocks

The chain of the spacer loops resulted in keeping the T-shirt a certain distance away from the skin surface, while being relatively light weight. However, due to the limited choice of sewing machinery, the spacer loops involved hand stitching. These hand stitches were time consuming and it was not easy to control the work quality, such as stitch density and fixity. Hence, a new design was explored to make sure that the loops could be easily prepared using sewing machines.

9.3 New development of the spacer blocks

A chain of spacer loops could not be generated by a sewing machine, although the stitches were important as they could lock two spacer loops firmly to solve the problem of bending and collapsing. Hence, a new design was developed as illustrated

in Figures 9.1, 9.2 and 9.3; Figure 9.4 shows a photo of the spacer blocks and Figure 9.5 explains the construction process. By using this new design, all the sewing could be done with a sewing machine, and the loops were still locked by stitch B (see Figure 9.2) in order to secure it and avoid collapse due to the relatively heavy weight of the T-shirt.

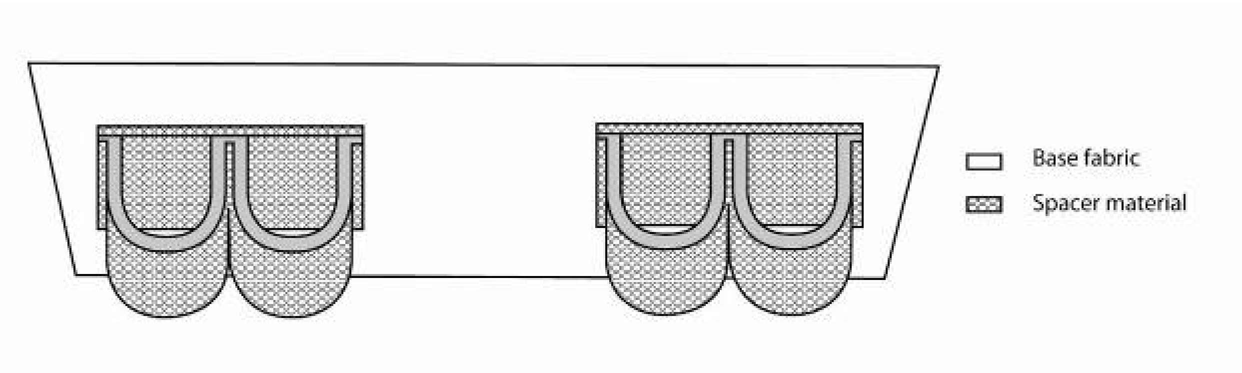


Figure 9.1 - Outlook of the spacer blocks formed by two loops

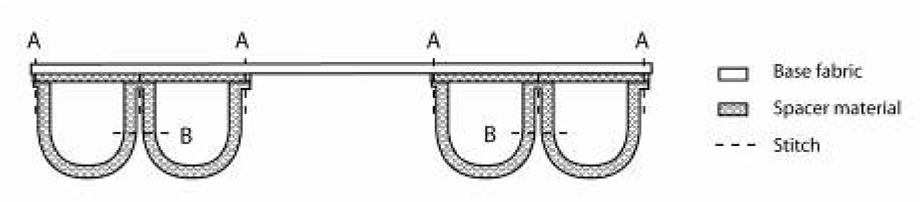


Figure 9.2 - Side view of the spacer blocks

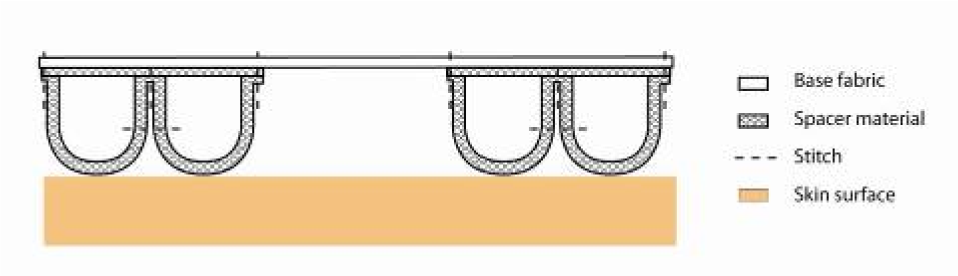


Figure 9.3 - Side view of the spacer blocks touching the skin surface

Figure 9.4 – Photo of the new spacer blocks

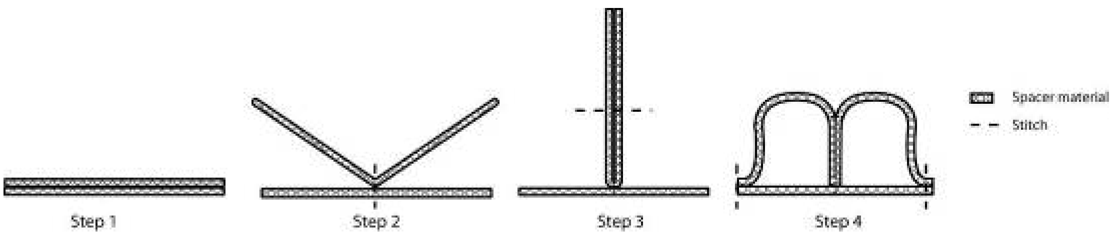


Figure 9.5 - Construction process of the spacer blocks (side view)

To make the spacer block, firstly two layers of spacer material were placed together for stitching (step 1). A stitch was then sewn to join the two layers of spacer materials in the middle (step 2). Then the top layer was folded and a stitch was sewn in the middle (step 3). Finally, the two sides were turned down to allow them to be stitched to the base (step 4). This process simplified the construction of the spacer loops without the need for hand stitching. The spacer loops were not placed continuously, instead they were placed two by two, and there was a certain space between them. This fabrication method did not only eliminate the hand stitching process, the space between the spacer blocks could provide a bigger air space that might be sufficient for better air circulation.

9.4 Placement of the spacer blocks on the new design

Some spacer blocks were placed at the chest to prop up that fabric layer away from the skin surface, in order to create a wider air space for air circulation. Apart from the chest area, some spacer blocks were also put underneath the neckline, so that the T-shirt fabric layer would not touch the neck, and the bigger aperture was assumed to help release body heat and moisture vapour when pumping effect or chimney effect was activated. Some spacer blocks were also put along the hem line of the T-shirt to create apertures to let in more ambient air for cooling. At the back of the body, however, the spacer blocks were only placed underneath the upper shoulder area, rather than the rest of the back, since spacer blocks in these areas might cause discomfort when the wearer leans against the back. Figure 9.6 shows the inside-out view of the T-shirt.

Figure 9.6 - Inside out view of the new T-shirt (Left: front view; Right: back view)

9.5 Evaluation of the new design

In order to compare the new T-shirt designs with those reported in Chapter 8, the fabrication and size of the T-shirt and the placement of the mesh panels was maintained the same (i.e. NM, MS, MSC, MSS and MO). The new design has been labelled as Group 3 and the measurement method was also kept the same as the one in Chapter 8. The target of this new T-shirt design was to achieve better ventilation than the one with a chain of spacer loops in the shoulder area, and therefore its results were compared with all the designs in Group 2 of Chapter 8. Tables 9.1 and 9.2 list the testing results for all designs in Group 3. Figures 9.7- to 9.10 display the charts for comparing all designs of Group 1 and Group 2, and Tables 9.3 and 9.4 list the percentage change for all designs in Group 1, 2 & 3 for standing and walking postures under no wind and windy conditions. The control piece was the NM of Group 1 again, the most basic T-shirt without mesh panels and spacer material underneath. Again, to evaluate the significance of the differences of the T-shirts in terms of thermal insulation and moisture vapour resistance values, independent t-test was carried out.

			Standing (no wind)		**Walking (no wind)**	
			Mean	S.D.	Mean	S.D.
Group 3	NM	R_t	0.122	0.005	0.115	0.004
		R_{et}	19.6	0.63	17.85	0.53
	MS	R_t	0.119	0.005	0.112	0.005
		R_{et}	18.13	0.69	17.382	0.29
	MSC	R_t	0.122	0.004	0.112	0.004
		R_{et}	18.34	0.57	17.008	0.32
	MSS	R_t	0.121	0.005	0.11	0.002
		R_{et}	18.01	0.64	17.062	0.53
	MO	R_t	0.121	0.006	0.11	0.002
		R_{et}	17.89	0.34	16.75	0.45

Table 9.1 - R_t and R_{et} values of all designs of Group 3 under no wind condition

			Standing (windy)		Walking (windy)	
			Mean	S.D.	Mean	S.D.
Group 3	NM	R_t	0.063	0.001	0.06	0.002
		R_{et}	7.28	0.11	7.193	0.15
	MS	R_t	0.062	0.001	0.059	0.001
		R_{et}	6.693	0.19	6.59	0.1
	MSC	R_t	0.06	0.001	0.056	0.001
		R_{et}	6.057	0.21	5.84	0.12
	MSS	R_t	0.06	0.001	0.056	0.001
		R_{et}	5.801	0.2	5.774	0.08
	MO	R_t	0.059	0.001	0.056	0.001
		R_{et}	5.68	0.28	5.663	0.16

Table 9.2 - R_t and R_{et} values of all designs of Group 3 under windy condition

