



# **An investigation of thermal comfort properties of abaya under heat stress**

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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## **Declaration**

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis/project is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Salwa Mohammed Amin A Tashkandi

02.10.2014

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## Abbreviations

Abbreviations	Full form
A	surface area (m <sup>2</sup> )
AO	abaya only (no daily-wear clothing underneath abaya)
AOTI	accumulative one-way transport index
C	heat loss by convection (W/m <sup>2</sup> )
CHEAN	college human ethics advisory network
C <sub>k</sub>	heat loss by thermal conduction (W/m <sup>2</sup> ).
clo	clothing insulation
C <sub>res</sub>	sensible heat loss due to respiration (W/m <sup>2</sup> )
DC	drape coefficient
DWC	daily wear clothing
ERC	energy reflection chemicals
E <sub>res</sub>	evaporative heat loss due to respiration (W/m <sup>2</sup> )
E <sub>sk</sub>	heat loss by evaporation from the skin (W/m <sup>2</sup> )
f <sub>cl</sub>	clothing area factor
H <sub>c</sub>	heating power (w/m <sup>2</sup> ) supplied to the plate to maintain a temperature of 35° C
H <sub>e</sub>	heating power for measuring water vapour resistance (w/m <sup>2</sup> )
i <sub>m</sub>	moisture permeability index
IR	infra-red thermal camera
KA	knitted abaya fabric
KAU	King Abdul Aziz University
L <sub>e</sub>	heat transfer by evaporation through clothing
L <sub>s</sub>	abaya worn from shoulder with loose sleeves and scarf
L <sub>t</sub>	dry heat transfer through the clothing system by conduction, convection or radiation
M	metabolic rate (internal energy production W/m <sup>2</sup> )
M <sub>a</sub>	percentage of moisture accumulation within clothing
MAR	moisture absorption rate
MMF	moisture management finish
MMT	liquid moisture management
MTP	moisture transport properties
N100	100% nylon
OH	abaya fabric worn from top of head and scarf
OMMC	overall moisture management capacity
OWF	on weight of fabric
P <sub>a</sub>	water vapour pressure at ambient temperature (Pa)
P <sub>s</sub>	water vapour pressure at skin temperature (m <sup>2</sup> .Pa)/W
P100	100% polyester
P50W50	50/50 polyester/wool
P63W37	63/37 polyester/wool
P65C35	65/35 polyester/ cotton
P96E4	96/4 polyester/ elastane
Q/A	area weighted heat flux (w/m <sup>2</sup> )
R	heat loss by thermal radiation (W/m <sup>2</sup> )
R <sub>ct</sub>	thermal resistance (m <sup>2</sup> .k/w)
R <sub>cto</sub>	thermal resistance without a sample (m <sup>2</sup> .k/w)
R <sub>cf</sub>	intrinsic clothing insulation (m <sup>2</sup> .° c /w)
R <sub>e</sub>	total resistance to water vapour transfer through clothing and air outside the clothing surface (Pa. m <sup>2</sup> /W)



Abbreviation	Full form
$R_{ef}$	intrinsic evaporative resistance of clothing ( $m^2 \cdot pa/w$ )
$R_{et}$	water vapour resistance ( $m^2 \cdot pa/w$ )
$R_{et0}$	evaporative resistance measured for the air layer
$R_t$	total thermal resistance of the clothing and the air layer outside the clothing surface and it is generally expressed in $^{\circ}C/W$ (ISO unit).
SC	Scarf
SEM	scanning electron microscopy
SGHP	sweating guarded hot plate
SH	shirt (long sleeves)
SH+SK	daily wear clothing (underwear + shirt (long sleeves)+ skirt + shoes)
SH+PA	daily wear clothing (underwear + shirt (long sleeves)+ slacks + shoes)
$T_a$	air temperature in the test enclosure ( $20^{\circ}C$ )
$T_p$	plate temperature in the test enclosure ( $35^{\circ}C$ )
$T_s$	abaya worn from shoulder with tight sleeves and scarf
$(T_s - T_a)$	temperature difference between the skin and environment ( $^{\circ}C$ )
U	underwear (bra and panties)
V80P20	80/20 viscose/ polyester
W	external work ( $W/m^2$ )
WA	woven abaya fabric
Wb and Wa	weight of clothing before and after the manikin testing
W100	100% wool
W50N50	50/50 nylon/wool
1P100	100% polyester
2P100	100% polyester
3D	three-dimensional body scanning

# Abstract

The abaya is a black outer garment mandated to be worn by all women (especially Muslims) in Saudi Arabia when they are outside their homes. It is designed to cover the whole body. It may be worn either from the shoulder or from the top of the head and reveals only the face, feet and hands. The abaya absorbs most of the heat from sunlight in a hot climate, as it is black, it tends to make the wearer very uncomfortable. In addition, multiple layers of clothing worn underneath the abaya increase thermal stress.

The present research obtained an overview of the types, variety and comfort of abayas worn by women in Saudi Arabia. This served as the basis for identifying the textile materials commonly used for the abaya and for understanding the comfort factors from the perspective of the wearers. The outcome was used to develop and investigate improvements to the thermal comfort properties of the traditional abaya using chemical treatments.

A survey was undertaken to obtain the opinion of women in Saudi Arabia regarding the problems of thermal discomfort associated with the current type of abaya. The key points considered were the types of fabrics and designs being used and the corresponding degree of perceived comfort. As may be expected, the survey confirmed that the discomfort is related to a specific type of clothing. It also revealed that the current abaya when worn over multi-layers of inner clothing is often thermally uncomfortable.

Objective evaluations of the thermal performance of abayas, made from commonly used woven and knitted fabrics were carried out using standard tests. Thermal comfort properties were determined based on thermal resistance, air permeability, thermal comfort, and vapour resistance. The results indicate that the fabric thermal comfort performance is greatly influenced by its fibre composition, construction (woven or knitted), weight and thickness. It was found that woven abaya fabric is more comfortable than that produced from knitted fabric.

A female sweating thermal manikin was utilised to evaluate the physical fabric properties related to the heat transfer and moisture management of abayas. This was conducted with clothing combinations used in daily-wear such as underwear with a skirt or slacks together with a shirt plus an abaya and scarf, as worn in Saudi Arabia. The thermal and evaporative resistances of clothing worn within the abaya were measured. The results can contribute to improvements in the design of abayas so as to minimise thermal and evaporative resistance in a hot environment.

In order to improve the comfort properties, woven abaya fabrics were dyed in black and treated with an energy-reflecting chemical, so as to reflect heat from the environment. This was expected to aid in keeping such fabrics cooler. The fabrics were evaluated to assess the thermal comfort properties, as described earlier

The outcome of the research confirms that wearing of abayas causes discomfort in hot environments. The degree of comfort was found to depend not only on the type of fabric and design but also on the clothing worn underneath. Most abayas are made from woven fabrics that mask body contours. Synthetic fibres (polyester) were found to be predominantly used because of their easy care features. It is evident that lightweight and thinner satin fabrics are most suitable for abayas and can provide better handling and thermal comfort in a hot environment. In addition, the results showed that energy-reflecting chemicals marginally improved the thermal comfort properties under the experimental conditions used and lowered the surface temperature of the fabric by 0.9–1.8° C.

# Research output from this thesis work

## Publication

- Tashkandi S, Wang L and Kanesalingam S. An investigation of thermal comfort properties of abaya woven fabrics. *Journal of The Textile Institute*. 2013;104(8): 830–837.
- Tashkandi S, Fergusson SM, Wang L and Kanesalingam S. Thermal comfort properties of wool and polyester/wool woven fabrics dyed in black. *Journal of Fiber Bioengineering and Informatics*. 2013;6(3): 265–275.
- Tashkandi S, Wang L and Kanesalingam S. Effect of abaya designs and daily wear clothing on thermal comfort measured with a female thermal manikin. *Journal of Fiber Bioengineering and Informatics*. 2014;7(2): 285–295.

## Conference papers

- Tashkandi S, Wang L, Kanesalingam S and Jadhav A. Thermal comfort characteristics of knitted fabrics for abaya. *Advanced Materials Research*. 2013; 627:164–169.
- Tashkandi S, Fergusson SM, Wang L and Kanesalingam S. Investigation of thermal comfort properties of black fabrics for abaya. In: Li Y, Yao M, Gao Y and Li JS, editors. *The 6th Textile Bioengineering and Informatics Symposium Proceedings*, September 26–28; Xi'an, China: Textile Bioengineering & Informatics Society Ltd; 2013. P 505-511.
- Tashkandi S, Kanesalingam S and Wang L. Evaluation of abaya design using thermal manikin. *Advanced Materials Research*. 2014; 834:1744–1748.
- Tashkandi S, Wang L and Kanesalingam S. Evaluation of heat loss in abaya and daily wear clothing using a heated thermal manikin. In: Yi L, Xin JH, Yoon KJ and Li J, editors. *The 7th Textile Bioengineering and Informatics Symposium Proceedings, jointed with The 5th Asian Protective Clothing Conference*; August 6–8; Hong Kong, China: Textile Bioengineering and Informatics Symposium Proceedings; 2014. P997-1002.
- Wang L and Tashkandi S. Abaya – a barrier to thermal comfort in hot environment. *Global Textile Congress*; 13, 14 & 15th February 2015 at Bangkok, Thailand.

# Chapter 1 Introduction

## 1.1 Introduction

The widely accepted basic requirements of mankind are clothing, food and shelter. Food provides sustenance and shelter protects humans from the elements of nature [1]. Clothing, in a broad sense, covers all items which serve to cover the human body. This broad class can be divided into garments, footwear, body decorations, etc. The primary function addressed by clothing is that of imparting or enhancing aesthetic appeal. From a functional point of view, garments can be regarded as providing a portable environment which supports the human body's abilities to maintain comfort and life [2].

Clothing, especially for women, is available in diverse colours, shapes and sizes while adhering to the dictates of fashion. In fact clothing may be considered to indicate the wearer's identity [3]. Women's clothing codes reflect not only social and cultural differences, but also economic and religious backgrounds.

Religious dress is acknowledged as a means of visual communication that reflects the wearer's beliefs in certain religious principles and practices. Religion often refers to a group of people who believe in a particular set of values or beliefs and follow the teachings of a spiritual leader. Such beliefs and teachings are usually set out in a book. The world's major religions follow this pattern; for example, Christianity originated with the historical Jesus Christ whose teachings are in the Bible, Buddhism revolves around the figure of Gautama, and Islam is guided by the Prophet Mohammed as described in the Qur'an.

Religious dress may be considered as a means of conveying distinctions of the power structure in the group [4]. Usually, there is a set of reasons that a religious group chooses to dress in particular manner. They may be following a belief of a scriptural dictum. In

addition, clothing patterns may reflect an ideology of simplicity and modesty through certain aspects of clothing design [5]. One of the well-recognised dress codes is for the female followers of Islam.

## 1.2 Islamic dress code (female)

The dress code for Muslim (the followers of Islam) females has been prescribed in a verse in (Chapter Alnoor24:31) of the Qur'an:

وَقُلْ لِلْمُؤْمِنَاتِ يَغْضُضْنَ مِنْ أَبْصَارِهِنَّ وَيَحْفَظْنَ فُرُوجَهُنَّ وَلَا  
يُبْدِينَ زِينَتَهُنَّ إِلَّا مَا ظَهَرَ مِنْهَا وَلْيَضْرِبْنَ بِخُمُرِهِنَّ عَلَى  
جُيُوبِهِنَّ وَلَا يُبْدِينَ زِينَتَهُنَّ إِلَّا لِبُعُولَتِهِنَّ أَوْ آبَائِهِنَّ  
أَوْ آبَاءِ بُعُولَتِهِنَّ أَوْ أَبْنَاءِهِنَّ أَوْ أَبْنَاءِ بُعُولَتِهِنَّ أَوْ  
إِخْوَانِهِنَّ أَوْ بَنِي إِخْوَانِهِنَّ أَوْ بَنِي أَخَوَاتِهِنَّ أَوْ نِسَائِهِنَّ أَوْ مَا  
مَلَكَتْ أَيْمَانُهُنَّ أَوِ التَّابِعِينَ غَيْرِ أُولِي الْإِرْبَةِ مِنَ الرِّجَالِ أَوْ  
الطِّفْلِ الذَّيْبِ لَمْ يَظْهَرُوا عَلَى عَوْرَاتِ النِّسَاءِ وَلَا يَضْرِبْنَ  
بِأَرْجُلِهِنَّ لِيُعْلَمَ مَا يُخْفِينَ مِنْ زِينَتِهِنَّ وَتُوبُوا إِلَى اللَّهِ جَمِيعًا  
أَيُّهُ الْمُؤْمِنُونَ لَعَلَّكُمْ تُفْلِحُونَ ﴿٣١﴾

*“And tell the believing women to lower their gaze and to be mindful of their chastity, and not to display their charms [in public] beyond what may [decently] be apparent thereof; hence, let them draw their head-coverings (khimar) over their bosoms. And let them not display [more of] their charms to any but their husbands, or their fathers, or their husbands’ fathers, or their sons, or their husbands’ sons, or their brothers, or their brothers’ sons, or their sisters’ sons, or their womenfolk, or those whom they rightfully possess, or such male attendants as are beyond all sexual desire, or children that are as yet unaware of women’s nakedness; and let them not swing their legs [in walking] so as to draw attention to their hidden charms and [always], O you believers-all of you-turn unto God in repentance, so that you might attain to a happy state”.*

As translated from Arabic into English by Muhammad Asad [6], this verse enjoins Prophet Muhammad’s wives and Muslim women to cover themselves in public or around strangers (men). In addition, (chapter Alahzab33: 59) of the Qur’an as quoted below asks Prophet Mohammed’s wives and Muslim women to draw a *jilbab* over themselves when they go

out, so that they are distinguished from others and safe from harassment. The *jilbab* is a dress that has the sleeves stitched to the main body of a cloak so as to be free and wide to cover the entire body [6].

يَا أَيُّهَا النَّبِيُّ قُلْ لِأَزْوَاجِكَ وَبَنَاتِكَ وَنِسَاءِ الْمُؤْمِنِينَ يُدْنِبْنَ عَلَيْهِنَّ  
 مِنْ جَلْبَابِهِنَّ ذَلِكَ آدَبٌ أَنْ يُعْرَفْنَ فَلَا يُؤْذَيْنَ وَكَانَ اللَّهُ غَفُورًا  
 رَحِيمًا

*“O Prophet! Tell your wives and your daughters, as well as all [other] believing women, that they should draw over themselves some of their outer garments [when in public]: this will be more conducive to their being recognised [as decent women] and not annoyed. But [withal,] God is indeed much forgiving, a dispenser of grace”.*

The references to women’s clothing in the above verses illustrate a promotion of modesty, as they specify women to cover and protect their private parts by throwing hijabs over their bosoms when strangers, especially men, are present. Muslim women in the Arabian Gulf region adhere to this directive to be modest and deflect undesirable male attention by wearing their ubiquitous all-covering black robes and headscarfs. The black colour also serves to clearly indicate, to men, the presence of a woman of Islamic faith who has to be treated with due respect.

Although there has been much debate about the accurate meaning of the hijab, two definitions are in major consensus. Firstly, ‘hijab’ is a term used to indicate the action of women covering up, which agrees with the traditional concept of hijab dress in Islam [7]. Secondly, the hijab is only a dress item to be worn, specifically a scarf covering the hair and neck. This meaning has been commonly used in the English language as a generic definition that carries a possibility of more or less than covering the hair and neck. However, many Islamic societies expect a girl to wear the hijab and cover her face once she attains physical maturity [8].

Muslim women, like most women in the world, wear different clothes in private than the ones worn in public (Figure 1.1). Generally, they are free to wear anything they desire

under their Islamic outfits. The abaya is an Islamic outfit for women that should be worn with a light and long veil called a scarf (shayla) wrapped in a way that completely covers the head, neck and hair. Abayas are one-piece garments with sleeves which are not actually stitched to the body of the garment but formed as one piece [9]. Modern abayas are a reinvention of a centuries old style and can be worn in different styles, either from the shoulder (Figure 1.2(a)) so that it can be opened all the way down the centre front and fastened closed with snaps, or it can be pulled on over the head (Figure 1.2 (b)) when it is over the normal day-to-day clothing called the 'ra's abaya' or 'judicial abaya'. It is a traditional and religious requirement for women to wear an abaya in public places. Based on that requirement, urban women in the Middle East tend to dress in black abayas when in public so as not to attract the amorous attention of men. The black and other dark colours distinctly identify the wearer to be pious Muslim who should be treated with respect and not as an object of desire. The variations in the abaya and the reasons thereof are discussed in the following paragraphs.



Figure 1.1 Women wearing desired clothing underneath the abaya.

(<http://secret-fashion.com/fashionable-dresses/43-casual-summer-dresses-for-comfort-and-cool.html>)





Figure 1.2 Abaya: uniforms for women in Arabian Gulf worn in different styles:  
 a) worn from the shoulder, b) worn from top of the head.

## 1.2.1 Variations of and reasons for Islamic outfits

### 1.2.1.1 Interpretation

The interpretation of what private parts must be covered differs from one country to another. It depends on cultural background, availability of materials, climate, ethnic and social bonds, technology, economics and trade [8]. Covering body outlines and specific body parts receives great significance in Islamic countries, in the Arabian Gulf making the abaya (Figure 1.2) the most common outfit for women there. Islamic communities of Asia and the Far East consider covering heads and wearing loose clothes to be acceptable. In Iran, the chador (Figure 1.3) [3] is the common outfit for women. Chador is a large semi-circular or rectangular length of cloth draped over a woman's head and body such that it covers the whole body. The Muslim women of South Asian communities wear a similar garment called a burqa (Figure 1.4) [5] made of two pieces, namely a head band and a face veil piece. These two pieces are usually sewn together at the temples and at the nose. In Morocco [3], the *takchita* (Figure 1.5) is women's common traditional hijab outfit, which is loose and constitutes two pieces: a dress for the first layer and a second over-dress layer that often closes in the front using loop closures for buttons. Women in Malaysia and

Indonesia [10] can dress casually in jeans and T-shirts, but a *tudong* (Figure 1.6) must be worn (Malay headscarf using a square of material folded into a triangle and fixed with brooches) to indicate their Islamic identity. Overall, many women believe that modesty is a personal quality and it differs from one to another [8].



Figure 1.3 Chador: outfit for women in Iran.

(<http://leavesandpages.files.wordpress.com/2013/09/chaador.jpg>)

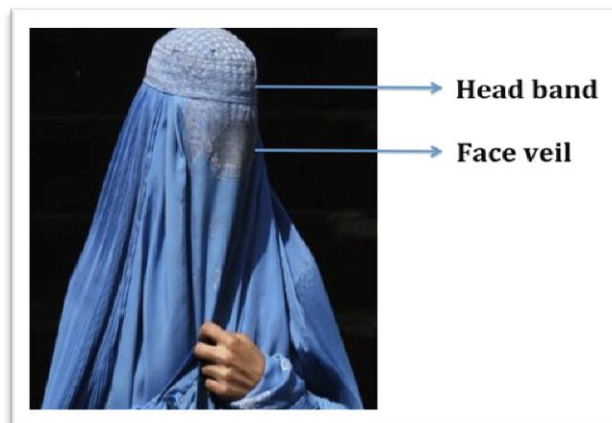


Figure 1.4 Burqa: outfit for women of South Asian countries.

(<http://www.telegraph.co.uk/news/religion/5616629/Muslim-leaders-condemn-Sarkozy-over-burqa-ban.html>)



Figure 1.5 Takchita: women's common traditional hijab outfit in Morocco.  
(<http://traditionmarocaine.blogspot.com.au/2012/10/les-caftans-2012.html>)



Figure 1.6 *Tudong* (Malay headscarf).  
(<http://tudong-sense.blogspot.com.au/>)

### **1.2.1.2 History and culture of the Islamic abaya**

An important fact is that traditional garments usually have associations with factors such as geographical area, climate and history. It can also indicate cultural, social and religious statuses. In the Arabian Gulf, there are basically three patterns of women's ensembles and garments, traditional, Islamic and Western style [11], as presented in Figure 1.7. The historical/traditional clothing is the *daraa* or *jalabiah*, which is a traditional dress falling straight from the shoulder to the ankle with a loose-fitting shape. It has two long sleeves shaped about the wrist. In the urban Arabian Gulf, a Westernised trend in women's clothing appeared in the early twenty-first century, typically in the form of a combination of blouse and skirt or slacks. Traditional garments were worn mainly at cultural celebrations and special events. However, the core factor about women's head wear and covers in the Arabian Peninsula (especially Saudi Arabia) lies not in the geography of the place or in the climate (hot or cold) but in its religious significance. This is true for all Muslims in the world and especially so for the residents of the two holy cities of Makkah and Madina [8].

Makkah is the meeting point for millions of pilgrims who come from around the world annually to share in the experience of Hajj. Hajj is a Muslim religious practice of worship that has been continued for thousands of years. Pilgrims usually bring their own cultural clothing during their settlement in Makkah and some bring textiles and garments for sale to cover pilgrimage expenses. Thus a diverse mix of women's clothing can be found in the eastern regions of Saudi Arabia [8].



Figure 1.7 Different clothing styles for Islamic women.

### 1.2.1.3 Reasons for wearing the hijab and abaya

There are considerable variations in the reasons that Muslim women cover their heads and bodies. The main reasons cited are religious beliefs, gaining respect and acceptance, and following historical and social bonds. Some women cover their head due to peer and family pressure usually from seniors and husbands [8]. The law enforces traditional garments for all residents in some countries like Bhutan [10]. In Saudi Arabia, wearing abayas is compulsory under Sharia law for all women whenever they are in public or outside their homes. Sharia is a divine law, as expressed in the Qur'an and the Prophet Muhammad's example. It reflects the belief that the black abaya will give an image of the individual's Arabian cultural heritage and religious background. The abaya protects a woman's privacy and modesty and her family's honour. It additionally signals that the wearer is a devout Muslim and there is a tacit cultural agreement that men should accord abaya-clad women respect and distance [12].

The changes and variations described above may be attributed to the increased communication between the Arab Gulf countries, Europe and America after World War II. Beginning in the 1950s, traditional Middle Eastern dress was discarded in favour of Euro-

American fashion by both men and women eager to express their wealth and status. Education and international travel became far more affordable and popular for citizens of the Middle East [13]. Therefore, it may be considered that the hijab dress code has changed over time and continues to develop and change. For example, fashion has implications for the colour and style of women's head covers. Change becomes imminent because fashion controls the materials available in the local markets [8].

### **1.2.2 Present circumstances of the abaya**

Nowadays, the abaya has become a stylish, personalised coat that many women in Arabian Gulf and some Islamic countries around the world enjoy wearing as an expression of individuality within the template of a physically modest robe. The Saudi market is the primary market of the Islamic countries (Gulf and Saudi Arabia) that need abayas because Saudi women are more conventional in terms of customs and traditions [14]. Such beliefs are mainly derived from the teachings of the religion, which mandate wearing a modest cover, the abaya. Many new styles of abaya, dubbed the 'abaya-as fashion,' are available in a dizzying array of cuts, colours and fabrics embellished with a myriad of decorations. Some designers draw inspiration from the Western fashions that many Gulf women wear underneath their abayas. Others pull from styles and cultures around the world. The abaya is not simply a religious or cultural expression, but an expression of individuality for women in the Gulf, heavily influenced by Western fashion through globalization. The abaya-as-fashion has gone even further, moving into the world of Western high fashion and being worn by non-Muslim women. Through globalisation, the wearing of the abaya became widespread through symbolising a person's faith and has transcended that stage to become a truly global garment [12, 14, 15]. Despite these events, the black abaya is considered the most conservative way for women to dress in the Arabian Gulf. It would prove useful to keep track of customer opinions and desires in this dynamic and growing market.

## 1.3 Clothing comfort

Modern consumers aim for certain features of clothes that need to be ethical and appealing as well as comfortable [16, 17]. Clothes need to possess key characteristics such as: ease of body movement, appropriateness, tactility, thermal comfort and several psychological considerations in order to be considered comfortable [18-22]. Protection, adornment, status and modesty are the four main categorised functions of clothing [23].

Comfort, according to Slater [24], is defined as “a pleasant state of physiological, psychological, and physical harmony between a human being and the environment”. It can be classified into three types:

1. Physiological comfort is mainly about the capability of the human body to sustain life.
2. Psychological comfort is the satisfactory functioning of the human mind with the help of external factors; and
3. Physical comfort is the impact of the outside environment on the human body.

Apparel comfort according to Fris [25] is a consequent result of the heat interchange process between apparel and the wearer’s outside environment. It is concerned with the ability of clothing to maintain a suitable micro-climate. The important factors to be borne in mind are the physical and physiological aspects of comfort, especially since apparel has the ability to protect the body from sudden changes in temperature (thermal shock) and transfer moisture and heat from the skin to the environment. Clothing stands as the first heat transfer barrier between the wearer’s body and its surroundings while creating an intimate environment. The heat may be generated by body metabolism or from the external environment [26, 27]. It is difficult to positively define comfort in one definition; however, discomfort can be easily defined via many aspects such as itch, prickle, heat and cold. Hatch [28] stated that comfort is “freedom from pain and from discomfort as a natural state”. On the other hand, conditions like much heat, too much cold, and odorous

or stale atmospheres lead to discomfort. As a natural physiological response, humans need clothes to put on in order to help their bodies in resisting adverse environments. Once clothes lie on the human body, the body's ability to control thermal balance with the environment is assisted.