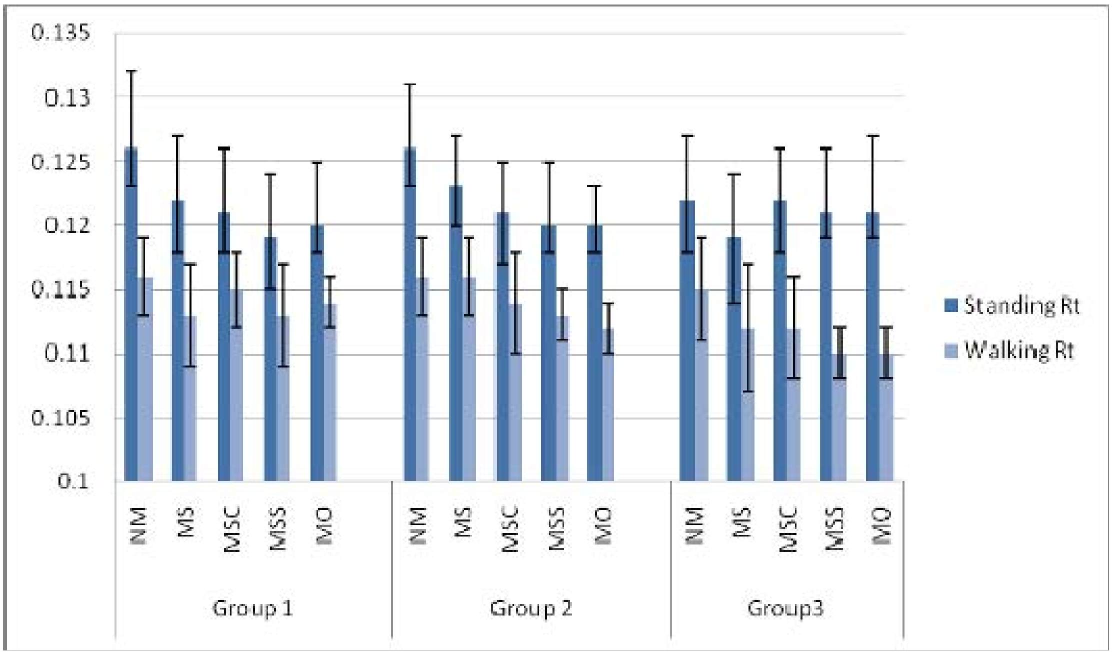


Figure 9.7 - Comparison of the total thermal insulation for all T-shirts for standing and walking postures under no wind condition

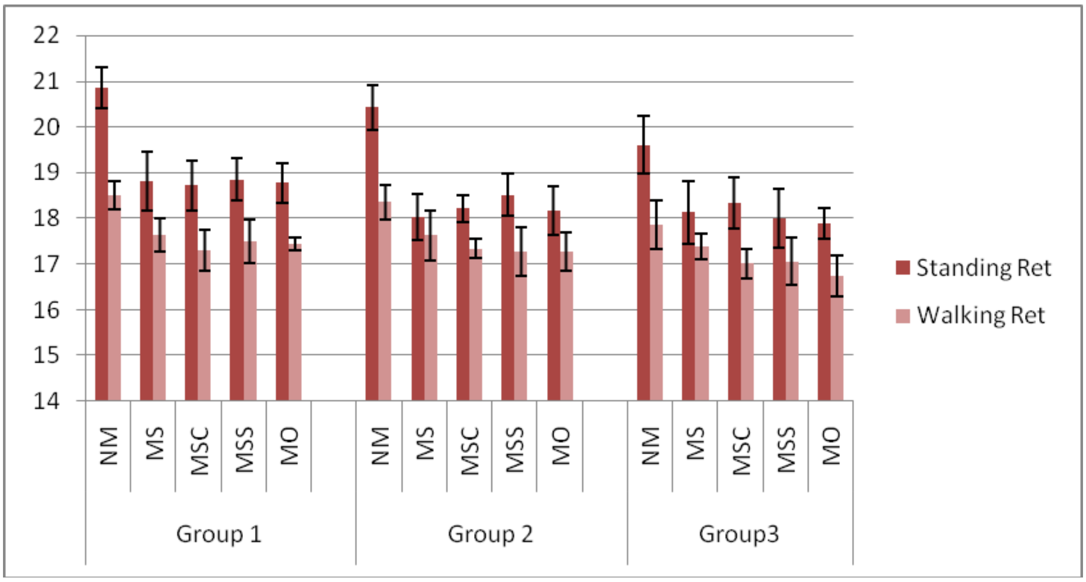


Figure 9.8 - Comparison of the moisture vapour resistance for all T-shirts for standing and walking postures under no wind condition

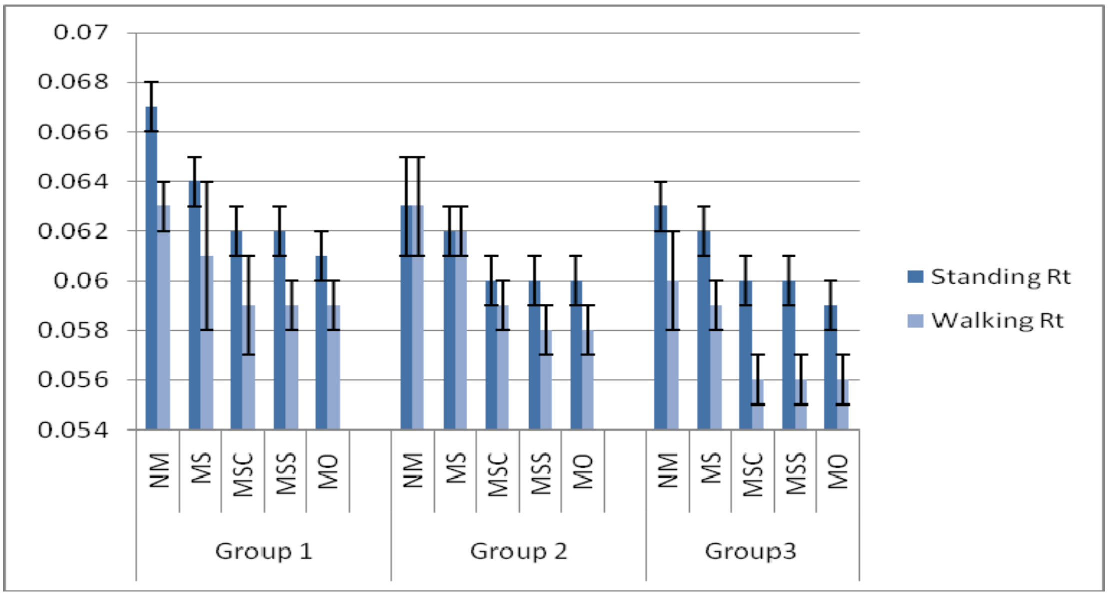


Figure 9.9 - Comparison of the total thermal insulation for all T-shirts for standing and walking postures under windy condition

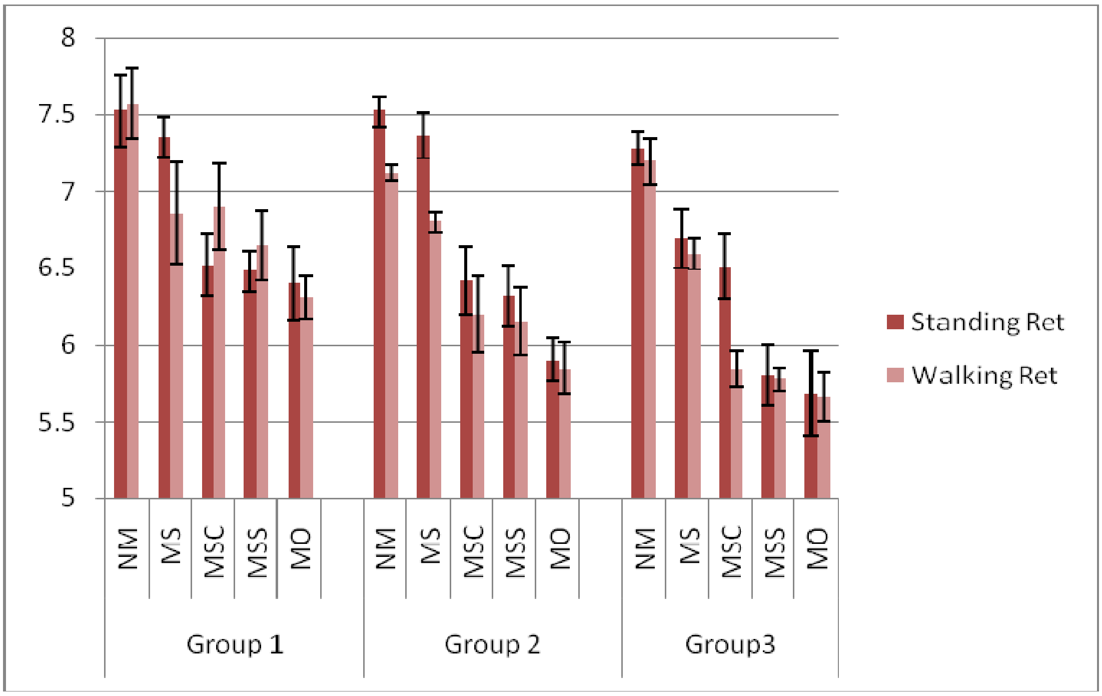


Figure 9.10 - Comparison of the moisture vapour resistance for all T-shirts for standing and walking postures under windy condition

No wind standing R_t

	NM	MS	MSC	MSS	MO
Group 1	0%	-3.17%	-3.97%	-5.56%	-4.76%
Group 2	0%	-2.38%	-3.97%	-4.76%	-4.76%
Group 3	**-3.17%**	**-5.56%**	**-3.17%**	**-3.97%**	**-3.97%**

No wind standing R_{et}

	NM	MS	MSC	MSS	MO
Group 1	0%	-9.74%	-10.22%	-9.59%	-9.98%
Group 2	-2.06%	-13.57%	-12.66%	-11.22%	-12.85%
Group 3	**-6.00%**	**-13.05%**	**-12.04%**	**-13.62%**	**-14.20%**

No wind walking R_t

	NM	MS	MSC	MSS	MO
Group 1	0%	-2.59%	-0.86%	-2.59%	-1.72%
Group 2	0%	0%	-1.72%	-2.59%	-3.45%
Group 3	**-0.86%**	**-3.45%**	**-3.45%**	**-5.17%**	**-5.17%**

No wind walking R_{et}

	NM	MS	MSC	MSS	MO
Group 1	0%	-4.68%	-6.53%	-5.46%	-5.79%
Group 2	-0.84%	-4.74%	-6.32%	-6.62%	-6.63%
Group 3	**-3.57%**	**-6.09%**	**-8.11%**	**-7.82%**	**-9.51%**

Table 9.3 - Comparison of R_t and R_{et} values for all designs under no wind condition

9.6 Results and discussion

9.6.1 Thermal insulation and moisture vapour resistance at standing posture under no wind condition

The thermal insulation and moisture vapour resistance of the new designs in Group 3 were not too different from those of the designs in Group 2. For R_t, only MS had a greater reduction than the same designs of Group 2, while MSC, MSS and MO had slightly higher values than those in Group 2. However, the difference was not significant (approximately 0.8%). In comparison, the new designs of Group 3 showed better results for R_{et} values than those in Group 2. For example, MSS and MO recorded lower values by 2.4% and 1.35%, compared with the designs of Group 2. In standing posture under a no wind condition, air circulation was not activated by wind or body movement, the body heat and moisture vapour could only escape through the fabric layer or mesh panels to the ambient environment. Although bigger apertures as in the neckline and hemline were created in this design, there was not a substantial difference in thermal insulation and moisture vapour resistance from the designs of Group 2, although this group of design was able to reduce total thermal insulation and moisture vapour resistance by a certain amount compared to the control piece.