Protection from cold (prevention of inordinate heat loss) or heat (retention of excessive metabolic heat and influx of excess environmental heat) is one of the basic necessities in order to keep the body thermally comfortable. It should be noted that metabolic heat is affected by factors such as body mass, physical activity and food habits. The performance and ability of clothing ensembles vary in supporting the thermal physiology of the human body. This performance is associated with features such as material, design and construction. Therefore, assessing clothes according to thermal comfort is very significant [29].

### **1.3.1 Thermal comfort**

The human body's physical and mental status and performance are directly affected by thermal comfort. So on the thermal functional level, clothing can stand as a transportable environment that assists the human body to maintain comfort and life.

As mentioned above, clothing thermal comfort simply summarises the ability to relatively maintain the body's temperature within small limits. In some cases such as too much cold or great heat, the human body's thermal-comfort regulation mechanism can fail. Then it becomes necessary to wear clothing for support in terms of resisting or facilitating the human body to exchange heat with the environment [30]. For example, in hot climatic conditions, the garment is ideally expected to release and exchange heat between the body and the environment [31].

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has defined thermal comfort as "the condition of the mind in which satisfaction is expressed with the thermal environment" [32]. Clothing thermal comfort is the ability of



clothing to help the human body to maintain a state of thermal comfort through its performance [2]. The combination of clothing, climate and physical activity is basically what thermal comfort is dependent on [16].

Thermal comfort is associated with thermoregulation, which means that the body needs to be at a core temperature of about 37° C by heat exchange [33]. Changes in this temperature affect the feeling of comfort produced by warm or cold sensations [34]. The standard temperature for human physiology is 37± 0.5° C [35]. Any changes in this temperature cause discomfort for most humans and can lead to serious illness on long exposure. In addition, human exposure to extreme climatic conditions for prolonged periods can destabilise the core body temperature and cause death in some situations. In hot environments, the garment should ideally be able to release heat from the body to the environment [36].

### **Heat balance**

Heat balance scales the rates of heat production and heat loss, maintaining a balanced level in the human body. The human body remains in a state of thermal equilibrium with its surrounding environment where heat loss and gain remain at exactly the same rate [37]. The blood flow regulates body temperature as it circulates from the core to the skin where convection, radiation and evaporation dissipate the heat [38]. Therefore, clothing is needed to guarantee protection to the body against climatic impact and to enhance the functions of the body's thermal control under the combination of a set of environmental and physical activities [39]. The heat generated from the human body is transferred to the environment, through the clothing, by conduction ( $C_k$ ), convection ( $C$ ), radiation ( $R$ ) and evaporation ( $E_{sk}$ ) which can be explained by the general heat balance equation, Equation 1.1 [40]:

$$M - W = C + R + E_{sk} + C_k + (C_{res} + E_{res}) \quad \text{Equation 1.1}$$

where,

$M$  is the metabolic rate (internal energy production  $W/m^2$ )

$W$  is the external work ( $W/m^2$ )

$C$  is the heat loss by convection ( $W/m^2$ )

$R$  is the heat loss by thermal radiation ( $W/m^2$ )

$E_{sk}$  is the heat loss by evaporation from the skin ( $W/m^2$ )

$C_{res}$  is the sensible heat loss due to respiration ( $W/m^2$ )

$E_{res}$  is the evaporative heat loss due to respiration ( $W/m^2$ ) and

$C_k$  is the heat loss by thermal conduction ( $W/m^2$ ).

### **1.3.2 The mechanism of heat and moisture transfer through clothing**

Heat transfer is the process by which heat energy travels from one environment to another. Following the second law of thermodynamics, heat transfer happens when a difference of temperature between the two environments exists [41]. This heat is transferred in two forms: sensible heat transfer and latent heat transfer. Sensible heat transfer is accompanied by a change in temperature and depends on the degree of molecular excitation caused by exposure to radiation, convection, or conduction. Latent heat changes the state of matter from solid to liquid or liquid to gas. The latent heat of fusion and latent heat of vaporisation are the heat needed per unit mass of solid for melting to liquid or per unit mass of liquid for vaporising to gas respectively [42]. Human perspiration is classified into two types: insensible perspiration and active sweating. Insensible perspiration usually means the insensible loss of body weight. Heat, mental stimuli, muscular exercise and carbon dioxide are well known to induce active sweating in human beings [43]. Clothing serves as an insulator between the two environments that can cause resistance to heat transfer from or to the body [44]. There are two ways to transfer heat from the clothing system to the environment: dry heat loss (which occurs through transmission of fibres and air, radiation and convection) and evaporative heat loss [45].

## **Conduction**

Conduction is the process of heat travelling within a substance or between a number of substances through which the motion of individual molecules is in contact [37]. In static substances, the interaction of solids, free electrons and liquid and gas molecules initiates the conduction of heat, which leads to transferring kinetic energy from high to lower temperatures [46]. A direct physical contact between the interacting elements is essential for this type of heat transfer to occur. In other words, conduction of heat needs direct contact and temperature difference in order for heat to transfer to the cooler object. Therefore, the more contact available, the more conduction can follow [27]. The conductive heat transfer rate is proportional to the temperature difference and inversely to the distance over which conduction occurs [47].

Although each fibre type conducts heat differently, the difference loses significance once the fibre is incorporated into fabrics or clothes. Garments trap a large amount of air, which has a considerably lower thermal conductivity (the rate of transmission of heat) than the fibre itself. Accordingly, the amount of air trapped inside the garment largely determines the thermal conductivity of the garment [28].

## **Convection**

Convection refers to heat transfer between a surface and a bulk motion of fluid such as gas or liquid on top of the surface. Convection occurs two ways: forced as a result of an external catalyst, such as a fan, or naturally through buoyancy and density differences [37]. The motion of the fluid and temperature gradient are the elements that affect the rate of convection [48]. Buoyancy forces subsequent from temperature differences such as the rise of warm air are the main factors for natural convection to occur [30]. Heat exchanges more rapidly with an increase in the temperature difference between mixed liquids or gases. On a clothing system level, convection can be achieved through differences of air density in various spaces, external wind and body motion. Ventilation is

an important way of convective heat transfer through clothing, which happens during the movement of the human body or in windy conditions. Ventilation is the process of exchanging hot-wet air in a clothing system for cold-dry air from the environment without passing through fabric layers. When the wearer walks in windy settings, ventilation can participate in the loss of an important amount of heat from the human body [49].

### **Radiation**

Radiation is the transmission of heat in the form of electromagnetic waves when no intervening matter is available. Electromagnetic radiation is emitted from all objects above zero degrees Kelvin (absolute zero) and the energy distribution is given by Planck's Law. The surface temperature of an emitting body is a major factor for the predominant wavelength emitted, with the consideration that the maximum wavelength decreases at increased temperatures. If the radiating temperatures of the surrounding surfaces are higher or lower than the body temperature, the radiant heat moves towards or away from the body respectively. In a cold room, the warmer body or its clothing transmits radiant heat to all cooler surfaces such as walls, glass, and any other construction within view. By putting curtains between the cold window and a person the radiant transfer of heat can be blocked in the same way that a person can cut off the radiant energy from the sun by stepping into the shade of a tree.

There are three scenarios for the infra-red energy received at a surface: it can be transmitted, scattered or absorbed. When absorbed, the energy results in raising the receiving surface temperature [37]. Objects such as the Sun emit a broad distribution of wavelengths with the maximum wavelength determined by the temperature of the object and the distribution encompasses the ultraviolet, visible and infrared regions. The human body and other ambient surroundings can only emit infra-red radiation because of its relatively low temperature. Heat from the Sun travels only a few millimetres into a fabric before being either scattered or absorbed by the fibres. Therefore, the fibre absorption

and emission properties are at the basis of indirect radiant heat transfer occurring between a clothed body and the environment [48]. Clothing spacing (air pockets) enables radiant heat to move directly from the skin surface to the environment, as well as between clothing materials.

### **Evaporation**

Evaporation is the conversion of water from liquid into gas. It is a critical thermoregulatory mechanism which depends on heat taken up by a liquid (sweat or perspiration) during conversion into vapour that cools the human body concurrently [50]. The availability of adequate air volume, movement, and low ambient relative humidity (RH) causes liquid moisture to evaporate. During the evaporation of perspiration from the skin surface, the body loses the heat energy (450 calories, or 0.00188 MJ per gram of water) required for evaporation, thereby cooling the body [44]. Perspiration occurs under conditions of thermal and / or physiological stress and is classified as sensible and insensible. The former is liquid sweat produced under hot and/or energetic conditions while the latter is where sweat evaporates within the skin layers and is released as moisture vapour [44].

#### **1.3.2.1 Dry heat transfer through clothing**

The temperature difference between the skin and the environment determines the different methods of dry heat transfer including conduction, convection and radiation. The dry heat transfer through a clothing system can be described by Equation 1.2 [51]:

$$L_t = A \cdot (T_s - T_a) / R_t \quad \text{Equation 1.2}$$

where,

$L_t$  is the dry heat transfer through the clothing system by conduction, convection or radiation

$A$  is the surface area (m<sup>2</sup>)

$(T_s - T_a)$  is the temperature difference between the skin and environment (° C)

$R_t$  is the total thermal resistance of the clothing and the air layer outside the clothing surface and it is generally expressed in °C/W (ISO unit).

Under high activity levels or high surrounding temperature, dry heat transfer cannot be sufficient to cool the body temperature of a clothed person. In such conditions, the best way to reduce body heat is through perspiration evaporation from the skin [36, 37].

### 1.3.2.2 Evaporative heat transfer through clothing

The evaporation loss relies on the ratio of air humidity and the mass transfer coefficient (the transport of material between a boundary surface, such as a solid or liquid surface, and a moving fluid, or between two relatively immiscible, moving fluids) to give a body surface temperature. A combination of the insensible heat loss produced by skin diffusion and heat loss via regular sweating together causes evaporation-based heat loss. Radiation, conduction and convection processes are ways the human body can gain or lose heat, while evaporation (of sweat) is entirely a cooling process [37]. High ambient temperature and low relative humidity can guarantee better evaporation performance. The energy of sweat evaporation from skin can be expressed as Equation 1.3:

$$L_e = A \cdot (P_s - P_a) / R_e \quad \text{Equation 1.3}$$

where,

$L_e$  is the heat transfer by evaporation through clothing

$A$  is the surface area (m<sup>2</sup>)

$P_s$  is partial water vapour pressure at skin temperature (m<sup>2</sup>·Pa)/W

$P_a$  is the partial water vapour pressure at ambient temperature (Pa); and

$R_e$  is the total resistance to water vapour transfer through clothing and air outside the clothing surface (Pa·m<sup>2</sup>/W) [50].

During exercise, the human body heat and sweat increase (within an assumed hot and dry environment). To release the heat of the body, dry and evaporative transfer should work

together and sweat will change into vapour through evaporation [50]. Thus the total heat transfer ( $L$ ) can be described by Equation 1.4.

$$L = L_t + L_e = A \cdot (T_s - T_a) / R_t + A \cdot (P_s - P_a) / R_e \quad \text{Equation 1.4}$$

where,

$L_t$  is the dry heat transfer through the clothing system by conduction, convection or radiation

$L_e$  is the heat transfers by evaporation through clothing

$A$  is the surface area ( $\text{m}^2$ )

$(T_s - T_a)$  is the temperature difference between the skin and environment ( $^{\circ}\text{C}$ )

$R_t$  is the total thermal resistance of the clothing and the air layer outside the clothing surface and it is generally expressed in  $^{\circ}\text{C}/\text{W}$  (ISO unit)

$P_s$  is the partial water vapour pressure at skin temperature ( $\text{m}^2 \cdot \text{Pa} / \text{W}$ )

$P_a$  is the partial water vapour pressure at ambient temperature (Pa); and

$R_e$  is the total resistance to water vapour transfer through clothing and air outside the clothing surface ( $\text{Pa} \cdot \text{m}^2 / \text{W}$ ).

In order to keep the wearer dry and consequently comfortable, the clothing worn must have the capacity to facilitate moisture transfer. Moisture can travel through the clothing system by diffusion, sorption or wicking [48]. Evaporation can remove water from both the skin surface and the surface of a textile fabric.

**Diffusion** is the main process of transferring moisture. The rate of water vapour transfer by diffusion is proportional to the gradient of water vapour concentration. Air spaces in fibres and yarns can provide access paths for moisture to diffuse through. However, the porosity and thickness of fabric control the effectiveness of diffusion. Loosely constructed fabric enables water vapour to diffuse easily through the large pores and spaces [36, 48].

**Sorption** comprises three processes: adsorption, absorption and desorption. Adsorption is where water is taken up and held at the surface. Absorption is the diffusion of molecular moisture into the material. In desorption, the release of absorbed or adsorbed water from a material occurs [36].

**Wicking** is the mechanism of liquid water transfer through the yarn and fabric's capillary interstices. Effective wicking relies on fibre surface wettability along with yarn and fabric structure [48]. The lower the moisture regain the greater the amount of wicking. Wicking directly contrasts with the dispersion of water vapour, which increases with increased absorbance [52].

The type of fabric used and the design of a garment should be considered in order to achieve clothing comfort as well as functional design [46]. The following sections review the key factors affecting thermal transfer through garments (fabrics) and current methods of measuring the same.

### **1.3.3 Factors related to the heat transfer through clothing**

Heat transfer through clothing is affected by both external and internal factors. Ambient relative humidity, temperature and wind speed are the chief external factors. Andersson [53] has listed three clothing factors directly correlated to thermal comfort. They are:

- a) Material overall thickness and air spaces between the skin and garment, an outcome of the fabric drape.
- b) Ability of air to transfuse (permeate) through the clothing both inherently and by wearer motion or wind. And,
- c) Ability of fabric to ease the evaporation of perspiration and not block it.

Predicting the comfort performance of a fabric can be achieved through measuring physical properties that include mass per unit area, thickness, evaporative resistance, thermal insulation, moisture management and air permeability [54-58]. These properties are briefly described below.

#### **1.3.3.1 Air permeability**

The permeability of air is the rate of airflow that passes through a fabric per unit surface area at a particular differential pressure (EN ISO 9237: 1995). The factor of air passage is of great significance for evaluating and comparing the 'breathability' of fabrics (coated and



uncoated). Typical fabrics of interest are utilised in raincoats, tents, uniform shirting, parachutes, industrial filter fabrics, sail cloth and the covering fabrics of pillows and duvets [59, 60].

Resistance to water vapour transmission is indirectly proportional to air permeability of clothing materials. Therefore, clothing made from low air permeability materials is not preferred for next-to-skin wear, as latent heat transfer is essential for thermal comfort. On the other hand, air penetration in windy conditions is directly related to high air permeability. Thus in order to reduce heat loss caused by air penetration in wintery and windy conditions, clothing should have as little air permeability as possible [2].

The air permeability of fabrics is influenced mainly by the fibre type, (surface characteristics and fineness), the yarn structure (geometry, count and hairiness), and the fabric construction (loop or stitch length, tightness factor, fabric thickness, density, and cover factor) [58, 61-65]. The cover factor is the percentage of constituent yarns covering the fabric surface area relative to the total fabric surface. A high cover factor results in low air permeability [66]. Ishtiaque et al. [67] indicated that there is an additional factor of yarn deformation properties in the fabric. In the case of woven fabrics, Ogulata [60] highlighted a direct relationship between air permeability and the porosity rate. The latter is the difference between the total fabric area and the projected area covered by the yarns [68]. Conversely, the air permeability of a woven fabric decreases with the increase of the number of warp yarns per centimetre. Ogulata and Mavruz [69] evaluated plain knitted fabrics and their porosity and air permeability values. They found the highest air permeability values in the fabric with the lowest courses per cm and yarn count in tex. Moreover, long loop length produces a looser fabric and therefore with increased air permeability.

Marmarali et al. [70] compared the dimensional and physical properties (including air permeability) of single jersey fabrics made from cotton alone and cotton/spandex blends.

They determined that fabrics that contained spandex showed lower air permeability. Sundaramoorthy et al. [71] advanced a model that aimed at connecting the number of layers with the structural parameters of a single fabric and the air permeability of a multilayered woven fabric system. This model indicated a hyperbolic decrease of air permeability with an increase in the number of layers.

Air permeability plays a significant role in transporting moisture vapour from the skin to the outer environment. Karaguzel [68] indicated that the diffusion mechanism transfers vapour in the air through fabric pores from one side of the fabric to the other. Jun et al. [72] investigated textile properties in terms of their effect on the microclimate inside caps and on subjective wearing sensations in a stable environmental situation. They found that because of a dense layer of hair between the skin and the cap, air and water vapour could not transfer easily to the outside environment because of the formation of a stationary air layer.

### **1.3.3.2 Fabric drape**

Drape illustrates the way fabric performs when hanging under its own weight. Different configurations and forms can be obtained by arranging and draping fabric. Fabric drape along with lustre, colour, texture, etc. defines fabric and garment appearance [19]. Drape is one of the vital textile characteristics in determining the air gap between fabric and skin and how clothing adapts to the human silhouette. Wearing clothing with exceptional drape gives a sense of fullness and elegant appearance [73]. The importance of drape for designers lies in its obvious influence on the appearance of garments [59].

Gravity-based horizontal deformation of a fabric annular ring is commonly employed to measure drape. This deformation (drape coefficient) calculated as a percentage of the area of the annular ring of fabric covered by a vertical projection of the draped fabric describes the fabric drape objectively [74].

The factors that affect fabric drape are fibre content and diameter, fabric weave and construction and the geometry over which it drapes. The effect of fibre diameter is usually overshadowed by that of the other factors. Chaudhary [75] related drape to the weaving parameters. Abdin et al. [76] and Jeong et al. [77] highlighted the impact of fabric cover factor because of its effect on the bending rigidity. In addition, the weave structure also determines fabric drape through the yarn interactions, fabric tightness and crimp. Fathey et al. [78] demonstrated that fabric tightness shows a strong correlation between fabric drape and stiffness. Hu and Chan [79] examined the relationship between the fabric drape coefficient (DC) and the KES-F system parameters. The importance of fabric mechanical properties to fabric drape was indicated, which included bending, lateral compression, shearing, and extension, surface roughness characteristics, and weight and thickness. Fibre fineness and softener applied to fabric were found to mainly affect the drapability of knitted fabrics [80]. The study also reported an estimate of 90% agreement between subjective and objective assessment of the drapability of fabrics.

### **1.3.3.3 Evaporative resistance**

The materials from which clothing is made usually obstruct the heat and moisture from flowing from the skin to the outer environment.[81]. Salmon [82] confirmed the SGHP as the most precise procedure for determining the thermal conductivity of insulation materials. Heat and moisture transfer can be simulated through clothing from the body surface to the environment. The thermal resistance of a fabric is important in evaluating the fabric's efficiency in providing a thermal barrier to the wearer [83].

The thermal properties of knitted and woven fabrics have been investigated to understand the impact of materials and fabric construction [84]. Yoo and Kim [85] examined fibre type (cotton broadcloth and polyester (PET) broadcloth, and cotton canvas), air layer thickness, fibre type and garment openings in terms of their effect on vapour pressure changes in the microclimate based on the vertical sweating skin model.

According to the observations of Shoshani and Shaltiel [86], a decrease in the density of fabric resulted in an increase of the thermal insulation. Milenkovic et al. [87] stated that heat transfer through fabrics is affected by fabric thickness, enclosed still air and external air movement. Greyson [88] and Havenith [89] noted that as material thickness increases and more air is trapped in the fabric, there is an increased resistance of heat and water vapour.

Dhinakaran et al. [90] reported that the structure, weight, moisture absorption, types of raw materials used, heat transmission and skin perception are the main factors that affect the comfort characteristics of fabrics. Ozdel et al. [91] mentioned that an increase in yarn twist and count as well as water vapour permeability values decrease thermal resistance values. Karaca et al. [92] investigated the thermal comfort of polyester fibres produced in two different weave patterns (plain and twill) with different cross sectional shapes (round, hollow round, trilobal and hollow trilobal). They pointed out that fabrics made from hollow polyester fibres present higher thermal conductivity and thermal absorption values on one level, and lower water vapour, thermal resistance and air permeability values than their solid fibre counterparts. Moreover, the lowest thermal conductivity and thermal absorption levels are found in the twill fabrics produced from trilobal fibres but with the highest thermal resistance, water vapour and air permeability.

Kakvan et al. [17] examined the thermal comfort properties of Kermel<sup>®</sup> (polyamide-imide), cotton/nylon and cotton/nylon-blended Kermel<sup>®</sup>-woven fabrics. The results indicated that with an increase in the Kermel<sup>®</sup> fibre blend ratio, the fabric porosity, air permeability and thermal resistance are increased. Nawaz et al. [93] reported 100% suitability of cotton for transferring heat, but this not desired in hot conditions, while wool and wool/bamboo blend fabrics demonstrated the most suitable outcome of vapour resistance. Srdjak and Skeneri [94] investigated the transfer of water vapour through knitted fabrics produced from different raw materials (cotton, cotton/modal, viscose and

Tencel®) within various settings. The results confirmed the influence of environmental conditions (temperature and relative humidity) on the transfer of water vapour.

#### **1.3.3.4 Clothing insulation using thermal manikin**

The US Army in the 1940s developed the first thermal manikin, which was a one-segment copper manikin with electrical circuits that uniformly heated the surface. The manikin did not have the ability to simulate sweating and body movement [95, 96]. The original purpose for thermal manikins was to investigate the thermal interaction between the human body and its environment, particularly in the design and fabrication of clothing due to its intrinsic thermal properties. There is increasing interest in using thermal manikins in research and measurement standards [95].

Currently, most manikins incorporate mobility characteristics such as being movable or articulated with more than fifteen body segments [96]. These manikins, are able to perform like a movable human shape and are created from different materials that can give reliable, relevant and accurate heat loss measurements of not only flat 12 x 12 sets of layered fabrics, but also of three dimensional garment ensembles [27]. Thermal manikins are put through extreme experimental conditions that could be fatal to humans. Sweating manikins have recently helped to create more realistic simulations of thermal interaction with the environment incorporating a method that is quick, easily standardised and repeatable [95].

The two major areas of research for thermal manikins are assessing the characteristics of heat transfer, and the influence that the human body receives from other thermal environments including clothing, sleeping bags, interiors, cars, and chairs [97, 98]. The following clothing factors can be varied with modern manikins [95, 97]:

1. Amount of body surface area covered by textiles and amount of exposed skin
2. Distribution of textile layers and air layers over the body surface (i.e. non-uniform)
3. Looseness or tightness of fit

4. Increase in surface area for heat loss (i.e. clothing area factor) due to the textiles around the body
5. Effect of product design
6. Adjustment of garment features (i.e. fasteners open, hood up, etc.)
7. Variation in the temperature (and heat flux) on different parts of the body
8. Variation in body position (i.e. standing, sitting, lying down); and
9. Variation in body movement (e.g. walking, cycling).

Researchers have exploited the above features and employed manikins to objectively investigate clothing insulation and the thermal comfort properties of garments [98]. Such manikins enable assessments to be made of heat flow and loss from various parts of the body surface. Data collected in this regard are useful in estimating the body's performance of thermal and evaporative resistance ratio in various clothing and climatic conditions [45, 97, 99-103].

The Newton model from measurement technology is one of the sweating thermal manikins [104-107] that meet ASTM F-1291-05, ASTM 2370-05 and ISO 9920 standards. It is largely used to evaluate garment and environmental heat loss. The manikin is constructed with separate sections having individual sweating, temperature measuring and heating systems. Sweat control occurs through evenly spread fluid ports over the surface, where an operator can control the sweating rate [108, 109]. Blood [110] reported that the Newton manikin system produced reasonable results when compared against human trial studies.

#### **1.3.3.5 Effect of garment fit and body movement**

Since the openings in clothing and the wearer's movement and position allow air, heat and moisture transfer to occur, garment design and fit are important [111]. Fashioning fabrics into clothing to wear on the body allows design and fit to be varied to produce air gaps between fabrics layers and openings around the body. McCullough [100] reported that about 75% of total body heat can be transferred to the environment through openings in

places like the neck, waist, wrists and ankles during body actions in windy conditions. Size and fabric properties (stiffness or extensibility) also contribute to the looseness or tightness of fit. In order for clothing to transfer heat, body motion and posture can help by changing the effective surface area, the entrapped air layers and the geometry of the clothing. According to Olesen et al. [112] and McCullough [100] measurements on thermal manikins found that a standing person has higher clothing thermal insulation than a sitting or moving person. However, the values of evaporative resistance for a sitting person increase and they decrease when a person is walking. Walking can result in relative air movement and air motion, by which the thermal insulation and vapour resistance of the clothing layer are affected [113].

### **1.3.3.6 Liquid moisture management**

Moisture management is the process of transporting sweat through fabric away from the body to keep the wearer dry and comfortable [114]. Liquid moisture management properties of knitted and woven fabrics' can be tested by a moisture management tester (MMT) operated according to AATCC TM 195-2009. The factors that the fabrics' moisture management properties depend on are water resistance, water absorption, water repellence, and wicking within the fibres and yarns, [59].

The MMT is a fairly new instrument that objectively characterizes the spread of moisture and the transfer properties on and between fabric surfaces [115]. Hu et al. [116] reported on the measuring principle and apparatus design of the MMT. Their findings confirmed agreement between the definition and values of performance indices and subjective perceptions of moisture sensations in sweating, such as "clammy" and "damp". Yao et al. [117] focused on the improvement of the test method and the evaluation of indices of liquid moisture management properties, grading and classification methods, data processing and the expression of test results for industrial applications.