9.6.2 Thermal insulation and moisture vapour resistance at walking motion under no wind condition

When Walter simulated a “walking” motion, all designs of Group 3 recorded lower R_t and R_{et} values than those in Group 2. The MSS and MO of Group 3 reduced the R_t value by 5.17%, the biggest reduction among all the designs (MSS: $t(4) = 2.882$, $p = 0.045$; MO: $t(4) = 2.882$, $p = 0.045$). With regards to the R_{et} value, MO design of Group 3 recorded the lowest value for both total thermal insulation and moisture vapour resistance ($t(4) = 5.637$, $p = 0.005$), suggesting that this design was the best for activating ventilation. Since the arms of Walter were moving during these tests, the pumping effect could allow air circulation within the micro-climate of the body. The main reason for propping up the neckline was to let warm and saturated body air to be released through the enlarged opening, unlike in design Group 2 where the neckline of the T-shirt stuck to the skin so that warm body air and moisture vapour accumulated around that area, thus causing the wearer to feel hot in the neck area.

Windy standing R_t

	NM	MS	MSC	MSS	MO
Group 1	0%	-4.48%	-7.46%	-7.46%	-8.96%
Group 2	-5.97%	-7.46%	-10.45%	-10.45%	-10.45%
Group 3	**-5.97%**	**-7.46%**	**-10.45%**	**-10.45%**	**-11.94%**

Windy standing R_{et}

	NM	MS	MSC	MSS	MO
Group 1	0%	-2.26%	-13.30%	-13.83%	-14.89%
Group 2	0%	-2.13%	-14.63%	-15.96%	-21.54%
Group 3	**-3.19%**	**-11.00%**	**-19.45%**	**-22.86%**	**-24.47%**

Windy walking R_t

	NM	MS	MSC	MSS	MO
Group 1	0%	-3.17%	-6.35%	-6.35%	-6.35%
Group 2	0%	-1.59%	-6.35%	-7.94%	-7.94%
Group 3	**-4.76%**	**-6.35%**	**-11.11%**	**-11.11%**	**-11.11%**

Windy walking R_{et}

	NM	MS	MSC	MSS	MO
Group 1	0%	-9.37%	-8.82%	-12.21%	-16.66%
Group 2	-6.01%	-10.17%	-18.11%	-18.73%	-22.79%
Group 3	**-4.98%**	**-12.95%**	**-22.85%**	**-23.73%**	**-25.19%**

Table 9.4 Comparison of R_t and R_{et} values for all designs under windy condition

9.6.3 Thermal insulation and moisture vapour resistance at standing posture under windy condition

At a standing posture under windy conditions, designs of Group 3 recorded lower R_t and R_{et} value compared to those in Group 2, although the R_t value was nearly the same. MO of Group 3 once again recorded the lowest R_t value among all the designs. MO of Group 3 also performed the best with regards to R_{et} value with a 24.47% ($t(4) = 8.795$, $p = 0.001$) reduction relative to the control piece, or nearly 3% ($t(4) = 3.382$, $p = 0.028$) better than the MO design of Group 2. The designs MSS and MSC led to a 22.86% ($t(4) = 9.769$, $p = 0.001$) and 19.45% ($t(4) = 8.136$, $p = 0.001$) reduction in $R_{et,}$ respectively relative to the control piece. Although Walter was standing still and not activating the pumping effect through movement, the wind was effective enough to bring cool and dry air to the air space created by the spacer blocks, and the body heat and moisture vapour were released out through the mesh panels. Therefore, the difference was remarkable compared to the same designs under no wind standing conditions.

9.6.4 Thermal insulation and moisture vapour resistance at walking motion under windy condition

The walking movement of Walter activated the pumping effect, and with the additional aid of wind, the new design created significant ventilation and chimney effects. To conclude, all the designs of Group 3 recorded lower R_t and R_{et} values than those of Group 2, thus showing that the new design and placement of the spacer blocks, plus the enlarged aperture around the neckline and the hem functioned well in transferring heat and moisture. MSC, MSS and MO designs of Group 3 had a 11.11% reduction in R_t, and a 22.85% ($t(4) = 11.55$, $p = 0.00$), 23.73% ($t(4) = 12.774$, $p = 0.00$) and 25.19% ($t(4) = 11.789$, $p = 0.00$) reduction in R_{et} values, respectively.

9.7 New design with moisture management fabric (100% polyester)

As mentioned in the literature review chapter, fabrication is always an important element influencing the effectiveness of heat and moisture transfer. Some of the sport clothing available in the market is made of 100% polyester because of its high air and moisture permeability. In order to test the workability of the new design concept, 100% polyester with "dry-quick" treatment was used as the base fabric for the T-shirt. Fabric 9.1 shows the fabric used in the coming test while Table 9.5 provides the data for the air permeability, water adsorption rate and other fabric details of this 100% polyester, and its comparison to the fabric (95% cotton 5% spandex fine knitted jersey) used for Groups 1, 2 and 3 designs. To keep the testing result consistent, the design, size, construction, placement of spacer blocks, positions of mesh panels were the same as those in Group 3. The measurement method was also exactly the same (using Walter in the chamber) which also included standing and walking postures under no wind and windy (same velocity) conditions.

Fabric 9.1 – 100% polyester with dry-quick treatment

	Thermal conductivity	Water vapour permeability	Air permeability	Wicking height (>100mm)	
	(unit W/mK)	WVP (g/m^2)	R (Kpa-s/m)	Warp	Weft
95% cotton 5% spandex	0.063	1034.14	0.6454	2	1.8
100% polyester	0.049	9193.96	0.0358	160	160.3

Table 9.5 – Fabric properties of the polyester and cotton jersey used in the study

Due to the different fabrics, the control piece was made from the new quick-dry polyester fabric, and therefore the design of Group 1 was not used in this experiment. To summarize, the new designs included:

<u>Group 4 without spacer blocks</u>

- NM, MS, MSC, MSS and MO (the styles and the position of mesh panels were exactly the same as those in Group 1, but the shell fabric was changed to 100% polyester with "dry-quick" moisture management).
- No spacer blocks were placed on the T-shirt (see Figure 9.11)
- As there was no mesh panels used for the NM style, this T-shirt was used as the control piece for the following testing. These designs have been coded as "Group 4 **without** spacer blocks".

Figure 9.11 – T-shirts of "Group 4 without spacer blocks

Group 4 with spacer blocks

- NM, MS, MSC, MSS and MO (the styles and the position of mesh panels were exactly the same as those in Group 3, the shell fabric was 100% polyester with "dry-quick" moisture management).
- Spacer blocks were placed on the T-shirt (see Figure 9.12)
- These designs have been named as "Group 4 **with** spacer blocks".

Figure 9.12 – T-shirts of "Group 4 with spacer blocks"

9.8 Results and discussion (100% polyester)

The results of the tests are listed in Tables 9.7 and 9.8. Figures 9.12, 9.13, 9.14 and 9.15 compare the R_t and R_{et} values for all designs made of polyester, for standing and walking postures under no wind and windy conditions.

			Standing (no wind)		Walking (no wind)	
			Mean	S.D.	Mean	S.D.
Without spacer blocks	NM	R_t	0.125	0.005	0.113	0.003
		R_{et}	18.936	0.821	16.823	0.661
	MS	R_t	0.121	0.005	0.112	0.004
		R_{et}	17.54	0.684	16.629	0.405
	MSC	R_t	0.121	0.004	0.112	0.001
		R_{et}	17.572	0.736	16.013	0.517
	MSS	R_t	0.12	0.003	0.111	0.003
		R_{et}	17.412	0.411	15.843	0.098
	MO	R_t	0.119	0.005	0.11	0.004
		R_{et}	17.204	0.75	15.765	0.753
With spacer blocks	NM	R_t	0.122	0.003	0.112	0.003
		R_{et}	18.804	0.675	16.589	0.694
	MS	R_t	0.118	0.004	0.111	0.003
		R_{et}	16.539	0.557	16.068	0.273
	MSC	R_t	0.119	0.004	0.11	0.003
		R_{et}	16.754	0.68	15.97	0.253
	MSS	R_t	0.12	0.003	0.109	0.004
		R_{et}	16.431	0.575	15.285	0.354
	MO	R_t	0.119	0.003	0.108	0.003
		R_{et}	16.352	0.695	14.897	0.267

Table 9.7 - R_t and R_{et} values for all designs of Group 4 under no wind condition

			Standing (Windy)		Walking (Windy)	
			Mean	S.D.	Mean	S.D.
Without spacer blocks	NM	R_t	0.063	0.001	0.061	0.001
		R_{et}	6.752	0.125	6.44	0.241
	MS	R_t	0.062	0.001	0.06	0.001
		R_{et}	6.36	0.193	6.12	0.062
	MSC	R_t	0.062	0.002	0.06	0.001
		R_{et}	6.332	0.208	5.749	0.013
	MSS	R_t	0.06	0.001	0.058	0.001
		R_{et}	6.29	0.118	5.96	0.282
	MO	R_t	0.06	0.001	0.058	0.002
		R_{et}	6.249	0.114	5.715	0.06
With spacer blocks	NM	R_t	0.061	0.001	0.058	0.001
		R_{et}	6.733	0.176	6.11	0.089
	MS	R_t	0.061	0.001	0.058	0.001
		R_{et}	6.229	0.089	5.914	0.119
	MSC	R_t	0.058	0.001	0.057	0.001
		R_{et}	5.954	0.071	5.36	0.079
	MSS	R_t	0.061	0.001	0.059	0.001
		R_{et}	6.157	0.037	5.642	0.058
	MO	R_t	0.059	0.002	0.056	0.001
		R_{et}	5.767	0.105	5.32	0.113

Table 9.8 - R_t and R_{et} values for all designs of Group 4 under windy condition

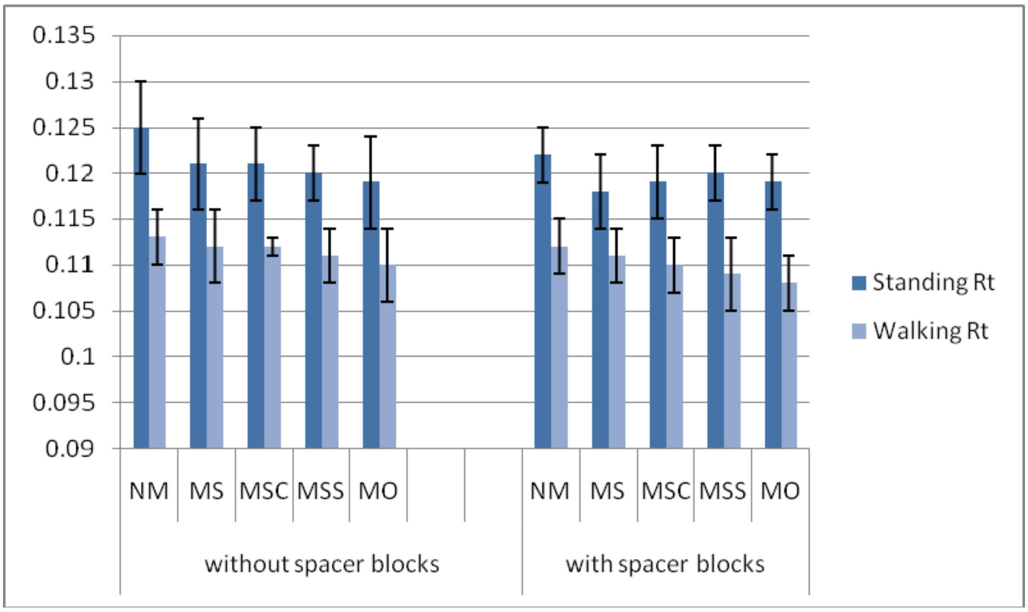


Figure 9.13 - Comparison of the total thermal insulation for all Group 4 T-shirts for standing and walking postures under no wind condition

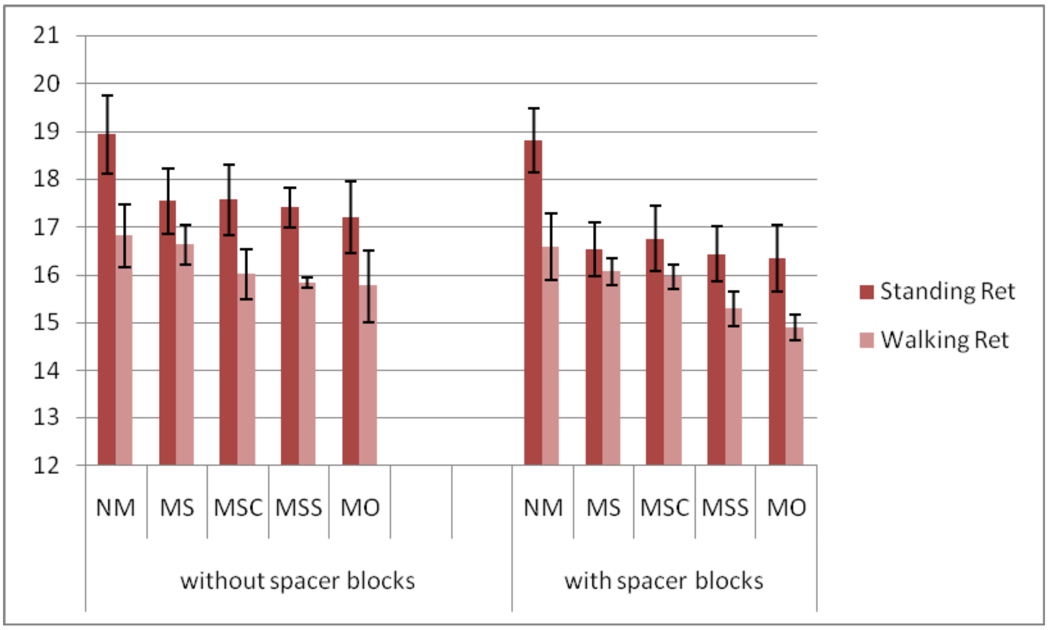


Figure 9.14 - Comparison of the moisture vapour resistance for all Group 4 T-shirts for standing and walking postures under no wind condition

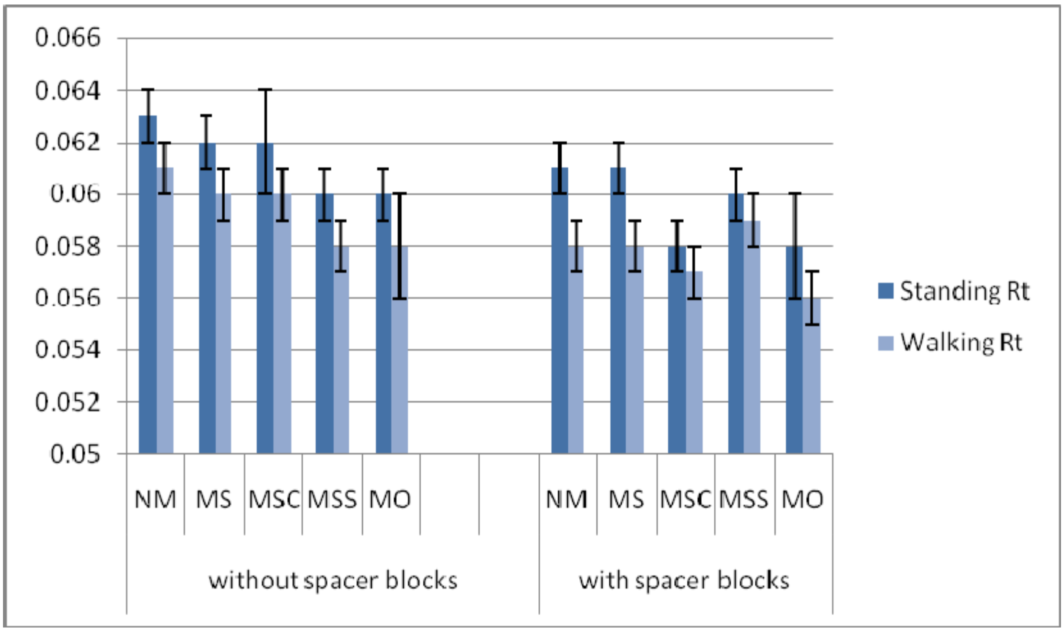


Figure 9.15 - Comparison of the total thermal insulation for all Group 4 T-shirts for standing and walking postures under windy condition

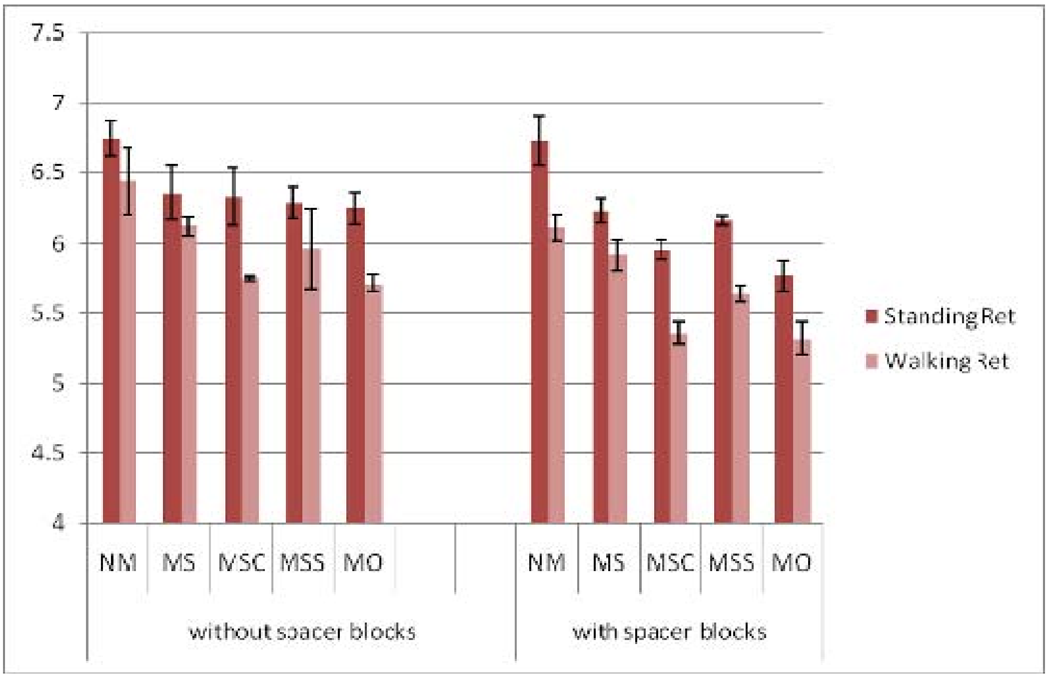


Figure 9.16 - Comparison of the moisture vapour resistance for all Group 4 T-shirts for standing and walking postures under windy condition

9.8.1 Thermal insulation and moisture vapour resistance under no wind condition

Table 9.9 plots the percentage change for all T-shirts in Group 4 design, including those with and without the attachment of the spacer blocks. It shows that although the fabric was changed from 95% cotton 5% spandex to 100% polyester with moisture management, the new design concept of ventilation garment was still able to reduce the total thermal insulation and moisture vapour resistance. For total thermal insulation, the MO with spacer blocks could reduce R_t by 6.4% for standing posture and 4.42% for walking posture; these values were less than the same design (MO) without spacer blocks attached (reduction of 0.8% and 1.77%). The result of the t-test showed that such differences were not significant (standing: $t(4) = 1.782$, $p = 0.149$; walking: $t(4) = 2.041$, $p = 0.111$). However, the reduction in R_{et} was more remarkable. Again MO design achieved the lowest R_{et} value in both postures i.e. -13.65% ($t(4) = 4.161$, $p = 0.014$) for standing and -11.45% ($t(4) = 4.679$, $p = 0.009$) for walking postures. Their differences were significant.