According to Öner et al. [118], who compared polyester and cellulose-based fabrics, polyester fabrics had higher overall moisture management capacity (OMMC) values. Namlığöz et al. [119] observed that woven fabrics fashioned from cellulosic/polyester blended fibres showed more effective liquid transport than both 100% cotton and 100% polyester fabrics. Ozkan and Meric [120] measured the thermal and moisture management properties of six different types of polyester knitted fabrics (warp and weft) used in the production of summer cycling clothes. They found that warp knitted fabric made from 100% polyester was much better as a summer cycling material due to its good air permeability, and low thermal and water vapour resistance values.

Prakash et al. [121, 122] studied the thermal comfort properties of knitted bamboo fabrics in terms of blend ratio, loop length and yarn linear density. It was found in general that the thermal conductivity, thermal resistance, air permeability and relative water vapour permeability values of the fabrics depended on both the bamboo fibre content in the fabric and the linear density of the constituent yarns. Troynikov and Wardiningsih [123] showed that materials made of wool/polyester or wool/bamboo blend have improved moisture management properties as compared to fabrics of 100% wool and 100% bamboo. They [123] also examined the moisture-transport characteristics of knitted fabrics produced from regenerated bamboo with different cover factors, and concluded that overall moisture management capacity decreases when the fabric cover factor increases.

Fangueiroa et al. [124] used blends of wool and moisture management fibres such as Coolmax® and Finecool® to produce innovative yarns and knitted fabrics. Coolmax® polyester showed better moisture transport results followed by Finecool® polyester which performed better in drying rate. Sampath et al. [125] analysed the thermal behaviour of moisture management finish (MMF) fabrics to learn about the thermal comfort characteristics of selected knitted fabrics for different climatic conditions. The knitted fabrics made from yarns of micro-denier polyester filament, spun polyester, polyester/cotton, filament polyester, and 100% cotton were used for the study. Their test



results indicated that the knitted fabrics produced from different yarns nature greater influence on thermal characteristics. There was a significant effect of MMF treatment on the thermal behaviour of micro-denier polyester knitted fabrics in regards to thermal conductivity, water vapour permeability, thermal absorptivity and water vapour resistance.

Guo et al. [126] investigated the impact of fabric moisture transport properties (MTP) on physiological responses when wearing protective clothing. Bedek et al. [54] analysed the associations between the thermal comfort of six knitted types of underwear and textile properties. The fabrics were made from cotton/polyester/rayon blend simple rib, cotton, cotton/viscose blend, polyamide 1 × 1 interlock and polyester double rib. Their findings indicated that the fabric with the lowest porosity and thickness values had the highest water vapour transmission rate and greatest moisture management capability.

Supuren et al. [127] investigated double-face fabrics in terms of moisture management properties. The yarns selected for use on the face and back sides were: cotton/cotton, cotton/polypropylene, polypropylene/cotton and polypropylene/ polypropylene. The polypropylene (inner)-cotton (outer) fabric proved to have better moisture management properties and facilitated comfort, and can be favoured for summer active and sportswear.

### **1.3.4 Subjective methods**

In the past, subjective methods such as wearer trials and surveys have been used to evaluate the thermal comfort of clothing and textiles. They can be combined with the objective methods mentioned above.

#### **1.3.4.1 Wearer trials**

In this type of trial, a group of people selected for the test wears clothing chosen to be evaluated and then the test group is exposed to different real-life simulations [1]. For

instance, the test group may perform a number of indoor and outdoor activities wearing a particular type of sweater chosen for the test [57, 98, 128-131]. Kim et al. [132] opined that user-based tests or trials are the only method to give a realistic and comprehensive evaluation of clothing performance. Comfort related feelings and feedback from the test group are recorded during and after the trials and assessed. The wearer trial method shows several weaknesses such as:

- ❖ Large numbers cannot be evaluated.
- ❖ Tests are time consuming.
- ❖ Tested simulations may not match all real life scenarios.
- ❖ High possibility of bias and errors.

#### **1.3.4.2 Survey method**

This type of method is based on an opinion poll taken from a relatively large group of participants and the results are analysed [133]. Although several survey methods are available, the most popular ones for assessing comfort are:

1. The interview method – where the survey or personally interviews participants in person or over the telephone. Responses to open ended and responses to multiple-choice questions are collected and analysed [134].
2. The questionnaire method – in which a set of questions are prepared and circulated to a large group and the responses are collected after a set period. The questionnaire is designed to take into account the target audience so as to obtain the required information [135].

The survey method has similar defects to wearer trials but larger numbers of responses can be evaluated in a short time.

## **1.4 Research gaps**

Through globalisation, the wearing of abayas became widespread symbolising a person's faith but now it has transcended that stage to become a truly global fashion garment. Despite this, the black abaya is considered the most conservative way for women to dress in the Arabian Gulf. Several studies [12, 14, 15] examined the abaya as fashion but no one has studied the abaya from the comfort viewpoint. The most significant objectives of Arbreen's [7] study were to identify the properties which veil fabrics must have and to measure the properties so as to set an acceptable limit for each property to provide the Saudi standards council with fabric specifications in terms of modesty and body covering.

Al-Ajmi et al. [11] used both male and female thermal manikins to measure the thermal insulation and clothing area factors of a number of Arabian Gulf garments and ensembles for summer and winter seasons. Their studies provided the data intended to be added to ISO 9920 Ergonomics of thermal environment estimation of thermal insulation and water vapour resistance of a clothing ensemble. However, no research has been carried out to understand the thermal comfort properties of the abaya in a hot environment, in conjunction with studies using a female manikin. Such an investigation would be beneficial because the preferred traditional abaya is black and generally absorbs both visible (colour) and invisible (heat) rays of sunlight. The study gains further importance when considering the high summer temperatures prevalent in Saudi Arabia.

## **1.5 Research aims and objectives**

The present research aims to obtain an overview using a survey of the types, variety and comfort of abayas worn by women in Saudi Arabia. On the basis of the survey findings, it seeks to identify the widely used textile materials for abayas and understand the factors affecting their perceived thermo-physiological comfort properties. Improving the thermal comfort properties of the traditional abaya is attempted by an energy-reflecting chemical treatment. In addition, suggestions are made to improve the abaya design to minimise

thermal insulation in hot environments. The detailed objectives of the current research are listed below.

1. Conduct a survey in Saudi Arabia to understand the performance and comfort level of the current abaya.
2. Study the thermal comfort properties of existing abaya fabrics and garments using a female thermal manikin.
3. Discover the relationships between thermal and moisture management properties between the multiple layers of clothing worn under the abaya.
4. Assess fabrics made of polyester, polyester/wool or other blends of polyester for thermal comfort properties, along with moisture management properties.
5. Investigate the thermal comfort and moisture management properties of the fabrics after treatment with energy reflecting chemicals.

## **1.6 Research questions**

The questions in this research are formulated as:

1. What properties of abaya fabrics significantly affect wearer thermal comfort?
2. What level of thermal comfort and moisture management do knit abaya fabrics have?
3. How do abayas and multilayer garments worn underneath affect thermal properties?
4. Can a chemical treatment with an infra-red energy reflecting compound be effective in reducing the thermal stress of abayas by reflecting solar energy?

## **1.7 Thesis overview**

Chapter 1 provides a general introduction to the subject and includes an extensive literature survey on related research work. This literature review provides the

background and guidance for the entire study. It identifies the rationale for undertaking the study and provides the research objectives.

Chapter 2 describes the various survey techniques. It details the questionnaire used to obtain the opinion of women in Saudi Arabia and determine the presence and scale of thermal discomfort of the current abaya in terms of fabrics and designs. The sampling method is discussed, followed by an explanation of the survey instrument. Finally the data analysis procedure is described.

Chapter 3 elaborates on the laboratory based experiments and methodology adopted in this research. It describes the equipment, test instruments and facilities employed in the course of this thesis work.

Chapters 4 and 5 investigate fabrics of both woven and knitted structures currently used for the abaya to determine their comfort performance based on air permeability, thermal resistance, vapour resistance and moisture management. A description of the experimental setup and procedure is followed by the results and analysis.

Chapter 6 evaluates the range of clothing worn within the abaya in terms of thermal insulation and evaporative resistance under standing and walking conditions using a sweating thermal manikin.

Chapter 7 outlines the thermal comfort properties of plain-weave fabrics that were dyed black and treated chemically to reflect a proportion of solar energy. The effectiveness of using energy-reflecting chemical (ERC) treatment with different plain-weave fabrics is also evaluated. Finally, a comparison is drawn between fabrics with and without the ERC treatment.

Chapter 8 presents the conclusions that may be drawn from this research. It recommends pathways on how the present work could be further continued.

# **Chapter 2 Understanding the thermal comfort performance of the abaya**

## **2.1 Introduction**

A sense of comfort although being a critical aspect of all clothing, is subjective and difficult to measure. Questionnaire surveys in this chapter provide one avenue for assessing this elusive factor. The purpose of this study was to administer a questionnaire used to understand the opinion of women in Saudi Arabia to find out whether the problem of thermal discomfort of current abaya styles in terms of fabrics and designs exists, and if confirmed, to define its scale. The survey aimed to show whether thermal discomfort affects a specific type of clothing. The results were analysed to suggest an abaya design that will enhance comfort based on improved thermal and moisture management properties.

## **2.2 Survey administration**

This research followed the *Ethics Guideline Procedures* outlined by Royal Melbourne Institute of Technology University (RMIT) in the Ethics Review Process (<http://www.rmit.edu.au/dsc/chean>). Ethics approval by the College Human Ethics Advisory Network (CHEAN) (A-2000778-09/12) was obtained before any data were collected (Appendix A). In Saudi Arabia, King Abdul Aziz University (KAU) agreed to conduct the study (see Appendix B). KAU occupies a distinguished place among higher education institutions and is one of the second largest universities in Saudi Arabia. It was founded in 1967 as the first private institution in the kingdom and became a public university in 1971 [136]. In addition to that, the author is one of KAU the faculty members. A letter requesting permission to survey staff and students and describing the goals of the study, survey procedures and time commitment for participants was sent to KAU. After

permission was obtained, a packet containing the survey invitation and survey forms was delivered to a representative at the Clothing and Textiles department who assisted in the survey process at KAU.

The survey invitation contained a brief description of the research goals, time commitment and instructions for taking the survey (Appendix C). The questionnaire was attached to the survey invitation. Completion of the survey took approximately 20 minutes.

## **2.3 Questionnaire design**

A descriptive questionnaire survey was used in this research. Detailed needs were identified from women wearing abayas based on the analysis of survey data. The questionnaire survey form (Appendix D) was written in both English and Arabic, to facilitate comprehension and thereby completion of the questionnaire. All participants were informed that they could choose either the Arabic or the English version. The questionnaire was developed to obtain information pertaining to the opinion of women in Saudi Arabia on the comfort of current abaya garments in terms of fabrics and designs.

## **2.4 Data collection through questionnaire**

### **2.4.1 Sample size**

The participants at KAU in Saudi Arabia were invited by means of a global email from the university to all female students and staff. More than a hundred women aged between 18 and 50 years responded to the invitation.

The survey was explained in a personal face-to-face interview to the volunteer participants and any queries clarified. Further, the questions were orally posed to each participant so as to ensure their understanding. Participants responded by filling out the survey form during their free time.

## 2.4.2 Preparation and distribution of questionnaire

The questionnaire has 26 questions in five sections consisting of:

- a) Demographic data of the subject comprised of characteristics such as age group, profession and academic qualifications (questions 1–3).
- b) Characterisation of the abaya being used at present in terms of reasons for wearing an abaya, type and design of the abaya usually worn, annual purchase behaviour, reasons for changing currently worn abayas, places of purchase of abayas, type of materials and type of textile fabrics (questions 4–10).
- c) Comfort of an abaya with multilayers of clothing was assessed using questions about sensations while wearing abayas, the temperature at which discomfort was perceived, the longest period of staying outside, the breathability of the fabric, the level of comfort with multiple layers, the clothing usually worn underneath the abaya, the kind of sleeve worn underneath the abaya, the body area where the most heat stress was felt, the kinds of clothes that cause heat stress with an abaya, the ability of an abaya to absorb perspiration and the feeling of comfort while wearing an abaya during different activities (questions 11–22).
- d) Preference for abaya fabrics and design was determined by questions about the types of fabrics used in terms of; thickness, weight, transparency, structure and, colour. Abaya design was assessed in terms of the width of sleeve cuffs, the width of sleeves, the length of sleeve, the width across the shoulders and the length of the abaya (questions 23–26).

Both open-ended and closed-ended questions were included. Question 26 was an open-ended question about describing the ideal abaya. When a response was directly related to another question in the survey, the response was given with an appropriate further question.



A total of 110 participants completed the questionnaire. As ten survey forms were incomplete, they were discarded. Therefore, a total of 100 valid survey forms were used for data analysis. Subsequently, according to RMIT University protocol, the researcher collected all the completed questionnaires and stored them in a secure area for data entry and analysis.

### **2.4.3 Data analysis**

The data were analysed using the Statistical Package for Social Sciences (SPSS) Version 21.00 software. The detailed perceptions and requirements on an abayas, such as style, material, comfort and function were summarised.

## **2.5 Results and discussion**

### **2.5.1 Demographic data**

Questions 1–3 dealt with individual demographic information, related to the age group, profession and academic qualifications. Table 2.1 shows that 38% of respondents were aged 21–30 years. About 45% of respondents were employed in the workforce and 79% held a bachelor degree or postgraduate degree. Hence, the majority of respondents were well educated with a good understanding of the surveyed subjects. Nearly half were employed and 78% respondents were younger than 40 years. They were likely to have open minds on the subject of the abaya and likely to accept changes so as to become more fashionable. In addition, the survey results should be reliable because most of the respondents are from the university Clothing and Textiles department, and so should have more knowledge about the abaya in terms of textiles materials, fashion and design than the general public.

Table 2.1 Sample demographic

Demographic	Response	%
<b>1. Age group</b>		
From 18 to 20	8	8
From 21 to 30	38	38
From 31 to 40	32	32
More than 40	22	22
<b>2. Profession</b>		
University student	29	29
Employee/employer	47	47
Unemployed/housewife	24	24
<b>3. Academic qualifications</b>		
Up to high school	14	14
Diploma	7	7
Bachelor degree	44	44
Postgraduate	35	35

## 2.5.2 Type and demand of abaya

Table 2.2 shows that the majority of women (78%) cited religious reasons while the rest claimed tradition as the reason for wearing an abaya. Regardless, they were all abaya users.

Questions 4–10 dealt with information on the current type of abaya worn. It is related to the design of the abaya, whether abayas were bought every year, the reasons to change the current abaya, the preferred places to buy an abaya, the types of materials and textile fabric used for abayas, as presented in Table 2.2.

When asked about the type of abaya design they usually wore, many of the respondents reported that they liked to wear the abaya from the shoulder with either tight (37%) or loose sleeves (36%). In contrast, none of them liked to wear an abaya from the top of the head. The reason for wearing an abaya from the top of the head is that it covers the entire body, is very loose such that it does not describe the contours of the body and is non-clinging when compared with abayas worn from the shoulder. The reason for some

women not liking to wear an abaya from top of the head were because of feelings of discomfort while wearing an abaya on top of the head, this was associated with greater heat stress experienced, particularly with multilayers of a scarf worn under an abaya.

In addition, as a result of globalisation and the development of modern trends, women want to shift from the 'traditional style' (abaya worn from top of the head) to the new 'abaya as fashion' (abaya worn from the shoulder). This finding agrees with the work of Al-Qasimi [14], who reported that the 'abaya-as-fashion' presents a case of resistance and deviation from its original form (abaya worn from top of the head), while consent by the hegemonic order causes the ultimate preservation of the abaya's essential qualities (long and black).

Up to four abayas were bought by 61% of respondents every year for different occasions, the rest (30%) bought up to two abayas, and some respondents bought more than five abayas (9%). This is due to the different income of each person, as well as social relationships that oblige women to buy abayas for different occasions. An increase in comfort was given as the main reason for more than half of those surveyed to purchase new abayas, searching for fabric and design that would be comfortable, while some respondents purchased new abayas to replace old abayas. Moreover, some abayas were only worn once or twice before being donated to charity in a search for new abaya designs. This finding agreed with the results obtained by Al-Qasimi [14]. A minority (6.5%) liked to wear unique and more fashionable garments because they wanted to be distinct from other women in terms of design, materials, colour and decoration or accessories. Abayas were purchased from various sources, such as abaya shops and famous designers, to express the respondents' personal preferences.

Table 2.2 Information on the current type of abaya used

Information on the current type of abaya used	Response	%
<b>4. Why should you wear the abaya?</b>		
Religion	78	78
Tradition	22	22
<b>5. What type of abaya design* do you usually wear?</b>		
The normal one which is worn from the shoulder and has tight sleeves	37	37
The loose sleeves	36	36
The top of the head	0	0
The butterfly design	15	15
Other design	12	12
<b>6. How many abayas do you buy in a year?</b>		
From 0 to 2	61	61
From 3 to 4	30	30
More than 5	9	9
<b>7. What are the reasons that make you change the current abaya (multiple answers possible)?</b>		
New style	31	27.7
New fabric	14	12.5
More comfortable	52	46.4
Gift	8	7.1
Other (specify)	7	6.3
<b>8. Where do you buy your abaya (multiple answers possible)?</b>		
Abaya shop	89	80.9
Market stalls	9	8.2
Overseas	2	1.8
Homemade	6	5.5
Specify	4	3.6

\* The abaya design description is given in Chapter 1. Abayas can be worn in different styles, either from the shoulder (Figure 1.2 (a)) that can be opened all the way down the centre front and fastened closed with snaps, or it can be pulled on over the head (Figure 1.2 (b)) over the normal day-to-day clothing and called the 'ra's abaya' or 'judicial abaya'.

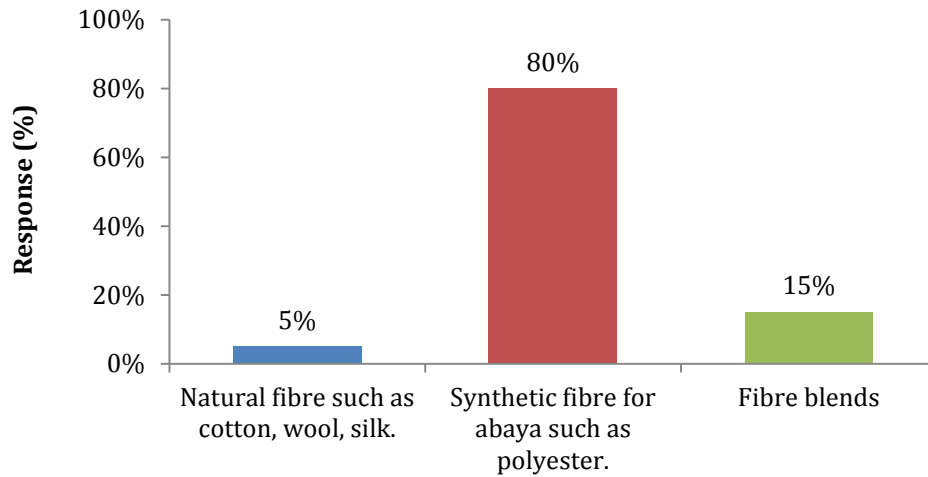


Figure 2.1 Types of materials used for current abaya.

Synthetic fibres such as polyester were the most popular materials for abayas as can be seen from Figure 2.1. In fact, fabric retailers and abaya salespeople said that polyester fabric is popular because it is durable and cheaper and easier to care than natural fibres or natural fibre blends [7]. The fabric used to make an abaya is around four metres in length and the abaya fabric cost for each metre was between \$10–30 (cheaper fabric). As can be seen in Figure 2.2, most of the abayas were made from woven fabrics. This is due to the fact that an abaya should hide a woman’s body contour and woven fabric does this better than knitted fabric, as discussed in earlier studies [137, 138].

The results of the survey also agree with the findings of Arbaeen in her study [7] conducted with fabric retailers and abaya factories, which found that most (96.6%) of the fabrics used for abayas were woven fabric made from polyester fibres. Chester [139] also reported that abayas made from polyester fibres, such as ‘Lexus Crepe’, a trade name of a crepe weave fabric, are generally cheaper than those made from satin materials and ‘Internet Crepe’, a trade name of a twill weave fabric.

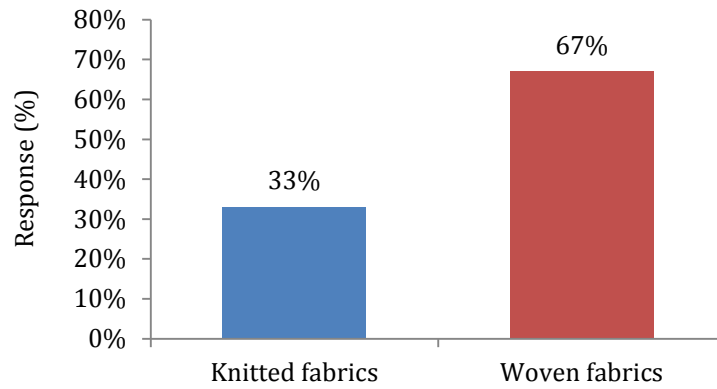


Figure 2.2 Types of textile fabrics used for current abayas.

### 2.5.3 Comfort of an abaya worn with multilayers of clothing

Questions 11–22 dealt with the perception of comfort while wearing an abaya over multilayers of clothing. A majority (79%) felt discomfort in hot weather (Figure 2.3). This could be because the added abaya layer inhibits air permeability while the black fabric absorbs more heat that does not dissipate quickly. This makes the wearer feel uncomfortable [140, 141].

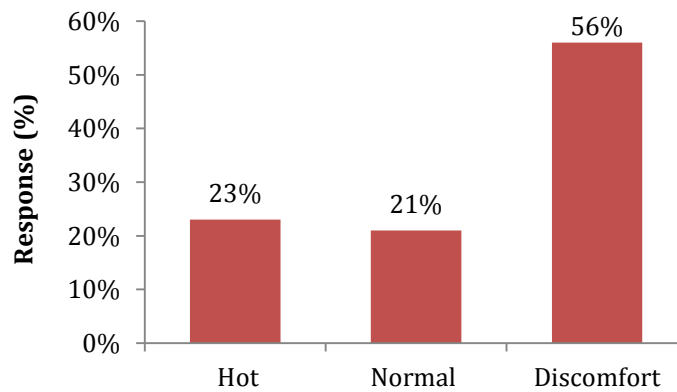


Figure 2.3 Sensations when wearing an abaya in hot weather.

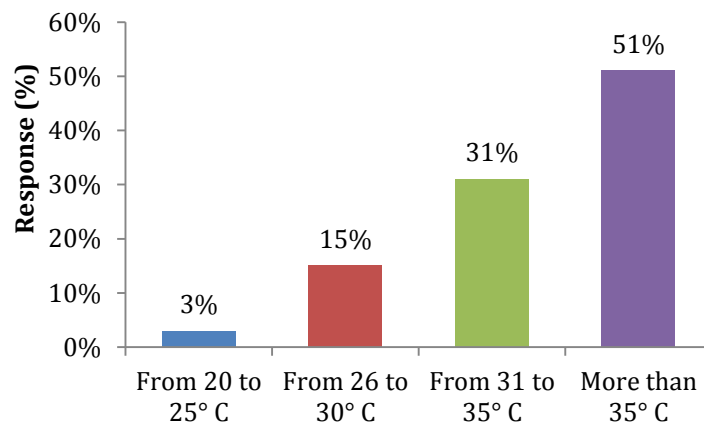


Figure 2.4 Environmental temperature at which thermal discomfort starts while wearing the abaya in Saudi Arabia.

Discomfort was pronounced at higher temperatures while wearing an abaya, as shown in Figure 2.4. People in Saudi Arabia may be more tolerant to heat although according to Parsons [142], if the environmental temperature is between 30–34.5° C the sensation is warm, uncomfortable and unacceptable and a sedentary person would begin to perspire. If the temperature is between 34.5–37.5° C the sensation is of being hot, is very unacceptable and a sedentary person would begin to perspire profusely. If the temperature is more than 37.5° C the sensation will be very hot, very uncomfortable and a person may become physiologically incapable of temperature regulation.

A significant factor in physical comfort has to do with temperature and moisture. Whether the wearer is comfortable wearing a garment made of a particular textile fabric depends on its ability to promote or restrict the passage of heat, air and moisture vapour through the fabric [44]. When working in the afternoon when the environmental temperature exceeds 30° C in Saudi Arabia, all abaya users will feel discomfort. The average period of wearing an abaya outside the home was three to four hours, while some wore it for more than five hours because they were working in occupations which required wearing an abaya for a longer time. This would result in prolonged thermal discomfort for women who have to wear abayas for hours in a hot environment. In order to improve the comfort

of wearers, most of the respondents desired increased ventilation in public places. The breathability of an abaya was generally unacceptable with 73% stating that the multilayers of clothing plus an abaya affected their comfort level in hot weather. Comfort is both physiological and psychological. It is a human feeling, a condition of ease or wellbeing influenced by many factors including textile properties [26]. It is apparent that improving the thermal comfort performance of the abaya is necessary.

The survey evaluated the variety and combination of clothing worn under the abaya. Women often wear uniforms at work, university or school. This usually comprises a shirt with long sleeves and a skirt, or '*jalabiah*', which is a traditional garment for women, as shown in Chapter 1 Figure 1.8. All the clothes are required to be covered with an abaya when women go outside the home for whatever reason. In response to question 17 about the clothes usually worn underneath the abaya, they often wore T-shirts with jeans or slacks when going shopping or to other places. Many respondents cited a feeling of increased freedom when they moved with an abaya than with other clothing such as a skirt or '*jalabiah*'. Wearing slacks with an abaya can make the wearer feel more comfortable and modest as these cover the lower part of the body, especially when riding in a car or walking in wind. When a woman rides in a car with a skirt, some part of her leg could be seen by others. Moreover, slacks provide a better fit and they can absorb more perspiration compared with a skirt [143]. Wearing combinations are investigated in Chapter 6. It was agreed by the respondents that wearing an abaya with a skirt makes the abaya drape more nicely than with slacks. However, because they face some problems with wearing a skirt such as exposure of the legs and friction between the legs, they prefer wearing slacks with an abaya. A minority (3.4%) (Figure 2.5) indicated that they may wear anything they like (such as pyjamas) but it depends on where they are going.



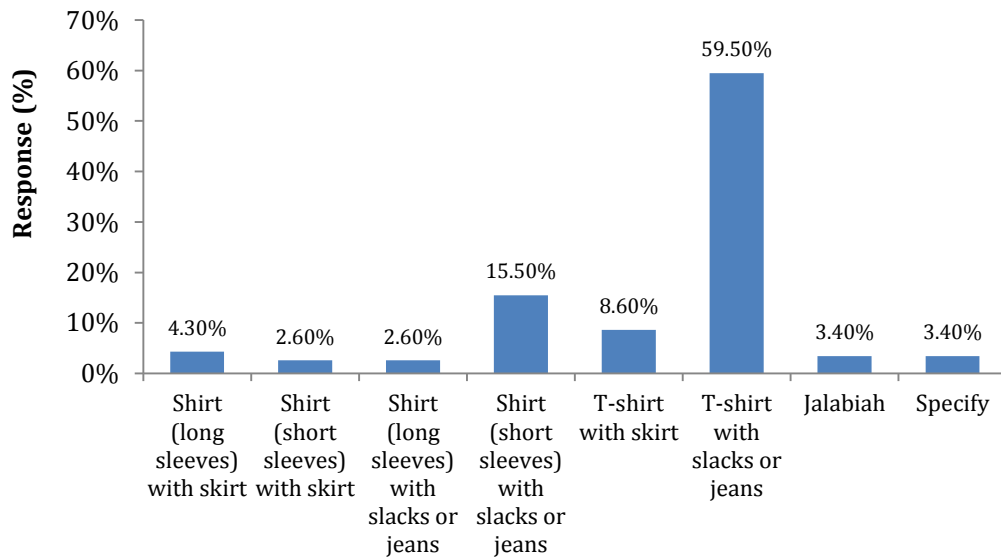


Figure 2.5 Clothing usually worn underneath an abaya.

An increase in comfort was given as the reason for choosing short sleeves or sleeveless, dresses underneath an abaya (Figure 2.6). While wearing long sleeves the wearers may feel warm and uncomfortable because they have two layers of fabric (long sleeves on both the shirt and abaya) that increase the heat sensation especially in hot and humid weather. In addition, wearing a long-sleeved shirt with an abaya makes the wearers feel warmer because of the increased amount of body surface area covered by the shirt and abaya. McCullough and et al. [144] reported that a long-sleeved shirt was warmer than a short-sleeved shirt, which again was warmer than a sleeveless garment. These differences resulted from variations in the amount of body surface area covered by the garment.

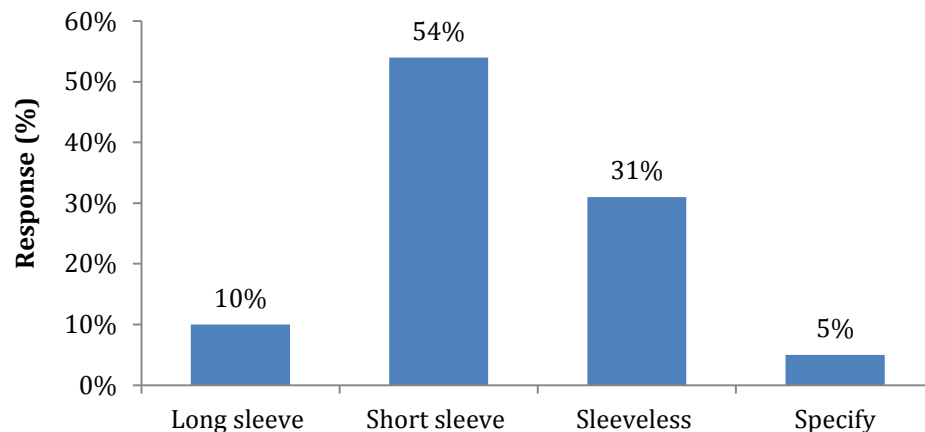


Figure 2.6 Type of shirt worn underneath an abaya.

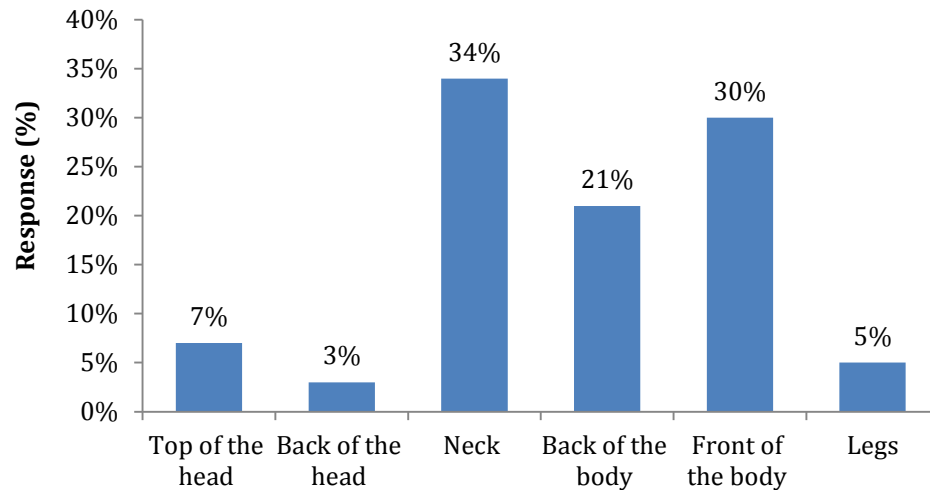


Figure 2.7 Body area in which the most heat stress was felt while wearing an abaya.

Figure 2.7 shows that 34% of respondents felt heat stress in the neck area, 30% felt heat stress in the front of the body (chest) and 21% felt heat stress in the back of the body. These areas (neck, front of body and back of body) comprise the torso area. The torso is commonly covered with multilayers of clothing. The neck is usually covered with a scarf, which is wrapped around twice. The chest and back areas also have multilayers of clothing including a bra, a shirt, an abaya and some part of a scarf. In addition, the effect of the clothes worn under the abaya on heat stress is depicted in Figure 2.8. Wearing a long- or short-sleeved shirt with a skirt or wearing a *jalbiah* resulted in more heat stress compared with wearing a long or short sleeve shirt with slacks. Chapter 6 contains more discussion about heat transfer through clothing covered with an abaya.

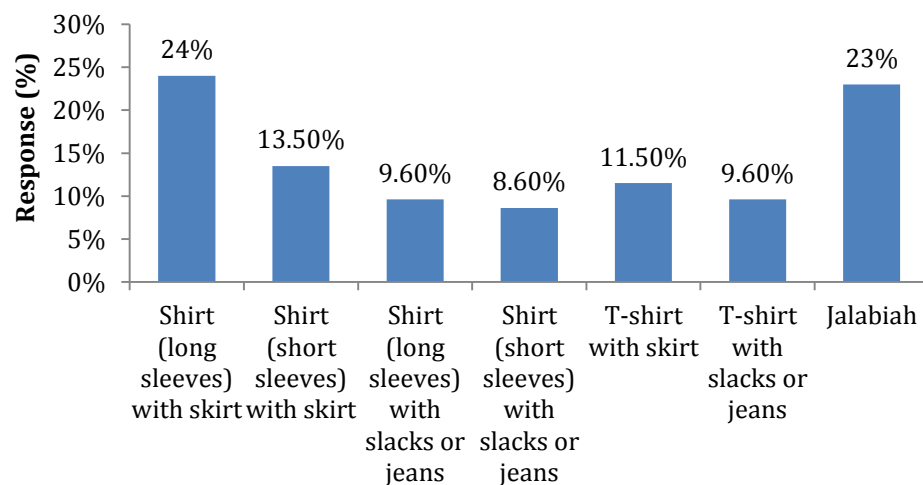


Figure 2.8 Types of clothes that caused heat stress with an abaya.

The hot and humid weather in Saudi Arabia in summertime causes people to perspire a lot [145]. Many respondents (60%) stated that the absorption of perspiration by an abaya was unacceptable while an additional 14% surmise the absorption to be very poor or almost unacceptable (Figure 2.9). This could be because most abayas were made from synthetic fibres (such as polyester) and had poor breathability. Fabric that does not breathe well will trap both perspiration and hot air near the skin, leading to considerable discomfort.

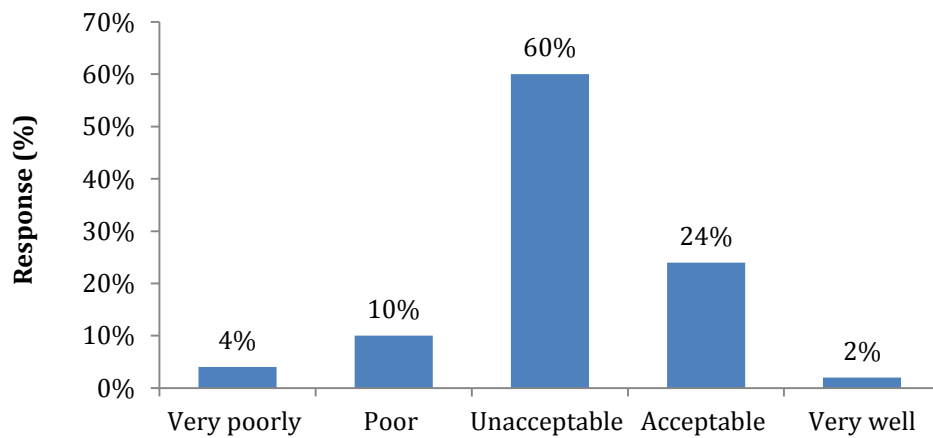


Figure 2.9 The ability of an abaya to absorb perspiration.

Figure 2.10 shows the comfort feeling of an abaya when the respondents engaged in various indoor and outdoor activities. 90% of respondents indicated that when walking outside in the sun they felt discomfort. The heat absorption due to sunlight in black garments was greater than with other colours [140]. However, when there was an air-conditioner, such as in a car or an indoor shopping place, 41% of respondents stated that wearing an abaya was acceptable.

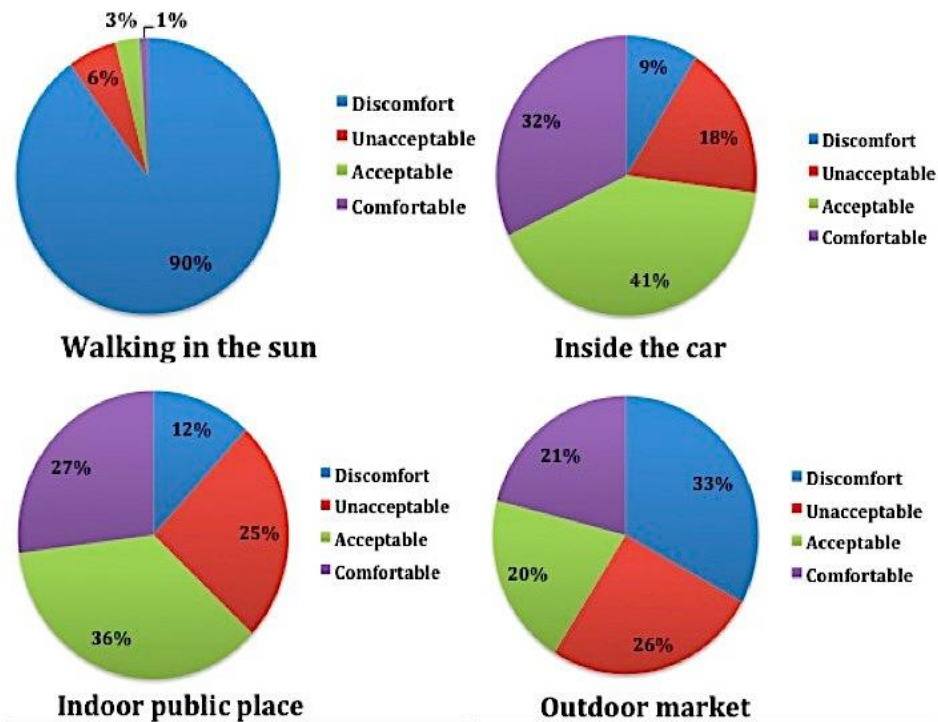


Figure 2.10 Comfort sensation of an abaya during different activities.

## 2.5.4 Abaya fabrics and designs

Questions 23–26 dealt with the details of future preferences for obtaining abayas, in terms of fabrics and designs. Table 2.3 and Table 2.4 represent the survey results of abaya fabrics and designs.

In Table 2.3, many of the respondents (52%) preferred that abaya fabrics be made from blended fibres. Blends of natural and manufactured fibres potentially have the advantage of combining the desirable properties of both fibre components, as reported by Prakash et al. [121]. Desirable properties included comfort, durability and easy care. A further 63% of respondents preferred fabrics to be of medium thickness, lightweight and opaque. 72% of respondents would like the fabric to be a tight structure, because such a structure makes the fabric coherent (mechanically stable) and non-transparent. In addition, tightly woven fabrics generally are of higher quality because they require more yarns during construction and are usually made of finer yarns [146]. All these parameters (thickness, weight, transparency and structure) affect the level of thermal comfort. Many previous researchers have found that physical parameters such as thickness, weight, transparency

and structure affected the comfort characteristics of fabrics [85-87, 89, 90]. Although lightweight and thinner fabrics are good for allowing more air to pass through in hot weather, this kind of abaya fabric may show the body contour due to its transparency and drapeability.

Table 2.3 Details of abaya fabric preferences the future.

Information about future abaya fabrics	Response	%
<b>23. Do you prefer abayas made from</b>		
Natural fibre	36	36
Synthetic fibre	12	12
Fibre blends	52	52
<b>24. What type of fabric is used to make your favourite abaya:</b>		
<b>a) In terms of fabric thickness:</b>		
Thin (< 0.20 mm)	36	36
Medium (0.23–0.46 mm)	63	63
Thick (> 0.74 mm)	1	1%
<b>b) In terms of fabric weight:</b>		
Lightweight (70–100 g/m <sup>2</sup> )	59	59
Medium weight (170–249 g/m <sup>2</sup> )	42	42
Heavy weight (300–75 g/m <sup>2</sup> )	1	1
<b>c) In terms of transparency:</b>		
Opaque	62	62
Medium transparency	24	24
Low transparency	14	14
<b>d) In terms of the structure:</b>		
Looseness	2	2
Moderate structure	26	26
Tightness	72	72
<b>25. Is it acceptable for abayas to be in a different colour rather than pure black?</b>		
No	47	47
Yes	53	53

In terms of changing the colour from black to different colours, more than half (53%) of the respondents expressed a desire to have a different colour. Apart from black, the most popular colours indicated were dark tones, including brown, dark blue (navy blue) and grey.

Table 2.4 Details of new abaya designs

Information about new abaya designs	Response	%
<b>26. How do you prefer the abaya to be in terms of:</b>		
<b>a) Width of abaya body:</b>		
Acceptable	38	38
Too wide	6	6
Comfortable	54	54
Tight	2	2
<b>b) Width of sleeve cuffs:</b>		
Acceptable	28	28
Too wide	5	5
Comfortable	61	61
Tight	6	6
<b>c) Width of sleeves:</b>		
Acceptable	42	42
Too wide	4	4
Comfortable	54	54
Tight	0	0
<b>d) Length of sleeves:</b>		
Up to the wrist	47	47
Cover the wrist	43	43
Under	10	10
<b>e) Width across shoulders:</b>		
Acceptable	43	43
Too wide	5	5
Comfortable	50	50
Tight	2	2
<b>f) Length of abaya:</b>		
To the ankle	29	29
To the ground	29	29
Below the knee	42	42

In terms of designing a new abaya (Table 2.4), the respondents wished to change the width of the sleeve cuff and the width and length of the sleeves to develop new fashions and designs as well as to feel comfortable while wearing clothing underneath an abaya. 50% of the respondents preferred the width across the shoulder to be comfortable because they would like a feeling of freedom when they move their hands. 42% of the respondents believed the length of the abaya should be below the knee to help with

movement during walking but not long enough to become dirty by contact with the ground.

Question 31 was about describing the best style for an abaya. Many interesting comments came from the participants regarding personal desires when answering this question. The respondents aged more than 40 suggested that an abaya should be chic but should not attract attention, for instance with drawings, decorations, writing and symbols, because the purpose of wearing an abaya is to be modest and inconspicuous in terms of amorous intentions. Other respondents aged 31–40 preferred the use of more lightweight and cool fabrics, that absorb perspiration easily without leaving any smell from the body on the fabric, and not too tight a design to show the body contour. In addition, an abaya should be opaque.

Other desirable aspects were good drape, beauty, uniqueness, simplicity and fashionable designs. Moreover, the respondents suggested that abayas should be easy to iron, easy to care for and clean, with good colourfastness to washing. As well there was a preference for styles that are easy to wear. Some existing abaya designs are very complicated; for instance, there can be many layers in an abaya itself, with complicated ways of locking each layer. Respondents with infants and children preferred that an abaya should look like a jumpsuit (combination of slacks and shirt in one piece) with a zipper in the front, and wide at the ankle to allow freedom of movement.

## **2.6 Summary**

This survey has revealed that wearing an abaya causes discomfort in hot environments. The degree of comfort depends on the type of the abaya fabric and design as well as the type of clothing worn underneath the abaya. Most abayas were made from woven fabrics that masked female body contours and synthetic fibres (polyester) were mainly used because they are easier to care for. Furthermore, many layers of clothing underneath an abaya decrease the comfort level. Wearing jeans or slacks with short sleeves or sleeveless

dresses underneath the abaya increased the comfort and the freedom of movement compared to other clothing such as a skirt or '*jalabiah*'. These dress combinations were used in conducting objective studies in the latter parts of this research.

The area of the body that experienced maximum heat stress was found to be in the neck, front and back of the body, which represent the torso area. The torso area invariably has multilayers of clothing including bra, shirt, abaya and some part of the scarf. These zones were particularly investigated during objective studies reported in Chapter 6.

Women wearing abayas with multilayers of clothing perspire a lot. The respondents preferred abaya fabrics to be made from blended fibres, of medium thickness, lightweight, not transparent (opaque) and with a tightly woven structure. These factors were taken into consideration in material selection for the objective experiments. Further, special finishes that reflect solar energy were also investigated in latter parts of this research in order to improve the comfort.

Moreover, the respondents desired to have abayas in different dark colours such as navy blue, grey and dark green. In terms of designing an abaya, the width of the sleeve cuffs, the width of sleeves and the length of sleeves should be comfortable. In order to improve the comfort of wearers, most of the respondents desired increased ventilation in an abaya. Abayas should be chic, absorb perspiration easily without leaving a smell on the fabric and be easy to iron, to care for and to clean with good colourfastness to washing. These characteristics are outside the scope of the present investigation and will be recommended for future work.

The present research demonstrates that wearing an abaya with multilayers of clothing creates problems of feeling uncomfortable in many circumstances. Therefore, there is plenty of scope for developing new designs and clothing combinations to give improved comfort in wear by modifying the construction of clothing itself and the use of new materials.



# Chapter 3 Experimental methodology

## 3.1 Introduction

This chapter describes the experimental methodology used together with fabrics, chemicals, equipment and instruments and relevant procedures employed in the course of the investigation.

## 3.2 Research design

The prime objectives of this study were to identify the materials used for the abaya, to understand the factors affecting the thermo-physiological comfort properties of the traditional abaya and to improve its thermal comfort performance. Figure 3.1 outlines the experimental design.

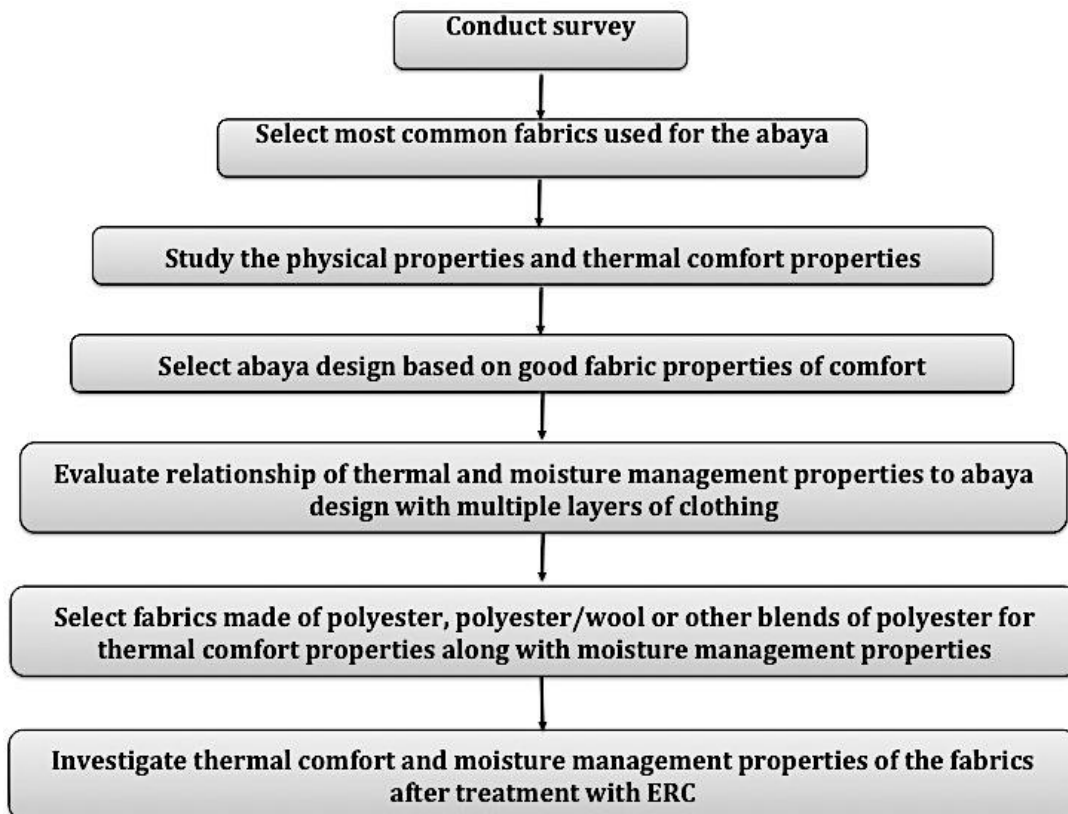


Figure 3.1 Experimental outline.

### 3.3 Selection of materials

#### 3.3.1 Commercial fabrics

Based on the survey done in Chapter 2, the fabrics were selected according to current popularity; these comprised four types of woven fabrics (Table 3.1) and five types of knitted fabrics (Table 3.2). All these fabrics were commercially available in Saudi Arabia. Each fabric was given a code; the first and second letter are the abbreviations of the first and second fibre and the number represents the percentage of fibre content, as indicated in Table 3.1 and Table 3.2.

Table 3.1 Abaya woven fabrics selected

Fabric code	1P100	2P100	P65C35	V80P20
Weave structure	Satin weave	3/1 × 1/3 Mixed twill weave	Plain weave	Crepe weave
Fibre composition	100% polyester	100% polyester	65/35 polyester/ cotton	80/20 viscose/ polyester

Table 3.2 Abaya knitted fabrics selected

Fabric code	N100	W50N50	W100	P65C35	P96E4
Knit structure	Interlock	Single jersey	Single jersey	Double jersey	Single jersey
Fibre composition	100% nylon	50/50% nylon/wool	100% wool	65/35 % polyester/ cotton	96/4% polyester/ elastane

#### 3.3.2 Experimental fabrics

Greige fabrics of four plain weaves were selected to be suitable for abayas: 100% wool (W100), 63/37 polyester/wool (P63W37), 50/50 polyester/wool (P50W50) and 100% polyester (P100) (Table 3.3). These fabrics were dyed black and then treated with the infra-red energy reflecting chemical to enable its effect on abaya comfort to be evaluated.

Table 3.3 Details of experimental abaya woven fabrics

Fabric code	W100	P63W37	P50W50	P100
Weave structure	Plain weave	Plain weave	Plain weave	Plain weave
Fibre composition	100% wool	63/37% polyester/ wool	50/50% polyester/ wool	100% polyester

### 3.4 Chemicals

The sources of the various chemicals used to dye the greige fabric to black are listed in Table 3.4. All the chemicals were of laboratory reagent grade. Energy-reflecting chemicals (ERC) were used to reflect heat radiation. ERC, a confidential commercial product.

Table 3.4 Chemicals used and their suppliers

Chemical	Supplier
Albegal SET wool-levelling agent	Huntsman
Albegal FFC	Huntsman
Isolan Black LS-LDN defoaming agent	Dystar
Dyapol BD as buffer dispersing agent	Yorhkchem
Optinol BTH	Oxford
Lanaset Black B	Huntsman
Lanaset Grey	Huntsman
Foron Black RD-E	Clariant
Acetic acid	Merck
Non-ionic surfactant,	SDC
Sodium hydroxide	Chem Supply

#### 3.4.1 Dyeing methods

##### 3.4.1.1 100% wool fabric

An electrically heated stainless-steel dye bath and the recipe given in Table 3.5 were used in the dyeing of the wool fabric. The bath was made with 25 litres of water at 40° C and auxiliaries. The fabric was treated in the bath for 5 minutes. The pH of the bath was then

adjusted to pH 4.4 by addition of 0.5% acetic acid and the pre-dissolved dye was added. While constantly stirring, the bath temperature was raised to the boil at 100° C at 2° C / min. Dyeing was continued at 100° C for 30 min. At this stage, 0.75% acetic acid on weight of fabric (OWF) was added to clear the bath. Boiling was continued for a further 15 min. Following this, the bath was cooled to 60° C by slow addition of warm water. Samples were then rinsed at 40° C. The dyeing cycle is shown as a line diagram in Figure 3.2.