One observation made here was about the percentage of reduction compared with the NM style without spacer blocks. The reduction of R_t and R_{et}, was larger for standing posture rather than walking posture. This could be explained by the use of material with moisture management, so that the new design concept has a greater effect during standing posture, where pumping effect was not activated and the body heat needed to be released through the structure of the fabric, or by natural convection through the vented panels. In this condition, the new design could help to enlarge the aperture and allow for a better chimney effect, while in a walking posture, the pumping effect could generate ventilation, and the body heat and moisture vapour could be released through the porous structure of the fabric and the apertures. However, since the moisture management fabric itself had already achieved significant heat and moisture transfer, there was relatively a lower percentage of reduction for R_t and R_{et} than those for standing postures. Referring back to the actual values for R_t and R_{et}, the new design concept achieved the lowest values during a walking posture.

No Wind Standing R_t

	NM	MS	MSC	MSS	MO
Without spacer blocks	0%	-3.20%	-3.20%	-4%	-5.60%
With spacer blocks	-2.40%	-5.60%	-4.80%	-4%	-6.40%

No Wind Standing R_{et}

	NM	MS	MSC	MSS	MO
Without spacer blocks	0%	-7.37%	-7.18%	-8.05%	-9.15%
With spacer blocks	-0.70%	-12.66%	-11.52%	-13%	-13.65%

No Wind Walking R_t

	NM	MS	MSC	MSS	MO
Without spacer blocks	0%	-0.88%	-0.88%	-2%	-2.65%
With spacer blocks	-0.88%	-2.00%	-2.65%	-4%	-4.42%

No Wind Walking R_{et}

	NM	MS	MSC	MSS	MO
Without spacer blocks	0%	-1.15%	-4.81%	-6%	-6.29%
With spacer blocks	-1.39%	-4.49%	-5.07%	-9%	-11.45%

Table 9.9 - R_t and R_{et} values for polyester T-shirts (with and without spacer blocks) for standing and walking postures under no wind condition

9.8.2 Thermal insulation and moisture vapour resistance under windy condition

Table 9.10 lists the percentage change of R_t and R_{et} under a windy condition for all T-shirts in Group 4 design, including those with and without spacer blocks attached. It shows that the new design concept could be also applied on this moisture management fabric in order to reduce total thermal insulation and moisture vapour resistance under a windy mode. Among all the designs, MO with spacer blocks again achieved the lowest values for reduction of R_t and R_{et} in both standing and walking postures under windy conditions.

When Walter was standing under a windy condition, MO with spacer blocks reduced R_t by 7.94% ($t(4) = 3.098$, $p = 0.036$) and R_{et} by 14.59% ($t(4) = 10.451$, $p = 0.00$) relative to the NM design without spacer blocks. MO with spacer blocks even had lower R_t and R_{et} values than MO without spacer blocks, with the difference being 3.21% for R_t ($t(4) = 0.775$, $p = 0.482$) and 7.14% for R_{et} ($t(4) = 5.387$, $p = 0.006$). This indicated that although Walter was standing still without moving arms, the wind was effective enough to strengthen the ventilation. The propping up effect and the placement of vented panels helped improve the release of moisture vapour.

The ventilation was even stronger under a walking condition. The MO design with spacer blocks reduced R_t by 8.2% ($t(4) = 6.142$, $p = 0.004$) and R_{et} by 17.39% ($t(4) = 7.288$, $p = 0.002$) compared to NM without spacer blocks. Comparing these results with the same style (MO) without spacer blocks, the T-shirt with spacer blocks contributed to lowering R_t by 3.28% (t (4) = 1.549, p = 0.196) and R_{et} by 6.13% (t (4) = 5.347, p = 0.006), the difference was significant for reducing the moisture vapour resistance. The data suggest that the new design concept could assist the garment made of moisture management fabric to further reduce the total thermal insulation and moisture vapour resistance.

Windy Standing R_t

	NM	MS	MSC	MSS	MO
Without spacer blocks	0%	-1.59%	-1.59%	-5%	-4.76%
With spacer blocks	-3.17%	-3.17%	-7.94%	-4.76%	-7.94%

Windy Standing R_{et}

	NM	MS	MSC	MSS	MO
Without spacer blocks	0%	-5.81%	-6.22%	-7%	-7.45%
With spacer blocks	-0.28%	-7.75%	-11.82%	-8.81%	-14.59%

Windy Walking R_t

	NM	MS	MSC	MSS	MO
Without spacer blocks	0%	-1.64%	-1.64%	-4.92%	-4.92%
With spacer blocks	-4.92%	-4.92%	-6.56%	-3.28%	-8.20%

Windy Walking R_{et}

	NM	MS	MSC	MSS	MO
Without spacer blocks	0%	-4.97%	-10.73%	-7.45%	-11.26%
With spacer blocks	-5.12%	-8.17%	-16.77%	-12.39%	-17.39%

Table 9.10 - R_t and R_{et} values of polyester T-shirts (with and without spacer blocks) for standing and walking postures under windy condition

9.9 Evaluation of the new design concept applied for moisture management fabric

The testing results show that this new design concept could be applied to T-shirts made of moisture management fabric. In general, the moisture management fabric could contribute to reducing R_t and R_{et}. Taking the NM and MO styles without spacer blocks, the MO styles reduced R_t and R_{et} by 5.6% (t (4) = 1.47, p = 0.216) and 9.15% (t (4) = 2.698, p = 0.054) under a no wind standing situation; and, by 2.65% (t (4) = 1.039, p = 0.357) and 6.21% (t (4) = 1.829, p = 0.141) under a no wind walking situation; and, by 4.76% (t (4) = 3.674, p = 0.021) and 7.45% (t (4) = 5.15, p = 0.007) under a windy standing situation; and lastly, by 4.92% (t (4) = 2.324, p = 0.081) and 11.26% (t (4) = 5.056, p = 0.007) relative to the NM design (without spacer blocks) respectively under a windy walking situation. If the spacer blocks were added to the design, the reduction was -6.4% (R_t) (t (4) = 1.782, p = 0.149) and -13.65 (R_{et}) (t (4) = 4.161, p = 0.014) under a no wind standing situation; -4.42% (R_t) (t (4) = 2.041, p = 0.111) and -11.45% (R_{et}) (t (4) = 4.679, p = 0.009) under a no wind walking situation; -7.94% (R_t) (t (4) = 3.098, p = 0.036) and -14.59% (R_{et}) (t (4) = 10.451, p = 0.00) under a windy standing situation and -8.2% (R_t) (t (4) = 6.124, p = 0.004) and -17.39% (R_{et}) (t (4) = 7.288, p = 0.002) compared to the NM (with spacer blocks) design under a windy walking situation. The new design concept was able to further reduce the R_t and R_{et} values, especially as the reduction was generally greater than 10% compared with the NM without spacer blocks in all conditions. However, comparing the polyester T-shirt with the 95% cotton 5% spandex used in the previous chapter, the percentage of reduction was slightly lower (as the MO of Style 3 design had more than 20% reduction in R_{et} compared to the control piece) when this new design was applied to moisture management fabric. It is easy to understand that the basic T-shirt style made of cotton or cotton spandex fabric had comparatively poor ability for heat and moisture transfer compared to the moisture management fabric, and thus the new design concept played the dominant role in body ventilation, and hence the percentage contribution was higher in the fabric without moisture management property. For the fabric with high wicking function, the moisture management fabric itself had taken responsibility for heat and moisture transfer, so that the relative contribution of the new design concept was lower than normal cotton fabric. However, if all designs are compared, while ignoring the percentage of the reduction, the one with moisture management fabric together with the new design concept recorded the lowest values of R_t and R_{et}, especially under windy conditions, no matter standing or walking.

Chapter 10

Design collection with the novel design concept

10.1 Introduction

As the new design concept had proved effective in reducing the total thermal insulation and moisture vapour resistance, this chapter aims at creating an aesthetically appealing collection incorporating the guidelines obtained from the previous chapters. The design collection will also showcase other variations of the new design concept. One of the styles will be chosen randomly for wearer trial.

10.2 Design Brief for the collection

Based on the testing results, a design brief was carried out for the collection:

1. Propping up effect by placing spacer material blocks.
2. The construction of the spacer material blocks should followed the results of Chapter 9.
3. The spacer material blocks should be placed around the front body such as neckline, shoulders, chest, and the hemline. Spacer material blocks should also

be placed near the upper part of the back shoulders to provide better performance.

4. Vented details should be placed on the garment.

5. The vented details or panels should be located near the shoulder area, in order to allow rising warm body air along with moisture vapour to be released.

6. Apart from the shoulder area, at least one more vented detail or panel should be put near other body parts, such as across the chest and vertical side panels near the side seams.

10.3 Design Collection

Designs 1 and 2

In these two designs mesh panels were placed in the shoulder area, across the chest and two vertical front panels near the side seams. Some spacer blocks were located around the front and the upper back. For design 2 the mesh area was placed in the shape of an “X” at the front and the back.

Figure 10.1 and Figure 10.2 – The front and side view of Design 1

Figure 10.3 and Figure 10.4 – The front and side view of Design 2

Designs 3 and 4

In these two designs special details were applied to the vented panels, in order to give an attractive design feature to the T-shirt. In order to show more variation of the style, the vented details were placed only in the shoulder area and two vertical panels near the side seams but not across the front chest. According to the testing results, this kind of design might not be the best design to achieve body ventilation; however it could provide more options for the market.