Table 3.5 Dyeing recipe – 100% wool.

Chemical	Concentration (OWF*)
Ammonium sulphate	2%
Albegal SET	0.75%
Acetic acid	0.5%
Isolan Black LS - LDN	4%

\* OWF: On Weight of Fabric

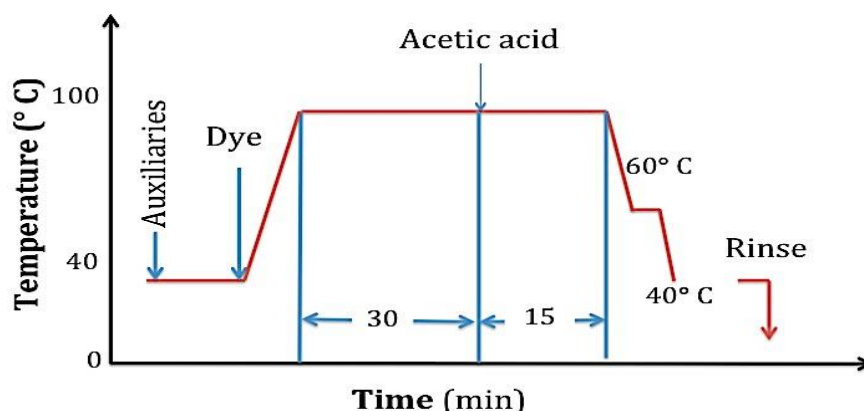


Figure 3.2 Line diagram of 100% wool fabric dyeing procedure.

The dyed fabric was cut into two pieces. One piece was kept for comparison and the other piece was treated with the ERC. The bath, consisting of 6 litres of water and 4% OWF of ERC, was maintained at a pH of 4 by adding 10% acetic acid. The dyed fabric was introduced into the bath and the temperature was raised to 70–80° C and maintained for 15 min. The bath temperature was then lowered to ambient temperature. The fabric was

rinsed, hydro-extracted and dried in a drying cabinet. The procedure is illustrated as a line diagram in Figure 3.3.

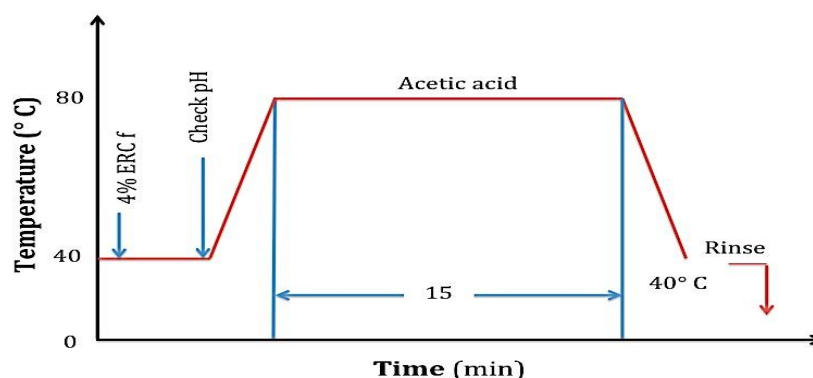


Figure 3.3 Line diagram of ERC treatment for wool fabric.

### 3.4.1.2 Polyester/Wool blends

The polyester/wool blends required a different dyeing process. The important consideration was that wool gets damaged at temperatures above 110° C while polyester usually gets dyed at 110° C or higher. A carrier and disperse dye were therefore used for polyester and wool union dyeing at 110° C. A Werner Mathis Lab high temperature HP Jumbo Jet JFO was used for both dyeing and treatment with ERC. The width of the fabric was 120 cm and the length of the fabric about 150 cm. The edges of the fabrics were lock stitched so that there were no loose threads entering the housing of the pump.

The dye bath was set at 40° C. After 5 min, the completely dissolved wool auxiliaries (Albegal SET 0.5% OWF levelling agent and Albegal FFC 1 gram per litre (g/l) defoaming agent) were added to the dye bath. Dyapol BD (2 g/l) as buffer and Optinol BTH (2 g/l) as a polyester carrier were mixed and added. Then 4% ERC was added for the wool. This was followed by adding the wool dyes, Lanaset Black B (2.5%) and Lanaset Grey (1%).

The bath temperature was raised to 60° C and then Foron Black RD-E (2%) polyester dye was added. The temperature was subsequently raised to 110° C at 1.5° C per min. Dyeing was continued at 110° C for 45 min. After 20 min the pH was checked and adjusted to 4.8–5.0 by addition of 0.5% acetic acid. The temperature was lowered to 70° C. The fabric

was rinsed twice using warm water at 50° C. Further treatment was performed using 3% ERC for polyester and 0.6% OWF of 10% acetic acid in 9 litres of water at 75° C at pH of 4 for 15 min. Finally the fabric was rinsed in cold water, hydro-extracted and dried in a relaxed state in a drying cabinet. Figure 3.4 shows the dyeing and treatment procedure as a line diagram.

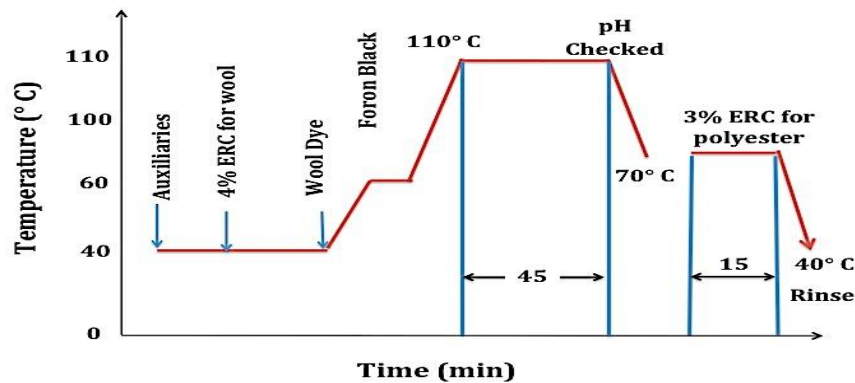


Figure 3.4 Line diagram of polyester/wool blends dyeing procedure and the ERC treatment.

### 3.4.1.3 100% polyester

The length of the fabric used was about 100 cm and the width about 30 cm. Dyeing was carried out in an Ahiba Turmomat pressure dyeing machine. The fabric was wound onto a perforated beam and the liquor circulated from inside to outside through the whole dye system.

The bath temperature was set at 40° C to which 2 g/L Dyapol BD (buffer dispersing agent) was added. This was followed by addition of the required concentration of ERC. After 5 min, 4% OWF Foron Black RD-E was added. The temperature was then raised to 130° C at 2° C/min and dyeing continued for 60 min. The temperature was then lowered to 70° C. After that, the fabric was rinsed using water at 50° C. This was followed by clearing with 2 g/l non-ionic surfactant and 2 g/L sodium hydroxide at 50°-60° C for 10 min. Samples were then rinsed in warm water at 40° C for 5 min and in cold water for 5 min. Finally,

samples were hydro extracted and dried at 60° C. Figure 3.5 shows the dyeing and treatment procedure as a line diagram.

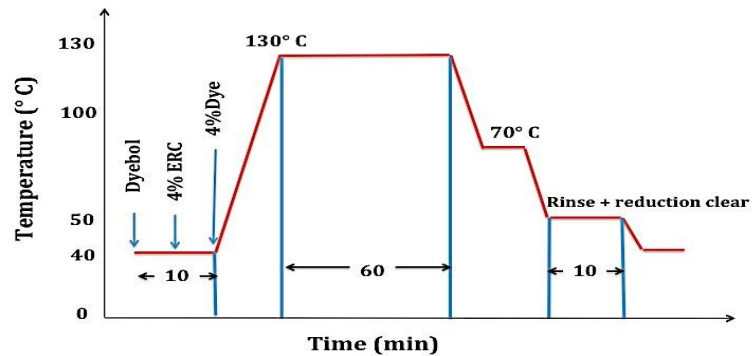


Figure 3.5 Line diagram of 100% polyester dyeing procedure and the ERC treatment.

## 3.5 Fabric evaluation

All samples were tested after conditioning for at least 24 hours under standard conditions of temperature ( $20 \pm 2^\circ \text{C}$ ) and relative humidity (RH) ( $65 \pm 2\% \text{RH}$ ), as specified in Australian Standard (AS) 2001.1-1995.

### 3.5.1 Physical properties

Fabric physical properties that could influence comfort were tested. This included the type of material, fabric construction (weave and ends/picks per inch for woven fabrics and wales/courses per inch in knitted fabrics), mass per unit area and thickness. Stitch density and cover factor were calculated based on the results obtained.

#### 3.5.1.1 Fabric mass per unit area

To determine fabric mass AS 2001.2.13-1987 was followed. Five specimens of size 100 mm x 100 mm from each fabric sample were prepared and weighed using a balance (FZ-iWP Precision Balance, A & D Company, limited) with 0.0001 g accuracy. Mass per unit area was calculated using Equation 3.1:

$$M_{ua} = \frac{m}{a} \quad \text{Equation 3.1}$$

where,

$M_{ua}$  is the mass per unit area of the fabric in (g/m<sup>2</sup>)

$m$  is the mass of the specimen in g; and

$a$  is the area of the specimen m<sup>2</sup>.

### 3.5.1.2 Thickness

Fabric thickness, the distance between the face and the back of a textile, was measured as the distance between the reference plate and a parallel presser foot, as described in AS 2001.2.15-1989. Ten readings were taken and the mean value was obtained for all samples.

### 3.5.1.3 Fabric count

Fabric count is the number of yarns per unit length along the warp or fill direction, based on the fabric count and width of the yarn. Fabric count was assessed according to the procedures described in AS 2001.2.5-1991 for woven fabric and AS 2001.2.6-2001 for knitted fabric. A pick glass, which is a device with a magnifying lens and a movable pointer that aids in counting the yarns, was used. An average of five counts in each direction was reported; positions evenly spaced along or across the fabric were selected, selvages were avoided.

### 3.5.1.4 Woven fabric cover factor

The fabric cover factor is defined as the ratio of projected fabric surface area covered by the yarn to the total fabric surface area [147]. The cover factor was determined using the procedure described by Booth [148], which is based on woven fabric count and yarn linear density. The total cover factor ( $K_c$ ) is calculated from Equation 3.2:

$$K_c = K_1 + K_2 - \frac{K_1 K_2}{28} \quad \text{Equation 3.2}$$

where,

$$K_1 = \frac{\text{Ends}}{\text{cm}} \times \frac{\sqrt{\text{Count of warp in tex}}}{10}$$

$$K_2 = \frac{\text{Picks}}{\text{cm}} \times \frac{\sqrt{\text{Count of weft in tex}}}{10}$$



### 3.5.2 Stretch and recovery

An Instron tensile tester (Model 5565A) was employed according to British Standard (BS) 4952:1992 to determine the stretch and recovery properties of the knitted samples. The quantities generally measured were: the extension at a given load, which is a measure of how well the fabric stretches; and growth or residual extension, which measures how well the fabric recovers from stretching to this load.

Five specimens from each wale and course direction were tested. The dimensions of specimens between clamps were 75 × 75 mm, i.e. the gauge length (L1) in Equations 3.3 and 3.4 was 75 mm. The fabric was stretched to 30 N force at a rate of 100 mm/min and the load was maintained for 10 sec, after which the extension (cross-head movement) was recorded as (L3). Then the sample was removed from the clamps and allowed to relax on a flat, smooth surface and its length was re-measured after 1 min as (L2). Equations 3.3 and 3.4 calculate the stretch and recovery results respectively:

$$\text{Extension percent, } E = \frac{L3}{L1} \times 100\% \quad \text{Equation 3.3}$$

$$\text{Residual extension after 1 min, } R1 = \frac{(L2-L1)}{L1} \times 100\% \quad \text{Equation 3.4}$$

### 3.5.3 Drape testing

Assessment of fabric drapeability was carried out using the Cusick drape tester (Shirley Developments Limited, Stockport, UK, Figure 3.6) to measure the drape coefficient (DC) values of the fabric samples investigated. The testing method involves measuring drape from the deformation by gravity of an initially horizontal annular ring of fabric, as specified in BS 5058:1973.

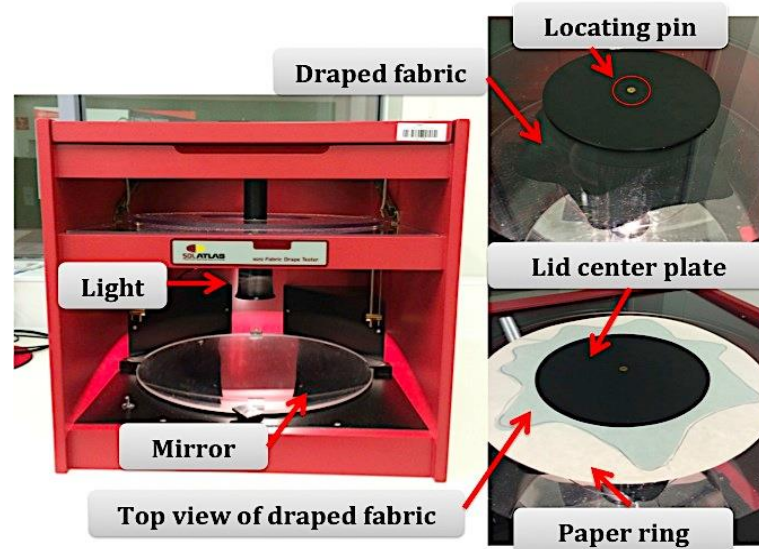


Figure 3.6 The Cusick drape tester.

The DC is defined as the percentage of area of the annular ring covered by the projection of the draped sample [148]. Figure 3.6 shows the light underneath the specimen; the shadow that the fabric casts is traced onto an annular piece of paper the same size as the unsupported part of the fabric specimen. Since uniform paper rings, as ordered, were used for area measurement, the shaded area of the paper ring is proportional to the paper weight [149]. A standard sample diameter of 30 cm was used for all the fabrics. Both fabric face and back DC values were measured. Each face and back value was the average of six readings from three test samples for each fabric. The DC was calculated from Equation 3.5:

$$\text{Drape coefficient(DC)} = \frac{M_2 \times 100}{M_1} \quad \text{Equation 3.5}$$

where,

$M_1$  is the total mass of the paper ring, and

$M_2$  is the mass of the shaded area of the paper ring.

## **3.5.4 Microscopy**

### **3.5.4.1 Optical porosity**

Optical porosity is represented by voids between yarns in the fabric. The light from a microscope was transmitted through the voids and was converted into white pixels while the yarn that blocked the light is converted into black pixels. Equation 3.6 was used to calculate optical porosity. A Motic stereomicroscope and Motic image Plus 2.0 software were used to determine fabric optical porosity. UTHSCSA Image Tool software was used to determine the optical porosity of the obtained images. Three images from three specimens were captured.

$$\text{Optical porosity \%} = \frac{\text{whitepixels}}{\text{whitepixels}+\text{blackpixels}} \times 100 \quad \text{Equation 3.6}$$

### **3.5.4.2 Scanning electron microscopy (SEM)**

A FEI Quanta 200 scanning electron microscope was used to capture the surface images of fabric samples under different magnifications. The instrument is an adaptable high performance, low vacuum scanning electron microscope with a tungsten electron source. It has three imaging modes (low vacuum, high vacuum and SEM) to provide wide ranges of sample magnification. Fabric samples were cleaned by air spray to remove any foreign materials from the surface and mounted on the sample holder inside the test chamber. Scanning was performed in low vacuum mode with a water vapour pressure of approximately 1000 Pascal. The scanned images were stored with a 1024 × 884 pixel resolution and TIFF (Tagged Image File Format) format for further analysis.

## **3.6 Fabric comfort properties**

### **3.6.1 Air permeability**

An M021S air permeability tester (Figure 3.7) from SDL ATLAS Ltd was used to measure the air permeability by drawing air through the specimen with a vacuum pump. The airflow was measured by a flowmeter (1 of 4) against any specified pressure drop, which

was indicated by the manometer tube. Test results were expressed as air permeability in mL/cm<sup>2</sup>/s at a specified pressure. The instrument incorporates 4 flowmeters covering a range of airflows from 5mL/min to 25L/min that were selected by switches on the front of the machine. Valves regulated the flow of air through the specimen and the selected flowmeter. The flow readings are taken when the manometers indicated the selected pressure drop. Air permeability was measured with 50 Pa and 100 Pa pressure differences across the fabric. With some fabrics the instrument could not generate a 100 Pa pressure difference as suggested by the EN ISO 9237:1995 standard. Five specimens, 5 cm<sup>2</sup> each, from every fabric sample were evaluated for air permeability and the mean airflow calculated.

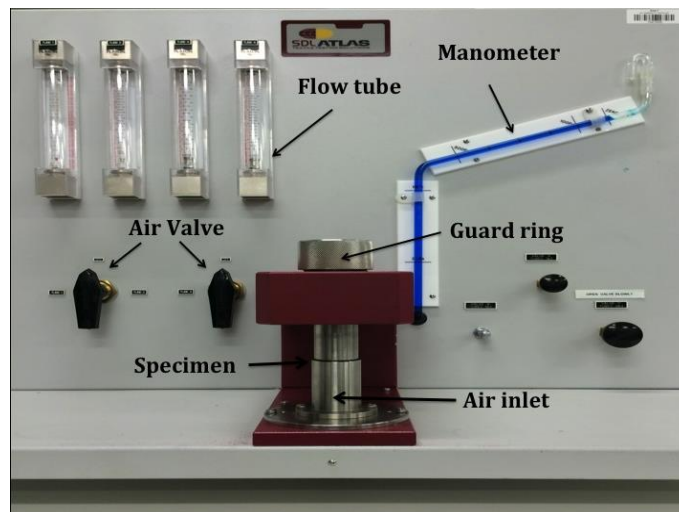


Figure 3.7 Air permeability test.

### 3.6.2 Sweating guarded hot plate (SGHP)

The sweating guarded hotplate (often referred to as the 'skin model') is intended to simulate the heat and mass transfer processes which occur next to the human skin. An M259B Sweating Guarded Hot Plate (Figure 3.8) conforming to the International Standard Organization (ISO) 11092:1993 from SDL ATLAS Ltd (Stockport, UK) was used for determining fabric thermal resistance and water vapour resistance, under steady-state

conditions. The test specimen was placed on an electrically heated plate with conditioned air ducted to flow across and parallel to its upper surface, as specified in the standard.

### 3.6.2.1 Thermal resistance ( $R_{ct}$ )

This was determined by the heat flux through the test specimen after steady-state conditions had been reached. The test apparatus consisted of a guarded hot plate assembly enclosed in a climatic chamber consisting of a metal plate approximately 3 mm thick and an area of  $0.04 \text{ m}^2$  (or a square with sides of 200 mm) fixed to a conductive metal block containing an electrical heating element. The test section was in the centre of the plate, surrounded by the guard and lateral heater that prevented heat leakage, as seen in Figure 3.8. The air speed was set to  $1 \pm 0.05 \text{ m/s}$  and the temperature of the guarded hot plate was maintained at  $35^\circ \text{ C}$  (temperature of human skin) and standard atmospheric conditions of 65% RH and  $20^\circ \text{ C}$  temperature were maintained [54, 150]. Data from three replicate measurements were averaged to determine the mean value for each fabric.

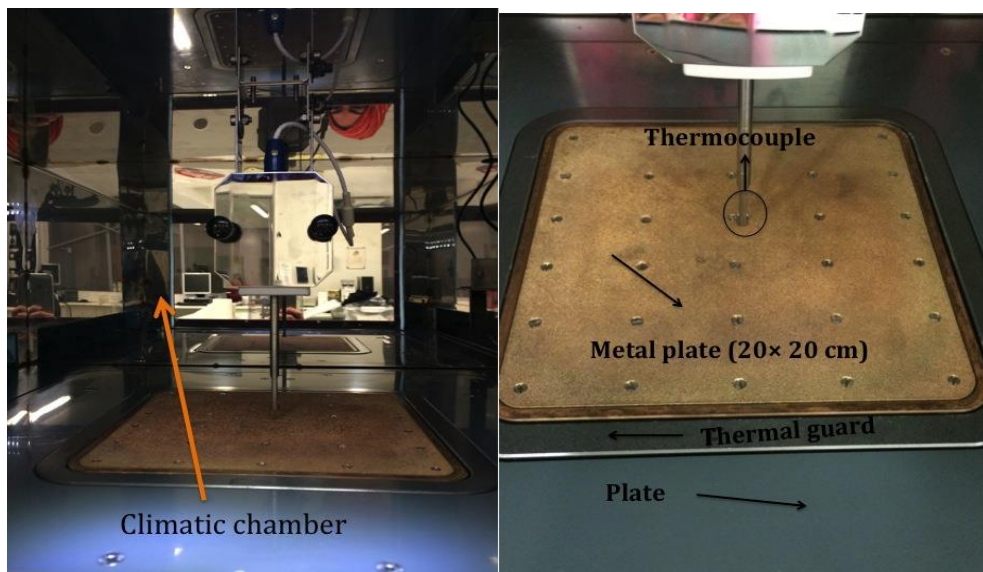


Figure 3.8 The sweating guarded hot plate: a) inside the chamber; b) bare plate.

From each fabric, three specimens  $30 \times 30 \text{ cm}$  in size were conditioned at  $35^\circ \text{ C}$  and 65% RH for a minimum of 24 hours. In order to determine the  $R_{ct}$  the sample was placed on a porous metal plate and the heat flux from the plate to the environment was measured.

After the system reached a steady state, the total thermal resistance of the fabric was calculated using Equation 3.7:

$$R_{ct} = \left[ \frac{(T_p - T_a) \cdot A}{H_c} \right] - R_{ct0} \quad \text{Equation 3.7}$$

where,

$R_{ct}$  is the thermal resistance ( $\text{m}^2 \cdot \text{k}/\text{W}$ )

$R_{ct0}$  is the thermal resistance without a sample ( $\text{m}^2 \cdot \text{k}/\text{W}$ )

$H_c$  is the heating power ( $\text{W}/\text{m}^2$ ) supplied to the plate to maintain a temperature of  $35^\circ \text{C}$

$T_p$  is the plate temperature ( $^\circ \text{C}$ ) in the test enclosure ( $35^\circ \text{C}$ )

$T_a$  is the air temperature ( $^\circ \text{C}$ ) in the test enclosure ( $20^\circ \text{C}$ ); and

$A$  is the area of the test section ( $\text{m}^2$ ).

### 3.6.2.2 Water vapour resistance ( $R_{et}$ )

Fabric resistance to evaporative heat transfer ( $R_{et}$ ) was also tested using the SGHP. The instrument simulates the moisture transport through textiles when worn next to the skin. It measures the 'latent' evaporative heat flux across a given area in response to a steady applied water vapour pressure gradient, as described in ISO 11092:1993. The air temperature was set to  $35^\circ \text{C}$  and the RH at 40% and the air speed generated by the airflow hood was  $1 \pm 0.05 \text{ m/s}$ . The total vapour resistance of the fabric was measured and calculated after the system reached a steady state.

The SGHP is an indirect method of measuring the vapour transmission properties of a fabric. To ensure only water vapour was in contact with the fabric, a polytetrafluoroethylene (PTFE) membrane supplied by the instrument manufacturer was placed on the plate.  $R_{et}$  was calculated using Equation 3.8:

$$R_{et} = \left[ \frac{(P_p - P_a) \cdot A}{H_e} \right] - R_{et0} \quad \text{Equation 3.8}$$

where,

$R_{et}$  is the water vapour resistance ( $\text{m}^2 \cdot \text{Pa}/\text{W}$ )

$P_p$  is the water vapour pressure ( $P_a$ ) at the plate surface

$P_a$  is the water vapour pressure ( $P_a$ ) of the air

$H_e$  is the heating power for measuring water vapour resistance ( $W/m^2$ ) by the instrument; and

$R_{et0}$  is the evaporative resistance measured for the air layer.

### 3.6.3 Moisture management testing

The moisture management tester (MMT) is equipment to measure the dynamic liquid transport properties of fabrics in three dimensions: absorption rate (moisture absorbing time of the fabric's inner and outer surfaces); one-way transportation capability (liquid moisture one-way transfer from the fabric's inner surfaces to outer surfaces); and spreading/drying rate (speed of liquid moisture spreading on the fabric's inner and outer surfaces). For testing the liquid moisture transport capabilities of the fabrics, an MMT from SDL ATLAS (Figure 3.9) was used according to the test method of the American Association of Textile Chemists and Colorists (AATCC) 195-2009. The instrument consists of upper and lower concentric moisture sensors, between which the fabric being tested is placed as shown in Figure 3.9.

Five 80 x 80 mm specimens were tested and an average value with standard deviation for each sample was calculated. The MMT apparatus is based on the physical principle that the surface contact electrical resistance of a fabric changes with the content of a water-based liquid solution near the surface [54, 116, 151, 152]. In order to simulate sweating, a saline solution was prepared by dissolving 9 g of sodium chloride in one litre of distilled water to achieve  $16 \pm 0.2$  mS of solution conductivity and dropped onto the fabric's top surface. During the test, the same quantity of solution (0.15 g) was injected onto each specimen's top surface automatically by the MMT. The testing time was two minutes.

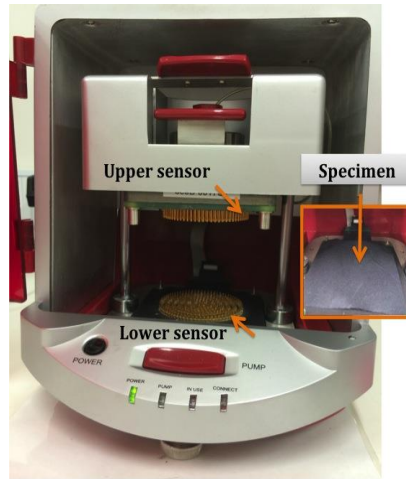


Figure 3.9 The moisture management tester (MMT) showing the upper and lower concentric moisture sensors.

The test liquid is dropped from the top part of the MMT to the top surface of the fabric, then the liquid will transfer onto the fabric in three directions, (1) spreading outwards through the top (inner) surface that will be in touch with the human skin, (2) transferring through the fabric from the top surface to the bottom surface of the fabric. (3) spreading outward on the lower surface of the fabric.

The MMT indices were used to determine the liquid moisture transport and distribution properties of the fabric samples. The indices are defined as follows [117]:

**Wetting time** is the time in which the top and bottom surfaces of the fabric just start to get wet respectively after the test commences.

**Absorption rate** is the average moisture absorption ability of the fabric's top and bottom surfaces during the rise of the water content, respectively.

**Maximum wetted radius** is defined as the maximum wetted ring radius at the top and bottom surfaces.

**Spreading speed** is the accumulative spreading speed from the centre of the fabric sample to the maximum wetted radius.

**Accumulative one-way transport index (AOTI)** represents the difference of the accumulative moisture content between the two surfaces of the fabric and determines to a



large extent whether the fabric has good moisture management properties. In terms of comfort, it means that the higher the one-way transport capacity, the quicker and easier the liquid sweat can be transferred from next to the skin to the outer surface of the fabric, thus keeping the skin dry.

**Overall moisture management capability (OMMC):** this is an index to indicate the overall ability of the fabric to manage the transport of liquid moisture, which includes three aspects of performance: moisture absorption rate of the bottom side (MAR); one-way liquid transport ability (OMTC); and moisture drying speed of the bottom side (SS), which is represented by the maximum spreading speed. The larger the OMMC, the higher the overall moisture management capability of the fabric [117, 125, 153].

Using the above indices, the test samples were evaluated for their liquid moisture management properties. To address this, the indices were graded and converted from values to grades based on a five-grade scale (1–5). The five grades of indices represented: 1– poor, 2– fair, 3– good, 4– very good, 5– excellent [117]. Table 3.6 shows the grading of the MMT indices.

Table 3.6 Grading table of MMT indices [117]

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

MMT can distinguish seven major types of fabrics as follows [117]:

1. **Waterproof fabric:** very slow absorption, slow spreading, no one-way transport and no penetration
2. **Water-repellent fabric:** no wetting, no absorption, no spreading and poor one-way transport without external forces
3. **Slow absorbing and slow-drying fabric:** slow absorption; slow spreading and poor one-way transport
4. **Fast-absorbing and slow-drying fabric:** medium to fast wetting, medium to fast absorption, small spreading area, slow spreading and poor one-way transport
5. **Fast-absorbing and quick-drying fabric:** medium to fast wetting, medium to fast absorption, large spreading area, fast spreading and poor one-way transport
6. **Water-penetration fabric:** small-spreading area and excellent one-way transport
7. **Moisture-management fabric:** medium to fast wetting, medium to fast absorption, large spread area at bottom surface, fast spreading at bottom surface and good to excellent one-way transport.

### 3.6.4 Sweating thermal manikin

A sweating thermal manikin (Figure 3.10) of female form MTNW (Seattle, USA) was used for the investigation. The manikin was located in a temperature-controlled chamber. It hung from a metal stand by a hook in the head and was 1.70 m tall with a body surface area of  $1.8 \pm 0.3 \text{ m}^2$ . This manikin contained 20 independently controlled thermal zones. Figure 3.11 shows the different zones of the manikin. All the thermal zones were fitted with heaters that simulated metabolic heat output rates and distributed thermocouple sensors were used for measuring skin temperature. Additionally each thermal zone had sweat control through evenly distributed fluid ports on its surface. There was a fluid heater inside the manikin for preheating water before it was distributed to the ports on the manikin surface [108]. The thermal zones were grouped according to their position on

the manikin to obtain detailed heat-loss information for specific areas. Measurements were recorded after equilibrium had been maintained for at least 1 hour as indicated by a steady-state power reading that changed by a maximum of 3%. The measurements of the heat loss were recorded every second and averaged over 30 minute periods.

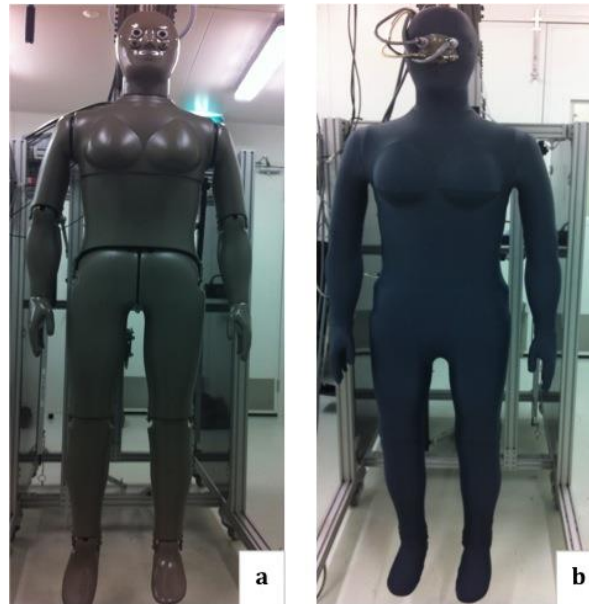


Figure 3.10 The female sweating thermal manikin;  
a) manikin without skin; b) manikin with fabric skin.

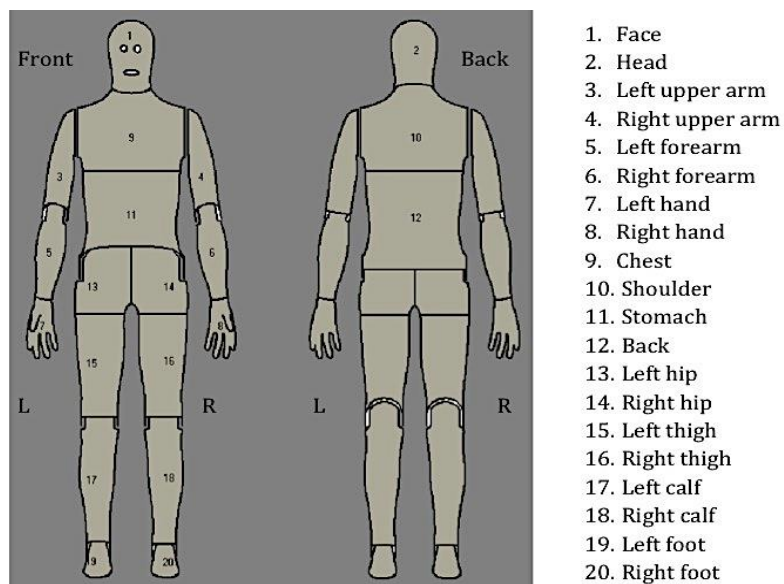


Figure 3.11 Front and back views of the sweating manikin showing labelled zones.

The female manikin used was designed to generate smooth, realistic walking movements in compliance with EN 342. The operating speed was 30 double-steps per minute (DSPM). Every stride of the manikin was approximately 25" (63.5 cm); so the maximum walking DSPM translates to a speed of around 3 miles/hr (4.8 km/hr). The speed could be changed using an AC frequency regulator to regulate the power supply to the motor that drives the motion. The speed could be varied from 0 to 4.8 km/hr. The walking stand could be operated manually or through the ThermDAC8 control software.

### 3.6.4.1 Calculation of thermal resistance $R_{ct}$

The thermal resistance  $R_{ct}$  was measured according to ASTM F1291-10. Thermal resistance (insulation) was then calculated by the parallel method, where the area weighted temperatures of all body segments were summed and averaged, the power levels to all body segments were summed and the areas were summed before the total resistance was calculated using Equation 3.9:

$$R_{ct} = (T_{skin} - T_{amb}) \cdot Q/A \quad \text{Equation 3.9}$$

where,

$R_{ct}$  is the total thermal resistance (insulation) of the clothing ensemble and surface air layer around the outer clothing or, when unclothed, around the skin surface ( $m^2 \cdot ^\circ C/W$ )

$T_{skin}$  is the zone average temperature ( $^\circ C$ )

$T_{amb}$  is the ambient temperature ( $^\circ C$ ); and

$Q/A$  is the area weighted Heat Flux ( $W/m^2$ ).

The intrinsic clothing insulation ( $R_{cf}$ ), defined as the insulation from the skin surface to the clothing surface, was deduced from the measured ( $R_{ct}$ ) value by Equation 3.10:

$$R_{cf} = R_{ct} - (R_{cto} / f_{cl}) \quad \text{Equation 3.10}$$

where,

$R_{cf}$  is the intrinsic of clothing insulation ( $m^2 \cdot ^\circ C /W$ )

$R_{cto}$  is the thermal resistance of air layer in unclothed condition ( $m^2 \cdot ^\circ C /W$ ) and

$f_{cl}$  is the clothing area factor (ratio of outer surface area of clothed body to surface area of unclothed body) estimated according to ISO Standard 9920.

### 3.6.4.2 Calculation of evaporative resistance $R_{et}$

The moisture vapour resistance  $R_{et}$  was measured according to ASTM F 2370-10. Evaporative resistance was calculated by the parallel method, where the area weighted temperatures of all body segment were summed and averaged, the power levels to all body segments were summed, and the areas were summed, before the total resistance was calculated. The total evaporative resistance of the ensemble was calculated using Equation 3.11:

$$R_{et} = \frac{(P_{sat} - P_{amb})}{Q/A - [(T_{skin} - T_{amb})/R_{ct}]} \quad \text{Equation 3.11}$$

where,

$R_{et}$  is the total evaporative resistance

$P_{sat}$  is the saturation vapour pressure at skin temperature ( $m^2 \cdot Pa/W$ )

$P_{amb}$  is the vapour pressure at ambient temp (Pa)

$Q/A$  is the area weighted Heat Flux ( $W/m^2$ )

$T_{skin}$  is the zone average temperature ( $^{\circ} C$ )

$T_{amb}$  is the ambient temperature ( $^{\circ} C$ ), and

$[(T_{skin} - T_{amb})/R_{ct}]$  is the dry heat loss ( $W/m^2$ ), which is the heat flux under dry conditions.

Using the clothing factor, the intrinsic evaporative resistance of the clothing ensembles is given by Equation 3.12:

$$R_{ef} = R_{et} - (R_{et0}/f_{cl}) \quad \text{Equation 3.12}$$

where,

$R_{ef}$  is the intrinsic evaporative resistance of clothing ( $m^2 \cdot Pa/W$ )

$R_{et0}$  is the evaporative resistance of air layer in unclothed condition ( $m^2 \cdot Pa /W$ ) and

$f_{cl}$  is the clothing area factor (ratio of outer surface area of clothed body to surface area of unclothed body) estimated according to ISO Standard 9920.

Data from three replications of the wet tests were averaged to determine the mean  $R_{et}$  for each ensemble (including the air layer) and for the air layer alone (tested using the wet skin alone). It should be noted that the Newton mode measures the clothing thermal resistance in the dry test and the moisture vapour resistance in the wet test based on the previous dry test in a non-isothermal condition.

### 3.6.4.3 Moisture permeability index ( $i_m$ )

The moisture permeability index ( $i_m$ ) of materials is defined by ASHRAE as “the ratio of the actual evaporative heat flow capability between the skin and the environment to the sensible heat flow capability” [32]. Equation 3.13 expresses the relationship:

$$i_m = K \cdot R_{ct} / R_{et} \quad \text{Equation 3.13}$$

where,

$K$  is a constant = 60.6515 Pa/° C [108, 154].

### 3.6.4.4 Moisture accumulation within clothing

It is important to understand the process of moisture accumulation within clothing, as it affects the measurement of clothing thermal insulation and evaporative resistance [99]. Since the manikin has a breathable ‘skin’ and generates perspiration, moisture passing through the ‘skin’ will be absorbed and condensed within the clothing materials. The percentage of moisture accumulation within clothing was calculated using Equation 3.14 [99]:

$$M_a = (W_a - W_b) / W_b \times 100\% \quad \text{Equation 3.14}$$

where,

$M_a$  is the percentage of moisture accumulation within clothing; and

$W_b$  and  $W_a$  are the weight of clothing before and after the manikin testing, respectively.

### 3.6.5 Three-dimensional (3D) body scanning

Three-dimensional (3D) body scanning technology was applied to measure the air gap layers between the outmost clothing and the clothed manikin. A [TC]<sup>2</sup> KX-16 3D body scanner image twin was used to collect point clouds. These points can then be used to interpolate the shape of the subject (a process called reconstruction). If colour information is collected at each point, then the colours on the surface of the subject can also be determined. The scanner uses 16 cameras to determine the shape of the subject and 4 cameras for the colour texture. The resolution of the scanner is approximately 3 mm. The volumes and surface areas of the unclothed and unclothed manikin were then calculated using Rhino software (from CAD International). Two types of daily-wear clothing underneath the abayas were selected to demonstrate the influence of air gaps between clothing layers on thermal and evaporative resistance. For the scanning process, the manikin was placed within the scanning volume with a fixed footprint and was kept steady. The unclothed manikin was scanned first and then scans were taken for each successive clothing layer and abaya as shown in Figure 3.12. All scan measurements were repeated three times to ensure reliability.



Figure 3.12 Clothing manikin with an abaya for 3D scans.

### 3.6.6 Temperature logging

Twelve sensors were attached per zone by sewing them tightly to the manikin skin fabric and the clothing to continuously measure the manikin temperature directly on the skin fabric and the surface of the daily wear clothing (DWC) and abaya combination. The components included an NI 4350 high precision temperature and voltage meter (from National Instruments), which converts analogue voltage from each temperature sensor into a digital signal, and LM35CAZ temperature sensors (RS Components Stock No. 533-5878). The whole unit can be connected via a USB cable to a computer where the data can be recorded through designated software.

The locations for the sensors in each zone of the manikin surface are shown in Figure 3.13, including the head, back neck, breast, stomach, hip and thigh on both front and back sides. The sensors were used to measure the temperature on the inner surface of the daily wear clothing (DWC) and in between the DWC and the abaya, and then at the outer surface of the abaya under dry conditions.

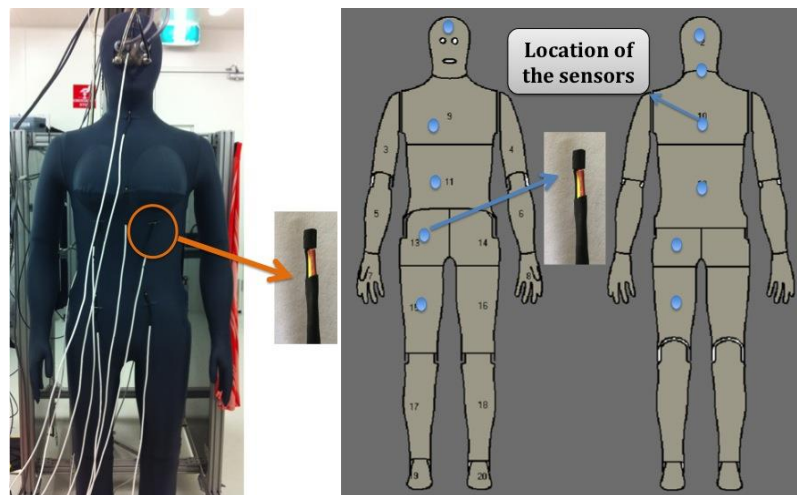


Figure 3.13 Location of the sensors in each zone of the manikin.

### 3.6.7 Infra-red thermal camera (IR)

An IR thermal camera FLIR T440 (FLIR Systems Inc., North Billerica, MA), with a measurement range from  $-20^{\circ}\text{C}$  to  $500^{\circ}\text{C}$  and resolution of  $0.06^{\circ}\text{C}$ , was used to detect



the temperatures on the clothing's outer surface and to measure the surface temperature of the fabric before and after treatment. The absolute temperature measured depends on factors such as emissivity of the object, ambient temperature and humidity. Relevant parameters can be changed in the software after the images are recorded. The frontal photos of the clothing surface were taken with an IR thermal camera. The clothing surface temperature was then analysed by thermal imaging software (FLIR quickreport 1.2).

### **3.7 Summary**

The above sections broadly outline the experiments carried out in this thesis. The materials of the fabrics used and the chemicals used for dyeing the fabric have been listed. Standard tests for evaluating the physical and thermal properties have been outlined. Procedures and equipment have been described. Further details of the experiments will be discussed and the results analysed in the following chapters.

# **Chapter 4 Thermal comfort properties of abaya woven fabrics**

This chapter is based on the paper “An investigation of thermal comfort properties of abaya woven fabrics” published in the *Journal of the Textile Institute* [137]. Some currently commercially available fabrics for abayas in Saudi Arabia were analysed to determine their comfort performance based on air permeability, thermal resistance, vapour resistance and moisture management properties.

## **4.1 Introduction**

Statistics reveal that 49.7% of women in Saudi Arabia aged over 10 years (an estimated 9.5 million females) wear the abaya [155]. In view of the extreme climate in Saudi Arabia, with a summer daytime temperature occasionally exceeding 45° C [156], wearing an abaya can be uncomfortable.

Many researchers have worked on improving comfort performance in clothing [20, 36, 99, 157-159]. However, to date limited research has been undertaken to assess the thermal comfort properties of the abaya. Therefore this thesis has attempted to fill the gap. It is expected that the results will help with selecting the right fabrics for abayas and using innovative fibres, fabric constructions and processing techniques to enhance the thermal comfort properties of abayas.

## **4.2 Experimental design**

### **4.2.1 Materials**

Four types of commercially available woven fabrics used for abayas as described in Sections 3.3.1 were chosen. They were 100% polyester (1P100), polyester (2P100),

polyester/cotton (P65C35), and viscose/polyester (V80P20). These woven fabrics were the most popular materials according to fabric retailers and abaya shops [7].

## 4.2.2 Physical properties

The key physical properties that affect comfort performance were determined according to the standards indicated in Table 4.1 and described earlier in Section 3.5. Scanning electron microscopy (SEM) was carried out following the procedure given in Section 3.5.4.2.

Table 4.1 Physical properties and standards

Fabric physical property	Testing standard
Fabric weight (Mass per unit area)	AS 2001.2.131987
Fabric thickness	AS 2001.2.15-1989
Thread count (ends and picks per unit length)	AS 2001.2.13-1987
Yarn linear density (yarn count)	AS/NZS 2001.1.2-1998
Drape coefficient (DC)	BS 5058-1973

## 4.2.3 Fabric comfort properties

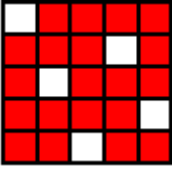
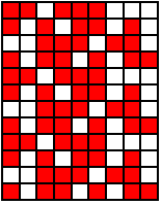
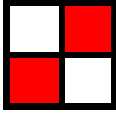
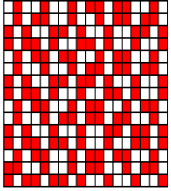
Test parameters related to comfort characteristics including air permeability, thermal resistance, vapour resistance and moisture management were evaluated, as described in Section 3.6. The constituent fibre content in each fabric was either analysed or obtained from the fabric specifications.

## 4.3 Results and discussion

### 4.3.1 Basic properties of abaya fabrics

Fibre blend specifications and analyses revealed that the commercial fabrics purchased were polyester (1P100), polyester (2P100), polyester/cotton (P65C35) and viscose/polyester (V80P20) (see Table 4.2).

Table 4.2 Details of the abaya woven fabrics studied

Fabric code	1P100	2P100	P65C35	V80P20
Fibre composition	100% polyester	100% polyester	65/35 polyester/cotton	80/20 viscose/polyester
Weave structure	Satin weave	3/1 × 1/3 Mixed twill weave	Plain weave	Crepe weave
Weave diagram				
Fabric thickness (mm)	0.17	0.63	0.20	0.50
Fabric mass (g/m <sup>2</sup> )	81	215	94	145
Warp yarn count (Tex)	4.4	12.9/12.5	13	8.5
Weft yarn count (Tex)	5.0	15.4	13.2	17.2
Ends/cm	110	64	44	62
Picks/cm	45	40	31	53
Cover factor	25.8	26.7	20.8	27.5

The fabrics made of polyester and polyester blends should have high strength and resistance to stretching with low wrinkle and shrinkage [146]. In addition, they do not require much ironing after washing. SEM images were used to observe the fabric weave structure at 100× magnification for all fabrics. Figure 4.1 confirms the woven structure of all samples and that there are notable differences between fabrics under the same magnification and imaging conditions.

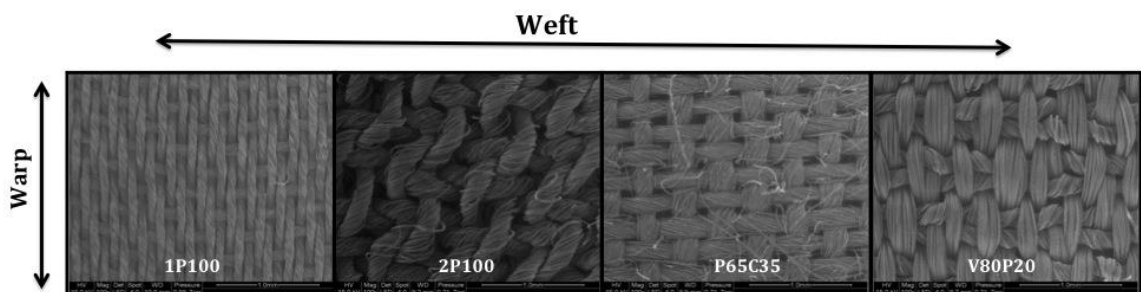


Figure 4.1 Woven fabric images from a scanning electron microscope.

The results in Table 4.2 show that abaya fabrics can have a wide range of properties. Fabrics 1P100, 2P100 and V80P20 were made of filament yarns while fabric P65C35 was constructed using spun yarns. Figure 4.1 shows that except for the warp yarns of fabric V80P20, all yarns possessed high twist, resulting in the fabrics having a crepe-like feel when touched. Table 4.2 indicates that fabric 1P100 was lighter, thinner and higher in warp thread count than the other fabrics. Fabric 1P100 appears to be more suitable for abayas in terms of comfort. According to the survey result described in Chapter 2, most of the participants prefer abaya fabric to be lightweight (70–100 g/m<sup>2</sup>) medium thickness (0.23–0.46 mm) and opaque. Fabric 1P100 was in the lightweight range but it was very thin and slightly transparent. Among the four fabrics studied, the yarn count ranged from 4.4 to 17.2 tex, which lies between fine (6–10 tex) and medium (12–20 tex) yarn counts. [146]. The finest filament yarns were used for 1P100, which is good for abayas, because fibre fineness and in turn yarn fineness represents an essential and significant influencing factor on the wear comfort [160].

Fabric 2P100 had medium weight, greatest thickness and a higher cover factor than the other samples. This fabric consisted of two types of warp yarns. One was high in twist (18.5 turns/cm) and slightly low in yarn count (12.5 tex), while the other was low in twist (3.4 turns/cm) and slightly high in yarn count (12.9 tex). This arrangement allows the low-twist coarse yarns to cover the fabric better and fill the gaps between the yarns. The warps of fabrics 2P100 and P65C35 were coarser than those of other two fabrics. Although the yarn count of fabric P65C35 was nearly three times that of 1P100, it was only slightly heavier and thicker than fabric 1P100. This was possible because of the low thread count. In addition, the plain weave maximises the fabric yarn coverage and imparts dimensional and structural stability.

### 4.3.2 Fabric drape

The average of three measurements of the fabric drape coefficient (DC) and the calculated error thereof are presented in Figure 4.2. It can be observed that the range of the DC values was from 26% to 51%, which is between the limp and medium fabric categories. A DC value of 30% and below indicates limp, between 40–60% indicates medium and greater than 65% is stiffer and less drapeable [59]. The fabric DC values found were measured on fabrics considered suitable for abayas, such fabrics appeared to strike a compromise between being too drapeable and too stiff. From Figure 4.2, fabric 1P100 had a lower DC value (26%) than the other fabrics. This may have been due to the satin weave structure and fine yarn count. Subjective assessment also revealed that compared to other fabrics, 1P100 was softer and had better drapeability than the other fabrics. Fabric P65C35 made from spun yarns had the highest DC (51%), which also means the fabric was in the medium category and relatively stiff. This could be due to the coarser yarn count and plain weave structure for fabric P65C35.