Figure 10.5 and Figure 10.6 – The front and side view of Design 3

Figure 10.7 and Figure 10.8 – The front and side view of Design 4

The four designs shown in the previous section are only some of the examples following the new design concept. The design and the style can be diversified so that designers could have more freedom to create based on the design brief that has been developed through this study.

Chapter 11

Subjective wearer trials for comfort assessment

11.1 Introduction

The interaction of a clothing system is derived from the physical properties of the clothing and ventilation effect. In order to study the influence of a clothing system on the physiological and subjective sensations, many researchers conducted experiments on subjects wearing different clothing under different conditions (Vokac *et al* 1973, Vogt *et al* 1983, Nielsen *et al* 1989, Havenith *et al* 1990, Bakkevig and Nielsen 1995, Kondo *et al* 1997, Kwon *et al* 1998, Patterson *et al* 1998, Zhang *et al* 2002, Ueda *et al* 2006, Fan and Tsang 2008).

In order to validate the effectiveness of the T-shirts with the novel ventilative designs, wearer trials were carried out to compare one typical new design with the conventional design in terms of wearers' subjective perceptions and direct thermoregulatory responses.

11.2 Human subjects

Four male volunteers participated as human subjects in the wearer trials. All subjects were healthy and exercised regularly. The details of the subjects are listed in table 11.1. The surface area was calculated according to the formula of DuBois and DuBois

(1916). In order to minimize the interference factors of fatigue, all subjects had a sufficient amount sleep on the night before the test, and refrained from other exercise before the trials. They also did not ingest food or water for two hours before trails began until the test was finished. They were required to wear different sets of T-shirts alternatively so that each subject wore each set of T-shirts once. Figure 11.1 shows one of the subjects during the test.

Subject	Age	Height (cm)	Weight (lbs)	DuBois surface area (m^2)
A	30	170	150	1.788
B	33	173	159	1.856
C	29	169	148	1.77
D	32	174	156	1.849

Table 11.1 – Details of the subjects

Figure 11.1 – One of the subjects

11.3 Condition of the chamber

The test was conducted in a controlled climate chamber at a temperature of 20.0 ± 0.5 ºC, relative humidity of 50.0 ± 2% RH and air velocity of 0.22 m/s. The T-shirts were hung in the conditioned climate chamber for at least 2 hours before the experiment.

11.4 Garment samples

Totally three T-shirts were tested by the subjects. They were washed once before used for the experiment. All of them were made of 100% polyester with dry-quick moisture management (the one reported in the Chapter 9). In order to make the surface of the spacer blocks smooth, a 100% cotton fabric was used to cover the surface of the spacer material. The code of each T-shirt was:

1. **T-shirt A**: Control piece (no mesh panels and spacer loops attached) (Figure 11.2)

2. **T-shirt B**: Design 1 but no spacer loops attached (Figure 11.3)

3. **T-shirt C**: Design 1 (with spacer loops underneath) (Figure 11.4)

In order to standardize the testing, the style of shorts, underwear and socks were the same for all subjects.

Figure 11.2 – **T-shirt A** (control piece)

Figure 11.3 – **T-shirt B** (without spacer blocks)

Figure 11.4 – **T-shirt C** (with spacer blocks) (Left: front view; Right: inside-out view)

11.5 Exercise

Subjects were required to run on a motorized treadmill for 30 minutes at the running speed of 5.0km/hr. After 30 minutes run, the subsets were asked to take a rest in the chamber for 10 minutes.

11.6 Measurement points

Olesen (1984) conducted a review on estimating the average skin temperature and humidity by analyzing the investigations by other researchers. Referring to his equations, temperature and humidity sensors were located at the chest, upper back, lower back, hand, shin and calf.

The average skin (Ts) temperature was calculated as:

$$Ts= 0.18\ T_{back} + 0.218T_{u\cdot chest} + 0.143\ T_{hand} + 0.15\ T_{l\cdot back} + 0.167\ T_{shin} + 0.142\ T_{calf}$$

The average skin humidity (Hs) was calculated as:

$$Hs= 0.181\ T_{back} + 0.218H_{u\cdot chest} + 0.142\ H_{hand} + 0.15\ H_{l\cdot back} + 0.167\ H_{shin} + 0.142\ H_{calf}$$

11.7 Procedure of wearer trials

1. A brief instruction was given to the subject in order to ensure that he understood the procedures and the detailed information of the wearer trial.
2. Wearer was required to take rest for at least 10 minutes after arriving at the chamber.
3. Weigh the garment (in gram) before dressing.
4. Subject dressed in the testing garments and provided shorts.
5. Subject sat down for 5 minutes.
6. Temperature and humidity sensors was placed on the subject's chest, upper back, lower back, hand, shin and calf.
7. Subject rated the comfort sensations before running.
8. Subject started to run on a motorized treadmill at a 5.0 km/hr for 30 mins
9. Subject rated the comfort sensations during 10 minutes, 20 minutes and 30 minutes of running time.
10. Subject took a rest for 10 minutes. Then he was required to rate the comfort sensation.

11. Subject took off the test sample.

12. Weigh the garment (in gram) after exercise.

11.8 Questionnaire

Apart from obtaining temperature and humidity of the subject, a questionnaire was set to ask the personal perception of comfort sensations. In this test, a ten-point thermal sensation scale was used. 10 was the best rating while 0 was the poorest. The questionnaire is shown in Table 11.2.

Comfort Criteria	Rating Scale										
	0	1	2	3	4	5	6	7	8	9	10
Lightness											
Breathability											
Coolness											
Dryness											
Smoothness											
Softness											
Easy movement											
Overall comfort											

Table 11.2 – Rating scale of comfort sensations

11.9 Results and discussion

11.9.1 The change of average skin temperature

Figure 11.5 shows the trends of the changes in the average skin temperature by wearing different T-shirts during the wearer trials.

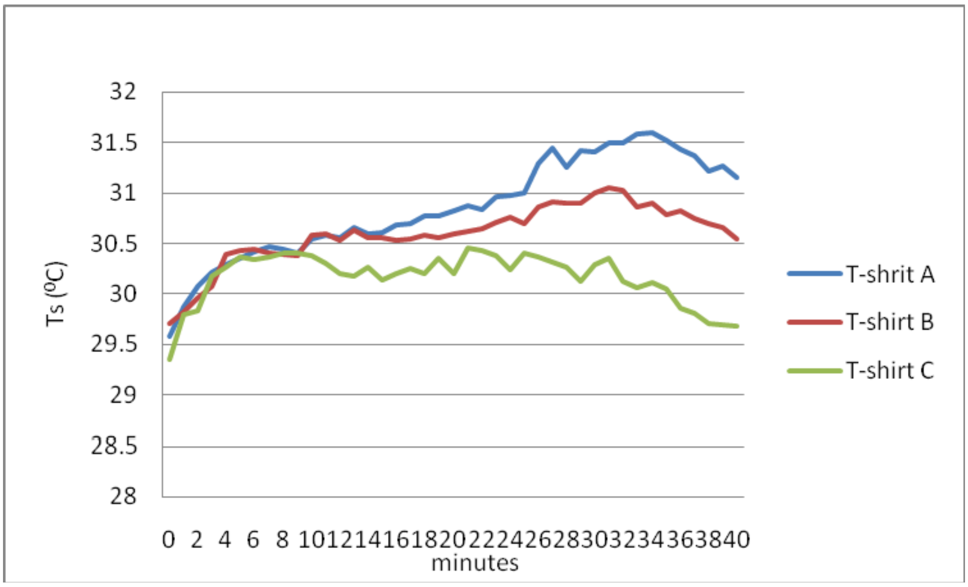


Figure 11.5 - Average skin temperature of subject wearing three different T-shirts

It showed that the average skin temperature among three T-shirts were similar in the initial 8 minutes. However, after this initial period, there were significant differences between the three T-shirt designs. The average skin temperature for T-shirt C was kept below 30.5 ^{o}C during the entire running exercise, while for T-shirt A and T-shirt B, the average skin temperature raised up to above 31 ^{o}C and 31.5 ^{o}C, respectively. After running, when the subject started to take a rest, the average skin temperature of T-shirt C tended to decrease more rapidly than the other two T-shirts. Table 11.3 shows the average skin temperature for three T-shirts in every 5 minutes. It is clear that when the exercise time was longer, T-shirt C became more advantageous in keeping the skin temperature at a lower level, as a result of the improved ventilation effect in T-shirt C.

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Time (minutes)	Average skin temperature (° C)		
	T-shirt A	T-shirt B	T-shirt C
5	30.354	30.429	30.36
10	30.545	30.578	30.376
15	30.606	30.557	30.134
20	30.824	30.6	30.201
25	31.011	30.703	30.41
30 (stop running)	31.416	31.001	30.285
35 (rest)	31.523	30.789	30.053
40 (test finished)	31.164	30.546	29.686

Table 11.3 – Average skin temperature of subject wearing all T-shirts at different testing periods

11.9.2 The change of average skin humidity

Figure 11.6 shows the trends of the changes in the average skin humidity when wearing different T-shirts during the wearer trials.