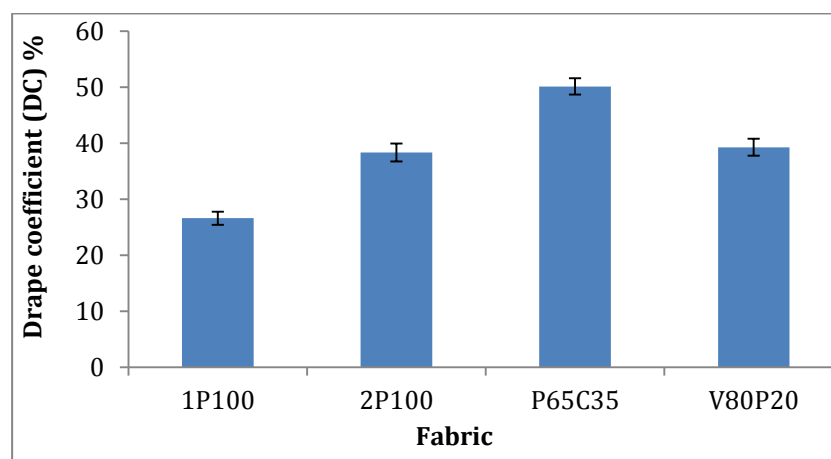


Figure 4.2 Comparison of drape coefficient of abaya woven fabrics

### 4.3.3 Air permeability

Figure 4.3 demonstrates that all the tested fabrics were highly air permeable. In fact, fabrics 1P100 and P65C35 could not support the 100 Pa pressure drop specified by the testing method (EN ISO 9237:1995). Fabric 1P100 had the highest air permeability value

with the smallest error bar. The finer yarns and satin weave structure may have been responsible for all its higher air permeability. This is supported by the findings of other researchers [161-163], who reported that fabrics of satin weave were more air permeable than other types of weaves. Although fabric P65C35 had a lower cover factor and lower fabric weight (Table 4.2), it showed slightly higher air permeability than fabrics 2P100 and V80P20. This was mainly due to different weave structures used for the fabrics, and P65C35 was plain weave. This finding disagrees with that of Backer and Kaynak [161, 163], who found that plain weave fabrics generally exhibit lower air permeability than satin or twill weaves. From the point of view of weave type, it has been observed that weave types with higher numbers of floats or lower numbers of interlacings have higher air permeability values. Because long-float weaves provide better mobility for yarns in their structure, gaps between these yarns become larger for air to flow more easily than with other types of structures [163].

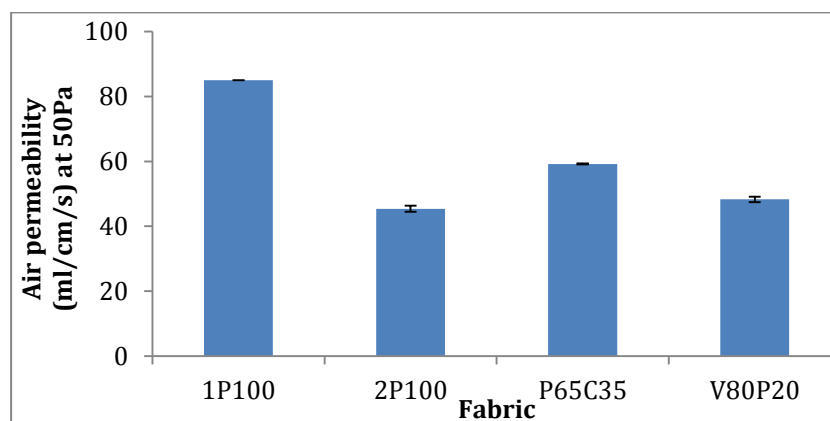


Figure 4.3 Comparison of air permeability values.

Air permeability plays an important role in facilitating transporting moisture vapour from the skin to the outside atmosphere. The assumption is that vapour travels by diffusion in air from one side of the fabric to the other mainly through fabric porosity [68]. In hot climates (humid tropics or hot desert), higher air permeability allows more air to move around the skin, facilitating the removal of humid air and reducing perspiration discomfort [23]. Although all fabrics were highly air permeable, the preferred fabric

structure among the fabrics studied for abayas was probably the satin weave, because it was a lightweight fabric and this type of weave provides better mobility for yarns in their structure, which allows air to flow more easily than other weave structures [164].

#### **4.3.4 Thermal resistance ( $R_{ct}$ )**

The  $R_{ct}$  of a fabric represents a quantitative evaluation of how good the fabric is in providing a thermal barrier to the wearer [165]. Results in Figure 4.4 illustrate that the  $R_{ct}$  of fabric 1P100 showed the lowest value. This was because fabric 1P100 was thin and lightweight and had a low cover factor. Higher air permeability also helps to remove heat and reduce the  $R_{ct}$  value. On the other hand, although the plain weave fabric P65C35 had the lowest cover factor, it showed the highest value of  $R_{ct}$ . This may be explained by the mechanism that the lower the proportion of fibre to air, the higher will be the resistance to heat flow of the cloth [166]. Another reason could be that cotton fibre in the blended fabric (spun yarn) has a higher  $R_{ct}$  value ( $0.0126 \text{ m}^2 \cdot \text{ }^\circ \text{C/W}$ ) and lower thermal conductivity ( $0.029 \text{ W/mK}$ ) [63] as compared with polyester filament ( $0.14 \text{ W/mK}$ ) or viscose ( $0.29 \text{ W/mK}$ ) [167-169]. In a hot environment, a low  $R_{ct}$  value is necessary to allow the heat from the body to dissipate to the outside environment [170]; among the fabrics tested, 1P100 showed the lowest  $R_{ct}$  hence, 1P100 is the best fabric for abayas amongst those tested. However it should be kept in mind that a low  $R_{ct}$  value may be counter-productive in that it would easily allow heat ingress (from hot environment) heating up the wearer and increasing discomfort.



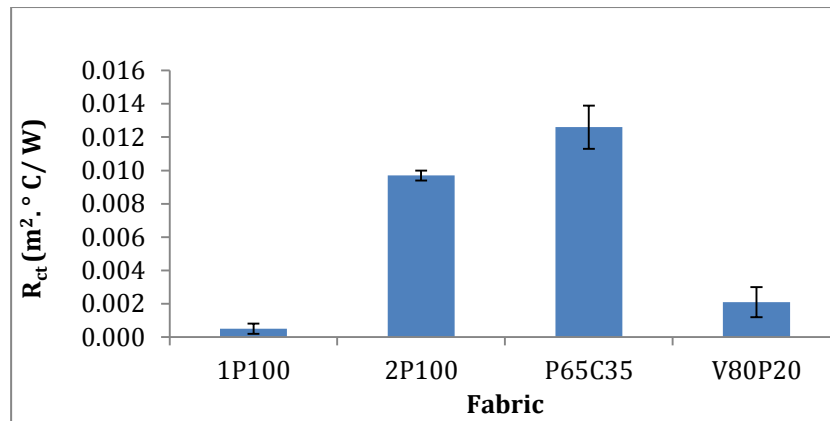


Figure 4.4 Comparison of thermal resistance  $R_{ct}$  of the fabric samples.

### 4.3.5 Water vapour resistance ( $R_{et}$ )

A lower  $R_{et}$  value is desirable for better moisture transport through the fabric and into the environment, resulting in drier skin and improved thermal comfort [99]. It can be observed from Figure 4.5 that the  $R_{et}$  value of fabric 1P100 was lower than all other fabrics due to its thinness and lightweight combined with high air permeability. This makes fabric 1P100 most suitable for abayas. The  $R_{et}$  value of fabric 2P100 was higher than those of P65C35 and V80P20 due to its higher thickness and weight. This result agrees with that of Özkanan [120], who stated that thickness and weight of fabrics are the most important factors affecting the water vapour resistance property. The fabric becomes uncomfortable with increasing thickness, weight and water vapour resistance. Consequently, it can be difficult to release sweat from the body in the form of water vapour as the water vapour resistance increases. The water vapour resistance is directly proportional to material thickness and air entrapment [89]. In other words, fabric 2P100 may not be the best choice for a summer abaya from the vapour transmission point of view. Figure 4.5 indicates that all materials that had  $R_{et}$  values of less than 3 m<sup>2</sup> Pa/W (according to Hohenstein Institute's comfort rating system) had the best performance in terms of breathability and were most comfortable to wear when the environmental humidity was low [171]. In other words, all the fabrics had low resistance to moisture transfer and therefore higher breathability.

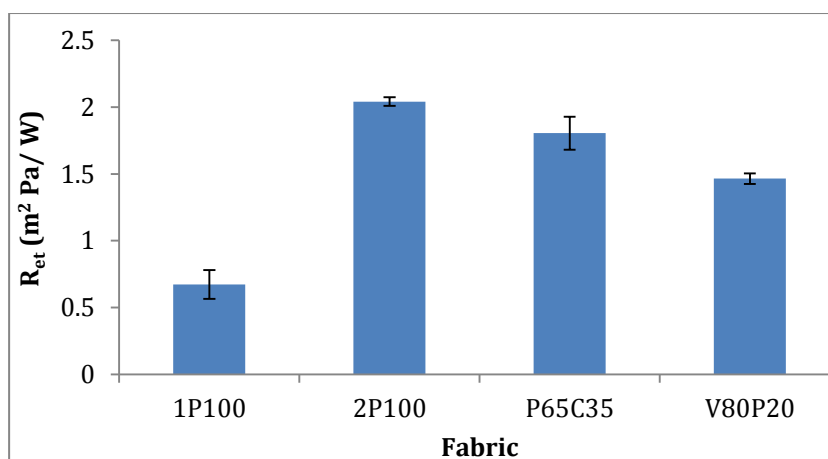


Figure 4.5 Comparison of water vapour resistance  $R_{et}$  of the sampled fabrics.

### 4.3.6 Liquid moisture management

The moisture management properties of fabrics are critical for comfort because they affect the removal of sweat from the skin surface [120]. The test results are summarised in Table 4.3 and converted into grades shown in Figure 4.6.

Figure 4.6 shows the wetting time grades of the top and the bottom surfaces of the four samples. Wetting time (top or bottom surface) is the time (in seconds) after which the surfaces of the fabric just start to get wet, after the test commences [117]. It can be observed from Table 4.3 that 1P100 was slow to wet on the top surface and had a medium wetting time on the bottom. This indicates that 1P100 can transfer moisture to the outside quickly. The likely reasons are the finer yarn count and the resultant thinness of the fabric [120]. P65C35 has a medium wetting time on both surfaces. This was probably due to the high attraction between the liquid and the fibre surface [119]. However, 2P100 and V80P20 had higher wetting times, indicating that wetness on the top surface transfers moisture slowly to the bottom surface.

Table 4.3 Moisture management results of the evaluated fabrics

Fabric		Wetting times (sec)		Absorption rate (%/sec)		Max wetted radius (mm)		Spreading speed (mm/sec)		Accumulative one-way transport (%)	OMMC
		Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom		
1P100	Mean	119.95	7.52	0.00	98.27	0.00	5.00	0.00	0.76	1217.88	0.73
	S.D	0.00	1.43	0.00	15.65	0.00	0.00	0.00	0.16	40.07	0.03
2P100	Mean	9.29	119.95	264.24	0.00	5.00	0.00	0.65	0.00	-908.82	0.00
	S.D	2.39	0.00	174.66	0.00	0.00	0.00	0.13	0.00	20.63	0.00
P65C35	Mean	34.82	10.46	265.36	114.62	4.00	5.00	0.30	0.50	1292.67	0.74
	S.D	47.63	2.64	165.65	20.80	2.24	0.00	0.17	0.15	36.61	0.01
V80P20	Mean	9.22	119.95	258.22	0.00	5.00	0.00	0.56	0.00	-850.14	0.00
	S.D	2.41	0.00	160.44	0.00	0.00	0.00	0.11	0.00	82.54	0.00

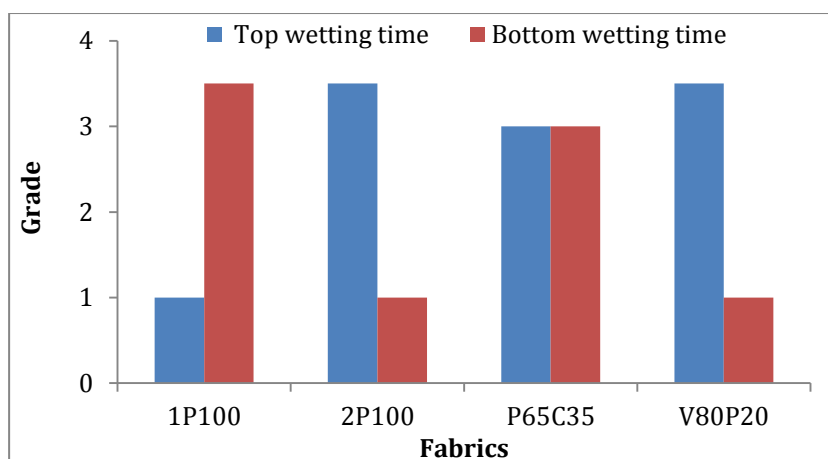


Figure 4.6 Wetting time grades for both top and bottom surfaces.

Figure 4.7 shows the mean grades of the absorption rates of top and bottom surfaces of the four fabrics evaluated. Absorption rates (top or bottom surfaces) indicate the moisture absorption ability of the fabric surfaces during the rise of water content. It can be seen that 2P100 and V80P20 were classified as having very fast absorption rates on the top and very slow drying rates on the bottom surfaces. This could be because 2P100 and V80P20 have almost the same cover factor and fabric count. This indicates that the fabric, if in contact with skin, will absorb sweat and transmit it to the surface by diffusion. This is highly desirable for the comfort of the wearer.

1P100 has a very slow absorption rate on top but a very fast drying rate on the bottom. This could be because it is a thinner fabric [120]. Inherently polyester fibre absorbs only a small amount of moisture (2%) because of its hydrophobic character, meaning that the surface has few bonding sites for water molecules. Hence, polyester fabrics tend not to get wet and have good moisture transportation and release [119]. This suggests that the bottom surface of the fabric started to get wet faster than the top surface [127]. In contrast, P65C35 has very fast absorption rates on top and bottom. This could be because fabric P65C35 contains hydrophilic cotton that tends to absorb and retain water, resulting in poor moisture transportation and release [119].

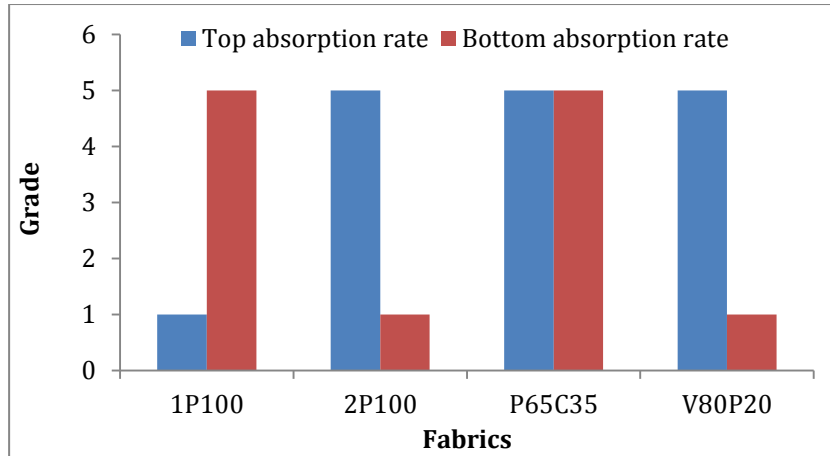


Figure 4.7 Absorption rates for top and bottom surfaces of the tested fabrics.

Figure 4.8 and Figure 4.9 show the mean grades of the maximum wetted radius and spreading speed on top and bottom surfaces of the four fabrics. It can be observed that 1P100, 2P100, P65P35 and V80P20 all have very slow liquid moisture spreading speeds on the surface of the fabrics with zero wet out radius.

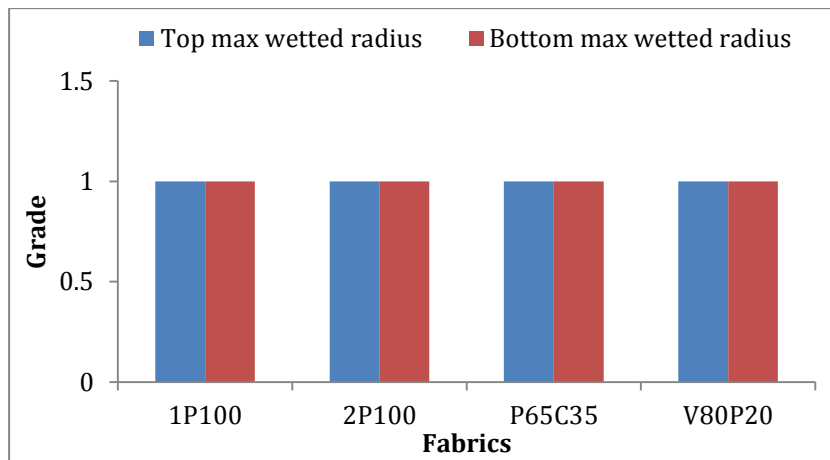


Figure 4.8 Wetted radius for top and bottom surfaces of the tested fabrics.

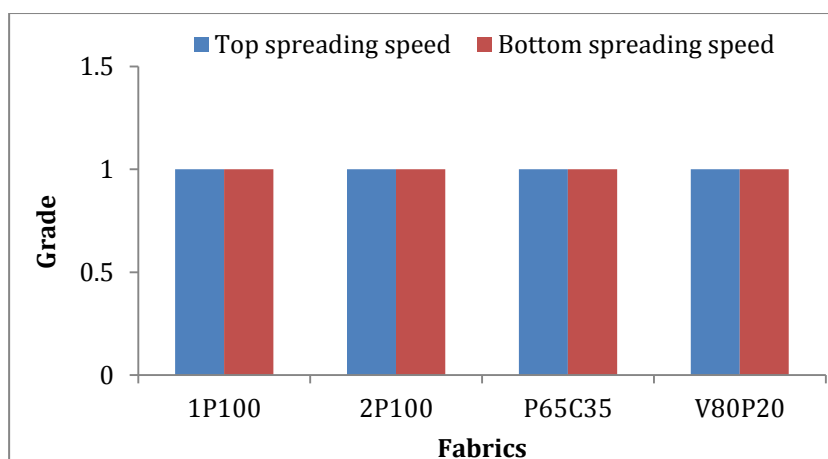


Figure 4.9 Spreading speeds for top and bottom surfaces of the tested fabrics.

Figure 4.10 shows the mean grades of the AOTI and OMMC of all the fabrics. A large OMMC indicates a high overall moisture management capability of the fabric. It can be observed that 1P100 and P65C35 had excellent liquid management capacity grades and an excellent (AQTI) one-way transport index. These fabrics had very good moisture management properties. This indicates that liquid sweat can be easily and quickly transferred from next to the skin to the outer surface to keep the skin dry. On the other hand, 2P100 and V80P20 had poor liquid moisture management properties and one-way transport capacities (AOTI = -908.81 and -850.13, respectively), indicating that liquid (sweat) cannot diffuse easily from the next-to-skin surface to the outer side and will accumulate on the top surface of the fabric. Sometimes when the weather is very hot, women wear sleeveless tops to feel more comfortable in the abaya; that means abayas are sometimes worn next to skin and should be able to transfer moisture to the outside environment.

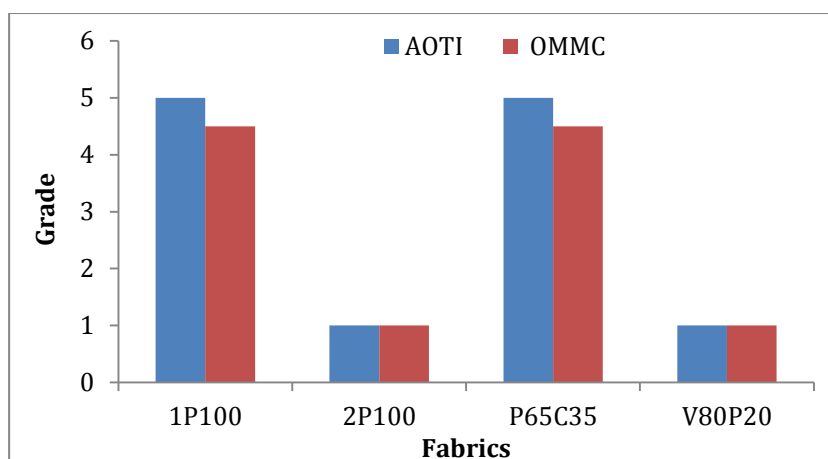


Figure 4.10 Accumulative one-way transport and OMMC of the tested fabrics.

Accordingly, 1P100 and P65C35 can be classified as fabrics through which water can penetrate, because they have low water spreading speeds and excellent one-way transport indices. 2P100 and V80P20 can be classified as being waterproof, since the fabrics had very slow rates of water absorption, low spreading speeds, no one-way transport and no water penetration. Therefore, 1P100 and P65C35 had better moisture management performance and should be more comfortable in hot weather than 2P100 and V80P20.

Overall, based on fabric comfort performance assessment, it is evident that the lightweight satin fabric is the most suitable for abayas and will provide better handling and thermal comfort in a hot environment. However, since abaya garments reflect the Arabian cultural heritage and religious belief, the thermal comfort performance of fabrics may not be the most important selection criteria for abayas. For instance, 1P100 showed better thermal comfort, but the fabric may not be so suitable because it is slightly transparent and may show the body contours through the fabric.

## 4.4 Summary

The main objective of this chapter was to understand the fabrics for abayas and investigate their comfort properties. Four commercially available fabrics (used for abayas) were studied. Results show that the abaya fabrics were mainly woven structures and made from polyester and its blends. It was found that fabric weave structure, fibre composition and other fabric properties significantly affect the fabric comfort performance.

Among the 100% polyester (3/1×1/3 mixed twill weave), 65/35 polyester/cotton (plain weave), 80/20 viscose/polyester (crepe weave) and 100% polyester (satin weave) fabrics, the last fabric, produced using a fine yarn count, has better air permeability, drapeability and moisture management. It also had the lowest thermal resistance and lowest water vapour resistance. Hence the satin fabric showed better thermal comfort for abayas. However, it was observed that the 100% polyester (satin weave) fabric was slightly translucent.



# **Chapter 5 Thermal comfort characteristics of knitted fabrics for abaya**

This chapter is based on the paper “Thermal comfort characteristics of knitted fabrics for abaya” published in *Advanced Materials Research* [138]. This study investigated five selected knitted fabrics that could be used as abaya fabrics for thermal resistance, air permeability, thermal comfort and vapour resistance. The results indicate that knit structures, fibre composition and fabric weight have the greatest influences on thermal comfort performance.

## **5.1 Introduction**

Recently the use of knitted fabrics has been gaining popularity for abayas due to their simple production technique, low cost, wide product range, greater fashionability and higher levels of clothing comfort [172]. Knitting technology meets the rapidly changing demands of fashion. Knitted fabrics not only possess stretch and provide freedom of movement, but also have soft handle and they easily transmit water vapour from the body. Several researchers [56, 93, 167, 173-176] have investigated the effects of fibre materials and fabric constructions on the thermal properties such as air permeability, thermal resistance, water vapour permeability, thermal conductivity and moisture management properties of knitted fabrics. Their findings indicated that the most influential parameters of thermal comfort in knitted fabrics are mass per unit area, fabric thickness, fibre type, yarn properties, fabric structure, fabric porosity and cover factor. Prakash and Ramakrishnan [177, 178] observed that the thermal properties of single jersey fabrics produced from bamboo/cotton blended yarns were significantly affected by the above parameters. In terms of comfort characteristics, knitted fabrics generally perform better than most woven fabrics [67, 69, 179, 180]. Therefore knitted fabrics are commonly preferred for sportswear, casual wear and underwear.

Traditionally, only woven fabrics were used for abayas in order to hide the body contour, as explained in Chapters 1 and 4. The increasing use of knitted fabrics globally is making them a fashion choice for abayas while continuing to hide body contour. The survey results in Chapter 2 showed that 33% of participants wear knitted abayas. It is possible that the porosity, low weight, high stretch and recovery of knitted fabrics may assist in the movement of air and thereby improve abaya comfort performance. Hence, it is important to investigate and select suitable knitted fabrics for abayas.

## **5.2 Experimental design**

### **5.2.1 Fabrics**

Five commonly available knitted fabrics in a range of fibre blends were selected for evaluation towards being used for abayas. They were 100% nylon (N100), 50/50 wool/nylon (W50N50), 100% wool (W100), 65/35 polyester/cotton (P65C35) and 96/4 polyester/elastane (P96E4).

### **5.2.2 Fabric characterisation**

Fabric physical properties such as yarn count (linear density), structure, mass per unit area, thickness, thread density (wales and courses per unit length), optical porosity, cover factor, stretch and recovery, and drape coefficient (DC) were ascertained according to relevant national or international standards as described in Section 3.5. The constituent fibre content in each fabric was either analysed or obtained from the fabric specifications. Scanning electron microscopy was carried out described in Section 3.5.4.2.

### **5.2.3 Fabric comfort properties**

Test parameters related to comfort characteristics such as air permeability, thermal resistance, vapour resistance and moisture management were evaluated as described in Section 3.6.

## 5.3 Results and discussion

### 5.3.1 Physical properties of knitted fabrics

The five knitted fabrics were analysed and their properties are presented in Table 5.1. The mass per unit area ( $\text{g/m}^2$ ) ranged from lightweight ( $70\text{--}100 \text{ g/m}^2$ ) to heavy weight ( $300\text{--}375 \text{ g/m}^2$ ), as classified by Collier and Epps [44]. These weight ranges were selected to evaluate which fabric could best hide body contour while retaining the benefits of a knitted structure. Among all the fabrics, fabric N100 was the heaviest at  $349 \text{ g/m}^2$  and thickest (1.15 mm) with the lowest thread density in both the course and wale directions. This is because fabric N100 was made from coarse yarn (20 tex) and had an interlock knit structure. This resulted in the tightest structure and the lowest optical porosity among the fabrics [63]. Fabric P96E4 was slightly heavier ( $184 \text{ g/m}^2$ ) than the other medium weight fabrics. It is likely that this was brought about by contraction of the 4% elastane component when the fabric came off the knitting needles. Fabrics W50N50, P65C35 and W100 were made of staple fibres. Fabrics P65C35 and W100 had similar medium weight, stitch density, optical porosity and cover factor, but different thickness and structure. Fabric P65C35 was thicker than fabric W100 because it had a double jersey knit structure. In addition, hairiness due to the cotton component (Figure 5.1) could also be a contributing factor. Comparing similar data for woven fabrics (Table 4.1), it can be observed that most of the knitted fabrics were thicker and heavier.