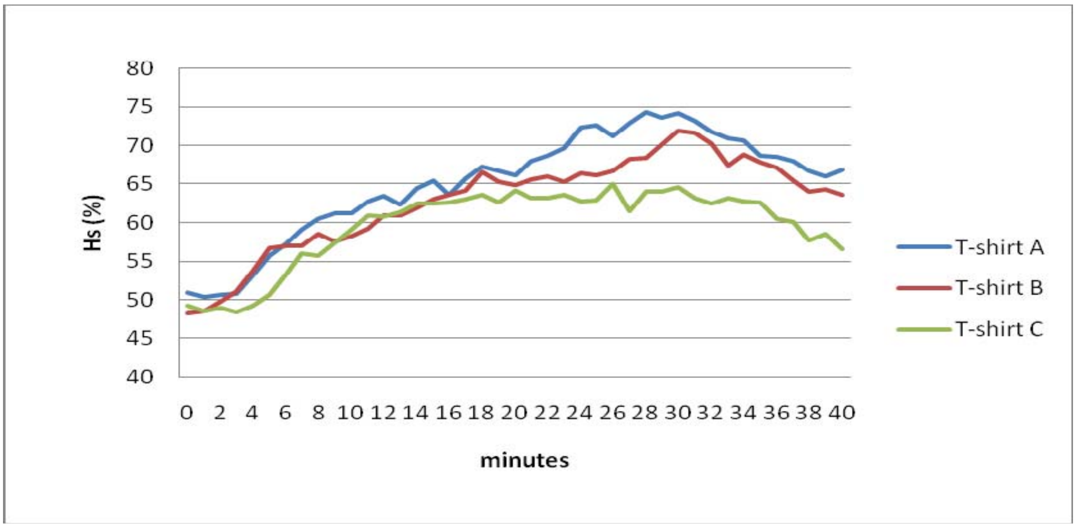

Figure 11.6 – Average skin humidity of subjects wearing different T-shirts

The results showed that T-shirt C could keep the average skin humidity at a lower level during the exercise, compared with T-shirt A and T-shirt B. The skin humidity values for the three T-shirts were quite similar in the running process until around 16 minutes. After that, for T-shirt C, the average skin humidity was maintained under 65%, but for T-shirt A and T-shirt B, the average skin humidity went up to 74% and 71%, respectively. Moreover, the average skin humidity for T-shirt C dropped more rapidly than those for the other two T-shirts when the subjects were taking a rest after the exercise. The results showed that T-shirt C could make the subjects feel drier in the testing. Table 11.4 shows the average skin humidity of the wearers when wearing the three different T-shirts in every 5 minutes.

	Average skin humidity (%)		
Time (minutes)	T-shirt A	T-shirt B	T-shirt C
5	55.677	56.713	50.651
10	61.148	58.284	59.115
15	65.378	63.11	62.387
20	66.076	64.836	64.106
25	72.604	66.15	62.924
30 (stop running)	74.154	71.894	64.474
35 (rest)	68.714	67.819	62.519
40 (test finished)	66.839	63.549	56.612

Table 11.4 – Average skin humidity of subject wearing all T-shirts at different testing periods

11.9.3 Comfort sensations of human subjects

In this part, the ratings of comfort sensation in different running periods are analyzed, and some valuable comments by the subjects are discussed. Table 11.5 lists the ratings of the comfort sensation at different exercise period, i.e. before running, 15 minutes of running, 30 minutes of running, and after 10 minutes rest. Figure 11.7, 11.8, 11.9 and 11.10 illustrates the comparison of the comfort sensation of each T-shirt by these four periods.

before running			
	T-shirt A	T-shirt B	T-shirt C
Lightness	10	9.75	9.5
Breathability	9.25	9	9.75
Coolness	9.25	9.25	9.75
Smoothness	8	7	6.75
Softness	8	7.25	6.75
Dryness	9.5	8.25	9
Movement	9.75	8.75	9
Overall Comfort	9	8.75	7.5

15 minutes			
	T-shirt A	T-shirt B	T-shirt C
Lightness	9.5	9.5	9.25
Breathability	8	7.75	9
Coolness	6.5	7.75	9.5
Smoothness	7.75	7	6.5
Softness	7.25	7	6.75
Dryness	6	7	9.5
Movement	8	8.25	9.5
Overall Comfort	7	7.25	7.5

30 minutes			
	T-shirt A	T-shirt B	T-shirt C
Lightness	9	9	9
Breathability	7.25	7	9.5
Coolness	6.25	6.75	9.25
Smoothness	7.5	7.5	7
Softness	7	7.5	7.25
Dryness	6.5	7	9.5
Movement	7.75	7	9.25
Overall Comfort	7.5	7	7.5

after 10 minutes rest			
	T-shirt A	T-shirt B	T-shirt C
Lightness	9.75	9.25	9
Breathability	7.5	8.25	10
Coolness	7.25	8.25	10
Smoothness	8	8	7.25
Softness	8	7.75	7.25
Dryness	8.25	8	10
Movement	9	8	9
Overall Comfort	7.75	8	7.5

Table 11.5 – Rating scale of comfort sensation during different periods of the test

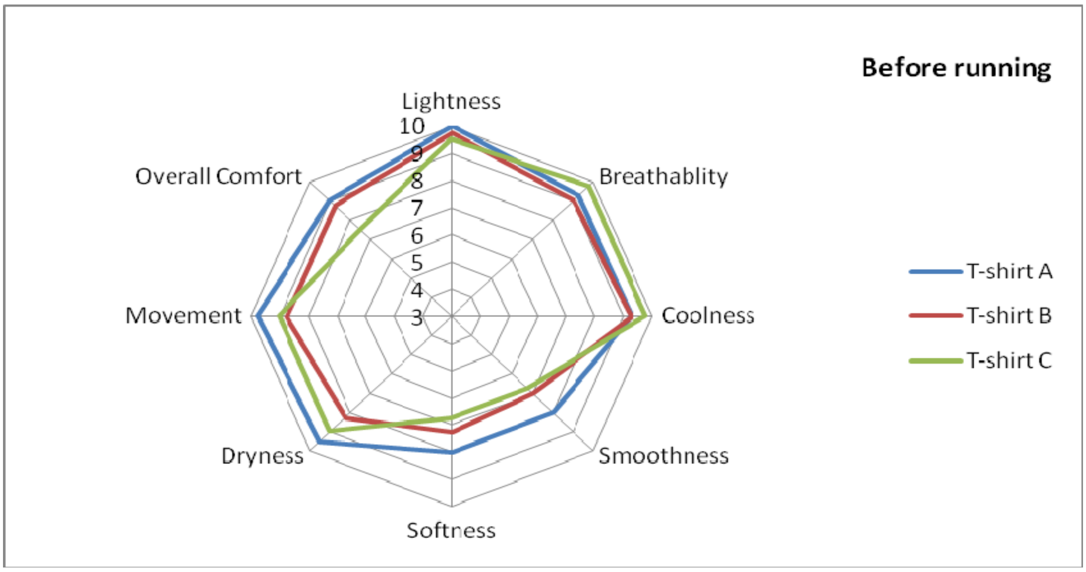

Figure 11.7 – Comfort sensation of the subjects wearing different T-shirts before running

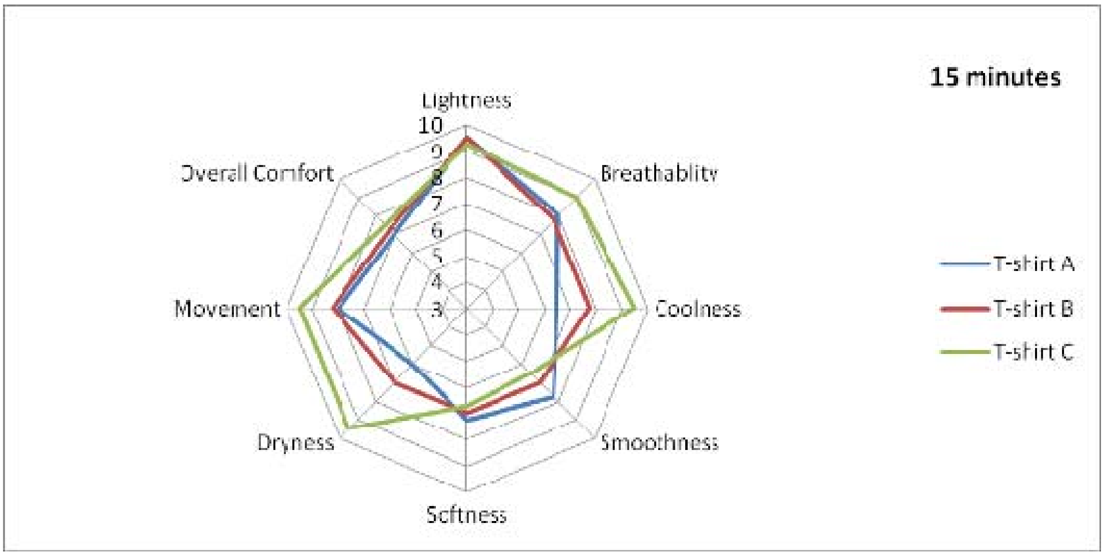

Figure 11.8 – Comfort sensation of the subjects wearing different T-shirts during 15 minutes run

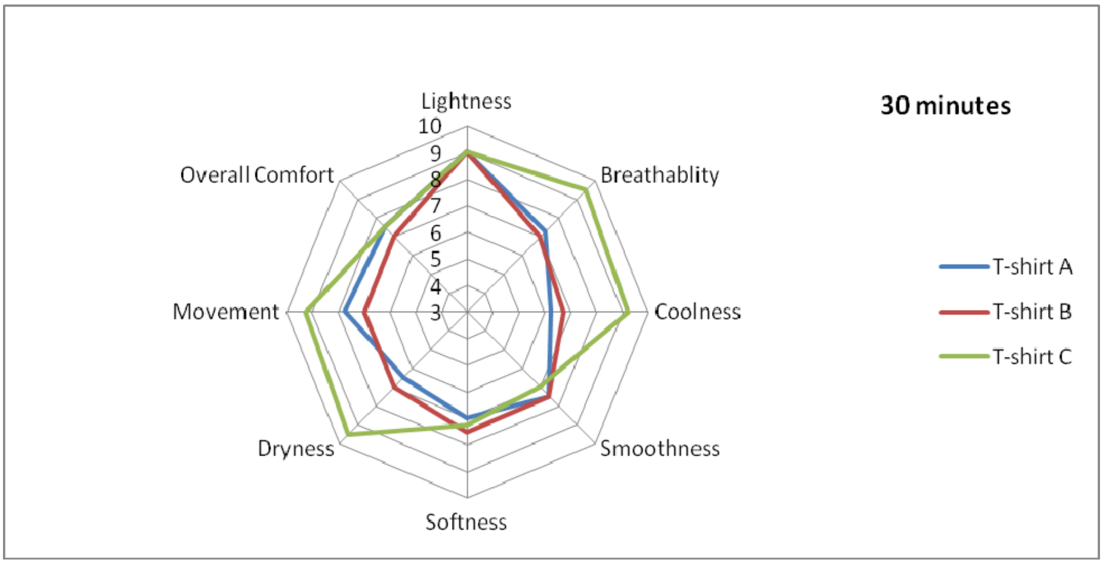

Figure 11.9 – Comfort sensation of the subjects wearing different T-shirts during 30 minutes run

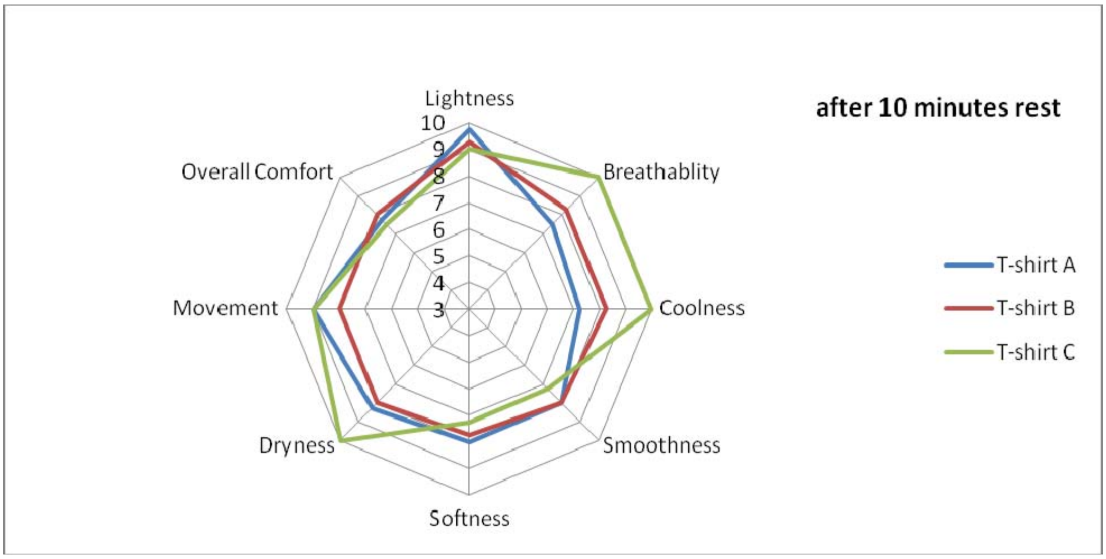

Figure 11.10 – Comfort sensation of the subjects wearing different T-shirts after 10 minutes rest

From the results, it can be seen that T-shirt C could make the wearers feel more breathable, cool and dry during the running period, while the wearers felt more breathable, cool and dry when wearing T-shirt A and T-shirt B before running. The comfort sensation of the wearers when wearing T-shirt A and B decreased during running exercise, and only recovered slightly after 10 minutes rest. This can be explained by the fact that the new design concept (T-shirt C) creates more ventilation than the designs of the other two T-shirts. Comfort sensation is directly related to the wetness of the skin; when the human subjects sweat during exercise, the fabric was wet and stuck to the skin, which restricted the movement of back, shoulders and arms. This would not occur when they wore T-shirt C because the fabric was no longer sticking to the skin due to the spacer loops.

Since T-shirt C is attached with spacer loops, its weight was slightly higher (T-shirt A: 145.7g; T-shirt B: 165.7g; T-shirt C: 249.3g), however the subjects noted that the difference was very little when they were wearing T-shirt C for running.

The subjects also commented that the spacer loops in T-shirt C would not cause them to feel scratchy, but they felt a little bit unnatural because the spacer loops were adding a little pressure to the skin, like someone slightly pressing the skin surface using fingers. However, this feeling was stronger before running, as the skin at that moment was still dry. After sweating, this kind of "pressure" sensation was less strong. Perhaps the sweat could reduce the friction between the spacer loops and the skin surface. However they agreed that the material or the form of the spacer loops could be improved.

11.10 Conclusions

In this chapter, a T-shirt in the new design concept is compared to T-shirts in conventional design through subjective wearer trials. By analyzing the average skin temperature and humidity as well as the ratings of the comfort sensation of the human subjects when wearing different type of T-shirts, it was shown that the T-shirt with the new design could have better ventilation then the conventional T-shirts. Furthermore, improvements of the new T-shirt design is needed to minimize the "pressure" discomfort sensation created by the spacer loops in the new design.

Chapter 12

Summary and suggestions for further work

12.1 Summary

Comfort is a key factor to be considered in clothing design. Of all the comfort factors, thermal comfort is the primary one, since an important function of clothing is to provide aid in maintaining the thermal balance of the human body and to ensure that heat loss, skin temperature, air movement and humidity at the body surface produce a sensation of comfort.

There are three main approaches in the development of clothing with improved comfort, i.e. the appropriate use of textile materials, the garment design and the attachment of special wearable devices onto the garment system. However, investigation into how garment design could contribute to heat and moisture transfer is still inadequate. This study was mainly focused on developing a novel design to reduce the total thermal insulation and moisture vapour resistance for the wearer.

Normally, people sweat abundantly while they are doing sports or exercises. In the case of professional athletes, the clothing layer is the layer that is between the body and the environment. Hence the clothing layer should ideally be able to transfer body heat and moisture out to the environment; otherwise the wearer may feel uncomfortable because the fabric layer sticks to the skin due to sweat, or in some cases heat stress may be suffered if body heat accumulates in the microclimate of the garment. Putting vented panels such as openings or mesh panels is very common in the market place. Some sports brandings such as Nike and Adidas provide many choices of garments with different placement of mesh or other vented panels, some of which are for both decoration and for releasing body heat and moisture vapour.

Among all garment types, T-shirts are typically worn when doing sports and exercise. When people feel hot, they can take off the jacket or coat to let body heat and moisture release. However, the T-shirt is the closest to the skin layer that is usually not taken off, especially during some professional games which do not allow the player to be nude on the field (with the exception of swimming). Additionally, keeping the body nude is not healthy as it absorbs solar light directly, which can be harmful to the skin. Therefore, because of the “basic” nature of the T-shirt, it was the focus of this study.

In order to simulate body movement, a thermal manikin “Walter” was used throughout the testing as it could provide quantified data on thermal comfort. Total thermal insulation (R_t) and moisture vapour resistance (R_{et}) are two important indices for indicating thermal comfort of the body. In this case, since the T-shirt was required to provide a cooling effect for the body, lower values of these two indices would mean that the body was kept cooler.

The present study investigated the relationship between heat and moisture transfer and the position of mesh panels and openings. The experimental investigation of the location of the mesh panels and openings showed that, mesh panels or openings that were located at the two vertical sides near the side seams resulted in the lowest R_t and R_{et} values compared to mesh panels or openings located at other positions, provided that the thermal manikin was standing and walking under a no wind condition. This was because the vented panels at the sides promoted the pumping effect generated by moving arms, thus air circulation could push warm body heat and moisture vapour out through the porous surface of the mesh fabric. Placing mesh on the back or shoulders did not contribute much to body ventilation because normally the fabric in these body parts closely touches the skin especially when the fabric layer gets wet during sweating. Hence air circulation in the microclimate of the garment layer becomes blocked and ventilation is not activated even when the thermal manikin moved its arms. This work provided important guidelines in the design of ventilative T-shirt in that, both the position of the vented panels and the separation of garment fabric from the skin are important to ventilative cooling.

In order to prop up T-shirts to promote ventilation, spacer blocks were used as the interlayer to keep the skin surface away from the skin. The tests using the sweating fabric manikin-Walter showed that putting vented panels alone along the shoulder areas did not contribute much to the natural convection, as indicated by the little change in R_t and R_{et} value. The results suggested that the position of the vented panels and the “propping up” idea should be combined to maximize the ventilative cooling.

In the present study, a novel way of fabricating spacer blocks was developed. Additionally, the placement of the spacer blocks was extended beyond the shoulder area to the neckline, hemline, and also at the front panels including across the chest to make sure that the whole garment was kept a certain distance away from the skin, instead of just the shoulder parts. In this design, when all the mesh panels were opened, ambient air could enter the microclimate of the garment layer, and cooler air could carry the relatively warm and wet body heat and moisture vapour away through the vented panels. With this design, the chimney effect is enhanced especially when the wearer is in motion under windy conditions. The R_t and R_{et} values were the lowest under body motion and windy condition. The advantage of this design concept was applicable to different fabrics including the quick dry moisture management fabrics.

12.2 Suggestions for further work

Our novel design concept has been developed in a short period of time. Due to limited time and resources, and the developed garment prototypes may not be perfect but the effectiveness of design concept has been proven. It is suggested to continue the improvement in future work through the following ways:

- Improvement in the material for the spacer blocks

The developed spacer blocks was suitable for the propping up effect, however, it added additional weight to the T-shirt. The limited fabrication sources investigated in this study show that the material for the spacer blocks could be further improved. A lighter weight material with good air permeability and wicking property may be preferable.

- Optimization of the thickness of the spacer blocks

In the present work, the thickness of the spacer blocks was approximately 1.5-2 cm. Future studies could test the effect of the thickness of spacer blocks. Thinner spacer blocks may not create sufficiently large air gap between the clothing layer and skin surface for the chimney effect, but too thick spacer blocks may make the T-shirt look strange.

- Optimum use of fabric materials

Our tests proved that the design concept was effective in three different kinds of fabrics (100% cotton, 95% cotton 5% spandex and 100% polyester with moisture management). Future studies could adopt more fabrications to test the appropriateness of all fabrications. A model could potentially be developed for estimating the effectiveness of this novel design concept with fabric properties such as air permeability and water absorption rate.

Due to limited time and resources, in the present study, only four wearer trials were conducted for the developed samples. More wearer trials could be carried out in the future to evaluate the developed garments in terms of ventilative cooling under various activities and environmental conditions.

(End, thanks!)

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