SEM images at  $100\times$  magnification were used to observe the fabric structure. Figure 5.1 confirms that there were notable differences between the fabrics under the same magnification and imaging conditions. Some key variations are the knit structures and the thread density.

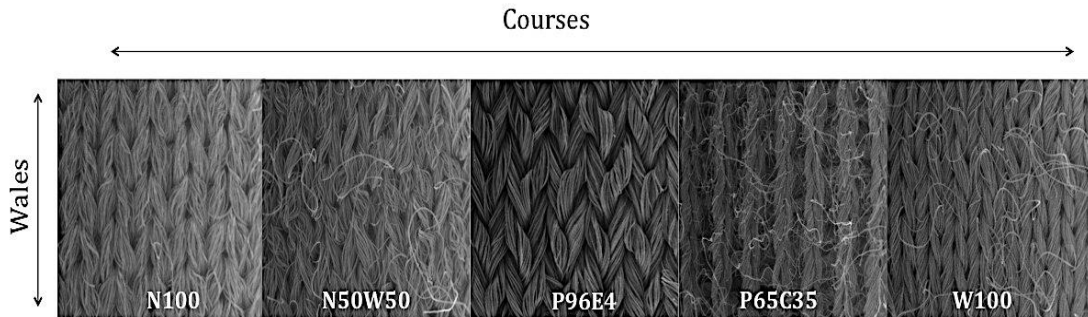


Figure 5.1 Knitted fabric images from a Scanning Electron Microscope.

Table 5.1 Physical properties of knitted fabrics.

Fabric code	N100	W50N50	P96E4	P65C35	W100
<b>Knit structure</b>	Interlock	Single jersey	Single jersey	Double jersey	Single jersey
<b>Fibre composition</b>	100% nylon	50/50 wool/nylon	96/4 polyester/elastane	65/35 polyester/cotton	100% wool
<b>Yarn structure</b>	Filament	Wool: spun, Nylon: filament	Filament	Spun yarn	Spun yarn
<b>Yarn count [tex]</b>	20	18	17	18	20
<b>Fabric mass [g/m<sup>2</sup>]</b>	349	127	184	176	174
<b>Thickness [mm]</b>	1.15	0.64	0.50	0.80	0.54
<b>Courses/cm</b>	18	16	22	20	20
<b>Wales/cm</b>	12	15	20	15	17
<b>Optical porosity [%]</b>	1.45	8.51	6.45	8.66	5.64
<b>Cover factor</b>	0.95	1.37	1.78	1.40	1.77

### 5.3.2 Stretch and recovery

The stretch and recovery properties of the fabrics are shown in Figure 5.2 and Figure 5.3. The results indicate that P96E4 had the highest stretchability and lowest residual extension in the course-wise direction as compared to the other fabrics. This is most likely due to the presence of elastane filaments [181, 182]. A higher percentage of recovery after stretching indicates better dimensional stability on loading of knitted fabrics [183]. According to Senthilkumar et al. [184], even a low percentage (2–3%) of elastane is sufficient to provide desirable stretch properties of woven or knitted fabrics. It should be

noted that here the elastane serves to promote dimensional stability rather than increase adherence to body contour. This is significant considering that the abaya is worn over other garments. Fabric W100 showed the lowest residual extension possibly due to its single jersey structure, which could be a suitable characteristic for abayas. It is advantageous if an abaya has excellent recovery properties in the wale-wise direction so as to maintain its original shape.

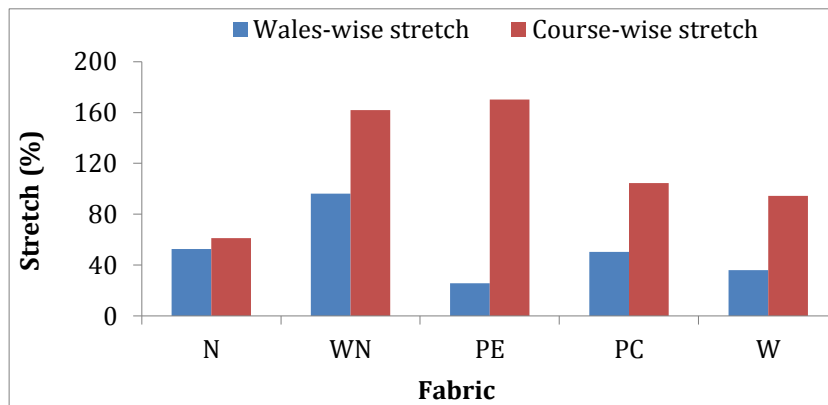


Figure 5.2 Stretchability of abaya knitted fabrics.

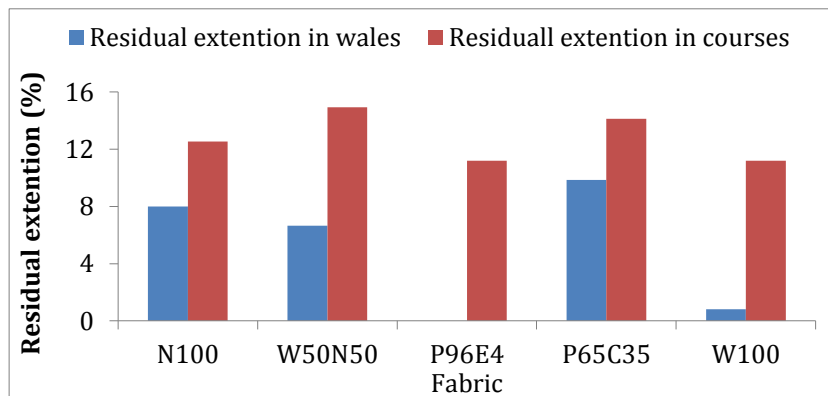


Figure 5.3 Residual extension after recovery under load of 30 (N) of the abaya knitted fabrics.

### 5.3.3 Fabric drape

The average values of the fabric drape coefficient (DC) (Figure 5.4) indicate a range from 20% to 50%. Thus the fabrics fall between the limp and medium categories [59]. Fabric N100 with nearly 50% DC is classified as a medium fabric. Fabrics W100, W50N50,

P65C35 and P96E4 exhibit drapeability in the range between 20–40% because they were thin and flexible. The results are in agreement with those of Wang [181], who stated that drape behaviour is affected by knit fabric structure. Fabrics W100, W50N50 and P96E4 would be more suitable for abayas, because drapeable fabrics display more nodes or folds in a circular draped configuration [185]. In addition, knitted fabrics with a lower drape coefficient (<20%) can be formed more easily and they fit easily to the shape of the body [186], hence, the DC property between the limp and medium categories is desirable for knitted abaya because the fabric will not reveal too much body contours. Although the abaya is a loose-fitting outer garment, it may occasionally reveal body contour if made from fabrics that drape well. Chen et al. [187] evaluated the relationship between fabric thickness and drape coefficient; they found that DC increases proportionately to thickness when fabric thickness is between 0.4 and 0.8 mm, which means drapeability is good. The thickness of fabrics W100, W50N50 and P96E4 was determined to be 0.54mm, 0.64mm and 0.5mm respectively. These are in the range studied by Chen and may be considered as possessing good drapeability. However, fabrics N100 and P65C35 with thickness  $\geq 0.8$ mm show higher DC values than the other fabrics. These fabrics may be expected to show medium drapeability compared with fabrics W100, W50N50 and P96E4.

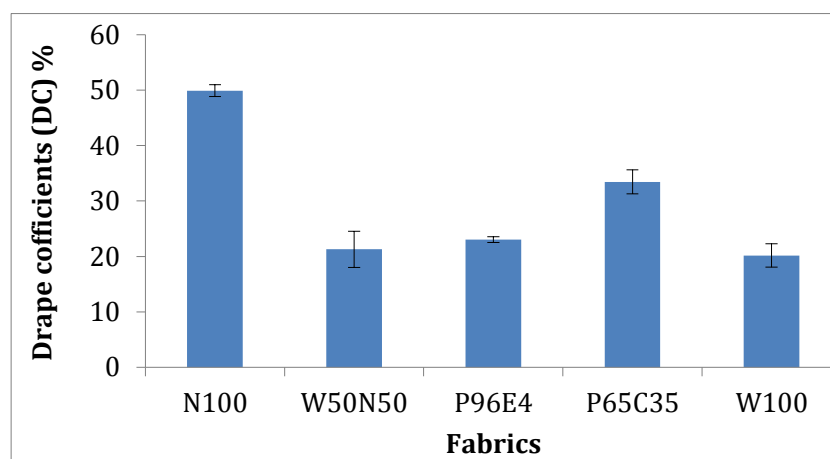


Figure 5.4 Comparison of drape coefficients of abaya knitted fabrics

### 5.3.4 Air permeability

The air permeability is mainly dependent on a fabric's weight and construction (thickness and porosity) [58, 175, 188]. Air permeability was measured with 50 Pa pressure difference across the fabrics because for some fabrics the instrument could not generate the 100 Pa pressure difference required by EN ISO 9237-1995. Figure 5.5 shows that all tested fabrics were highly air permeable, except fabric N100. This may be due to the fact that fabric N100 was thicker and heavier, with lower optical porosity, than the other fabrics. Thus the fabric is less porous, and this restricted the flow of air through the fabric. The air permeability of fabrics W50N50 and P65C35 was higher than that of the other fabrics because of their more open structures, as seen in Figure 5.1. Higher air permeability reduces perspiration discomfort [23]. These two fabrics had high optical porosity, low cover factor and fewer courses/cm (Table 5.1), which facilitated the passage of air through them. The experimental results agree with those of Ogulata and Mavruz [69], who found that fabrics with the lowest course count per cm and yarn number in tex had the highest air permeability values. Therefore, increasing loop length resulted in a looser surface on the fabric, thereby increasing the air permeability.

Linear regression line (Figure 5.6) shows that there was a significant relation  $r \leq 0.9762$ , ( $p < 0.001$ ) between air permeability and optical porosity: as air permeability increased, optical porosity increased. These results agree with those of Ogulata and Mavruz [69], who found that air permeability and optical porosity are strongly related to each other. If a fabric has very high porosity, it can be assumed that it is permeable. Fabrics P96E4 and W100 also showed moderate air permeability. These fabrics had almost the same stitch densities and lower porosities (Table 5.1) and the structures of the fabrics were a little tighter than those of W50N50 and P65C35. This observation agrees with various studies reported on the factors affecting the air permeability of knitted fabrics [62, 63, 67, 69, 189] depending on geometrical parameters such as courses per cm, wales per cm, stitch length, fabric thickness, yarn count and fibre density.

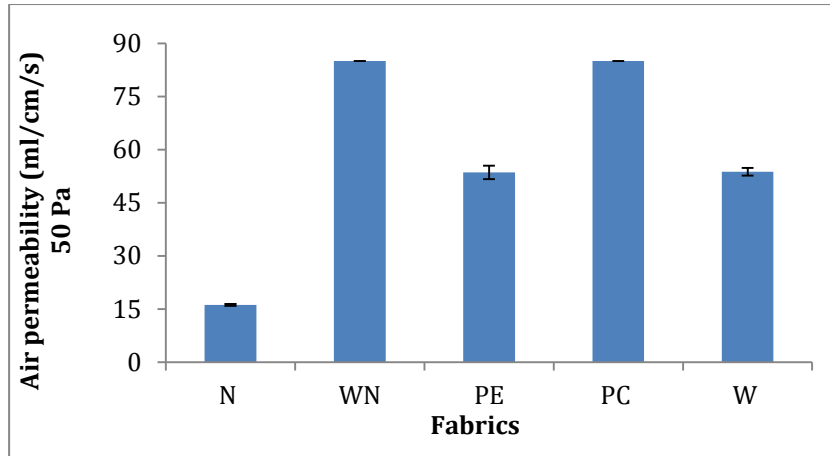


Figure 5.5 Comparison of air permeability values.

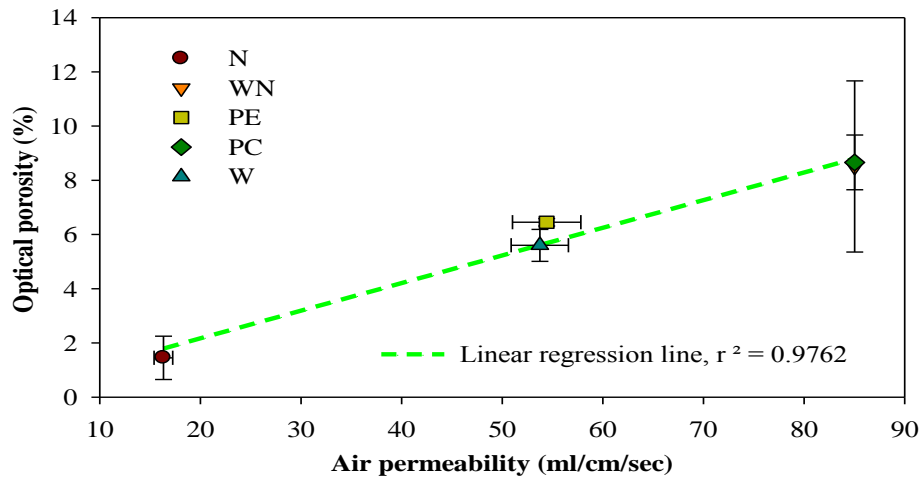


Figure 5.6 Correlation between air permeability and optical porosity.

### 5.3.5 Thermal resistance

Thermal resistance is a measure of a fabric's ability to prevent heat from flowing through it. This depends on the fabric thickness, weight, fibre type, yarn properties, fabric structure, fabric porosity, cover factor, thermal conductivity and air permeability [63]. In a hot environment, low thermal resistance is necessary to allow the heat from the body to flow outside to the environment. In Figure 5.7, the thermal resistance of fabric N100 shows the lowest value among all the samples because it was made of 100% nylon filaments, which have higher thermal conductivity (0.25 W/mK) [167] than the other fabrics. Therefore it allows more heat to pass through the fabric. Similarly, P96E4 also



showed a lower thermal resistance because polyester filaments have higher thermal conductivity of 0.14 W/mK [167] than wool (0.039 W/mK ) and cotton (0.029 W/mK) fibres [63]. Consequently fabrics W50N50, W100 and P65C35 showed higher thermal resistance than P96E4 and N100. Greater thickness may be another contributory factor for the low heat transfer, as thermal resistance is directly proportional to fabric thickness. The thermal resistance of fabric mainly depends on the resistance offered by the entrapped air within the fabric and the inherent thermal resistance of fibre content [1]. Air is known to be less heat conductive as compared with any textile fibre, so the amount of dead air pockets very much influences the overall resistance of the fabric.

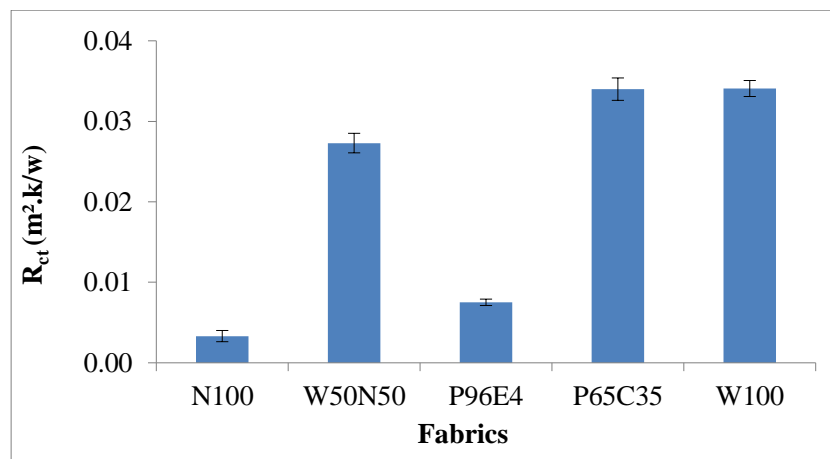


Figure 5.7 Comparison of thermal resistance of the tested fabrics.

### 5.3.6 Water vapour resistance

It can be observed from Figure 5.8 that P96E4 had the lowest value of water vapour resistance among all the fabrics. This may be due to its lower thickness. The water vapour resistance of fabric N100 was higher than the rest of the samples. This was due to its increased thickness and the compactness of its interlock structure. According to the result in Figure 5.8, fabric P96E4 may be suitable for abayas because it has a lower water vapour resistance value, which is desirable to enable moisture to pass through the fabric and into the environment. A lower water vapour resistance value results in drier skin, thereby improving thermal comfort [99]. Conversely, a high value of water vapour resistance

results in low vapour transmission from the body to the outside environment, making the body feel discomfort.

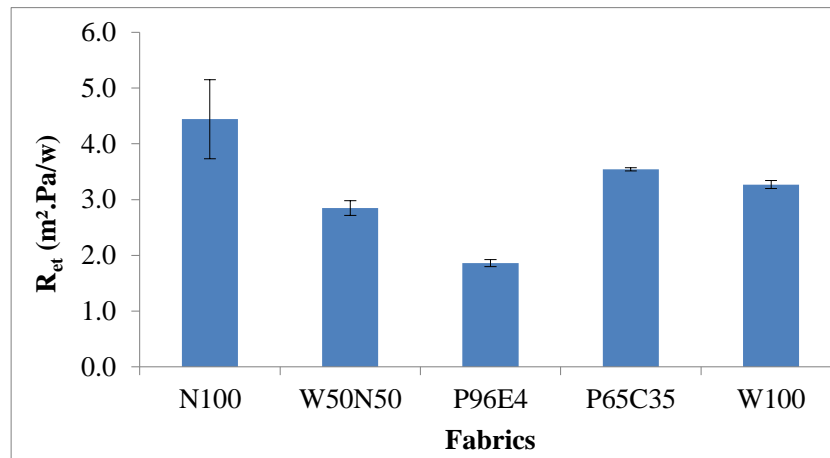


Figure 5.8 Comparison of water vapour resistance values.

### 5.3.7 Moisture management testing

The moisture management properties of knitted fabrics were tested and the results are summarised in Table 5.2. The moisture absorption radii are shown from **Error! Reference source not found.** to **Error! Reference source not found.**

The results in Table 5.2 reveal that fabric N100 also had good one-way transfer ability and fair liquid moisture management properties with slow spreading rates on both sides of the surface and a medium wetted radius. The fabric had slow absorption rates on both sides of the fabric and a medium wetting time (Figure 5.9), indicating that sweat cannot easily diffuse through the fabric and evaporate into the environment. The fabric possessed slow drying but fast absorption.

Fabric W50N50 was able to absorb more moisture than the other fabrics. It had the highest liquid moisture management capacity (OMMC=0.75) and excellent one-way transfer capacity (AOTI =745.88). The above values indicate that liquid sweat can be easily and quickly transferred from next to the skin to the outer surface and keep the skin dry. This fabric also exhibited a very fast spreading speed on the bottom surface and a

small wetted radius on the top and bottom surfaces (Figure 5.10). The interpretation is that liquid can spread on the surfaces and dry quickly.

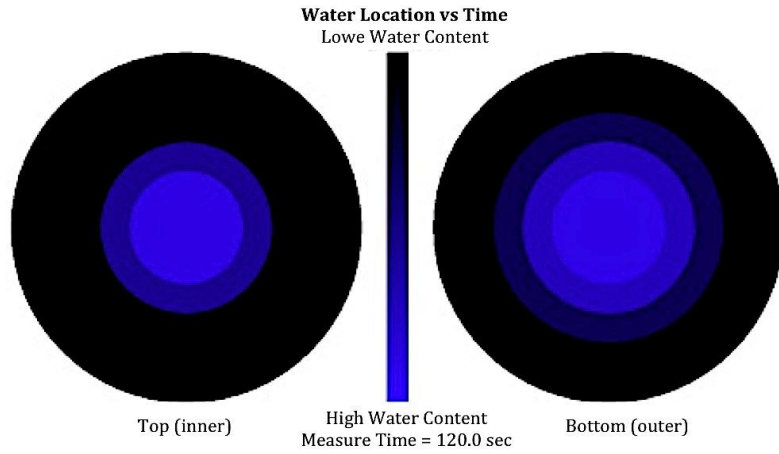


Figure 5.9 Water content of fabric N100.

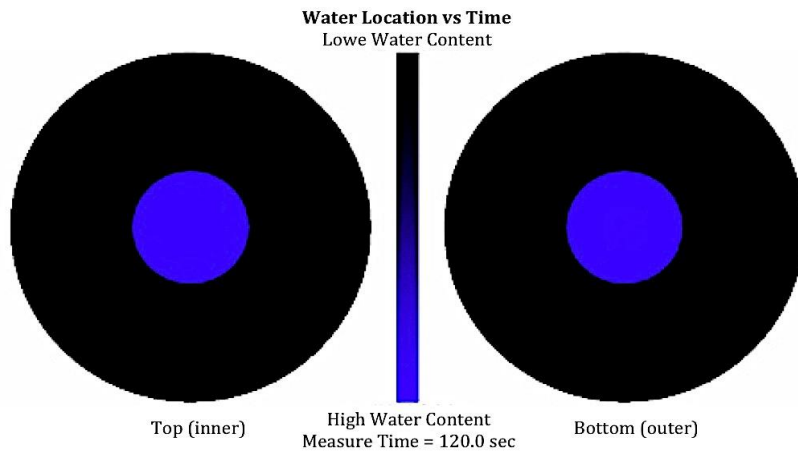


Figure 5.10 Water content location of fabric W50N50.

Table 5.2 Summary of fabric moisture management properties

Fabric		Wetting times (sec)		Absorption rate (%/sec)		Max wetted radius (mm)		Spreading speed (mm/sec)		Accumulative one-way transport (%)	OMMC
		Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom		
N100	Mean	6.53	6.29	22.37	28.60	13.00	14.00	1.62	1.88	154.04	0.35
	S.D	0.68	0.41	5.39	10.33	2.74	2.24	0.24	0.28	115.17	0.17
W50N50	Mean	38.22	11.32	17.18	119.98	10.00	10.00	0.23	0.51	745.88	0.75
	S.D	4.43	1.26	3.11	5.33	0.00	0.00	0.02	0.05	105.20	0.00
P96E4	Mean	8.18	119.95	321.27	0.00	5.00	0.00	0.60	0.00	-906.49	0.00
	S.D	0.92	0.00	131.71	0.00	0.00	0.00	0.06	0.00	59.57	0.00
P65C35	Mean	3.83	3.83	57.33	56.76	29.00	29.00	4.64	4.65	60.96	0.50
	S.D	0.23	0.18	2.50	2.94	2.24	2.24	0.32	0.31	11.29	0.02
W100	Mean	3.67	3.87	54.70	62.36	25.00	24.00	4.05	3.84	95.37	0.54
	S.D	0.22	0.34	3.08	2.63	0.00	2.24	0.07	0.09	29.84	0.03

Fabric P96E4 showed a negative one-way transfer ability (ATOI = -906.49) and poor liquid moisture management properties without any wet radius, as seen in Table 5.2. This fabric had very low liquid moisture spreading rates on both top and bottom surfaces due to the hydrophobic nature of polyester. Hence the liquid sweat could not diffuse from the inner surface into the fabric and it accumulated on the top surface of the fabric, as evident in Figure 5.11. Consequently, P96E4 cannot effectively evaporate water into the environment, as it would keep the sweat between the skin and the next surface of the fabric and so give a feeling of wetness to users.

Fabrics P65C35 and W100 had good moisture management capacity (OMMC=0.50 and 0.54, respectively) and fair one-way transfer capacity (AOTI=60.96 and 95.37, respectively). They also showed fast wetting times, fast absorption rates, very large wetted radii and fast spreading speeds. As mentioned earlier, this facilitates the transfer of liquid sweat from the surface next to the skin to the opposite surface and it spreads quickly with large wetted areas on both sides (Figure 5.12 and Figure 5.13). Fabrics P65C35 and W100 can be classified as good moisture management fabrics.

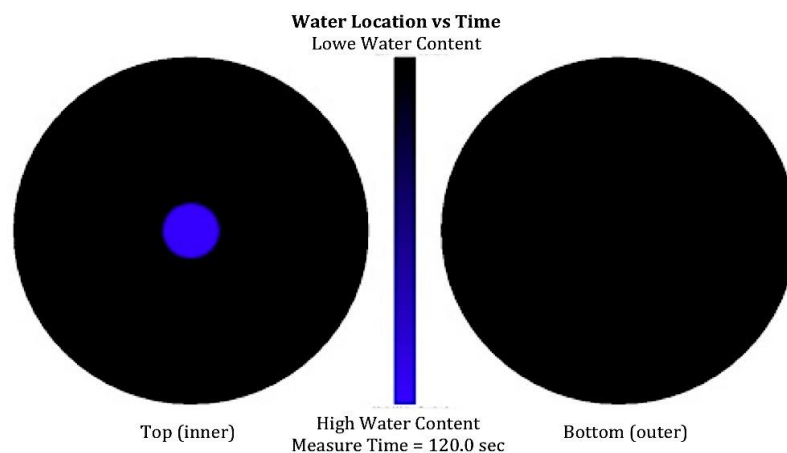


Figure 5.11 Water content of fabric P96E4.

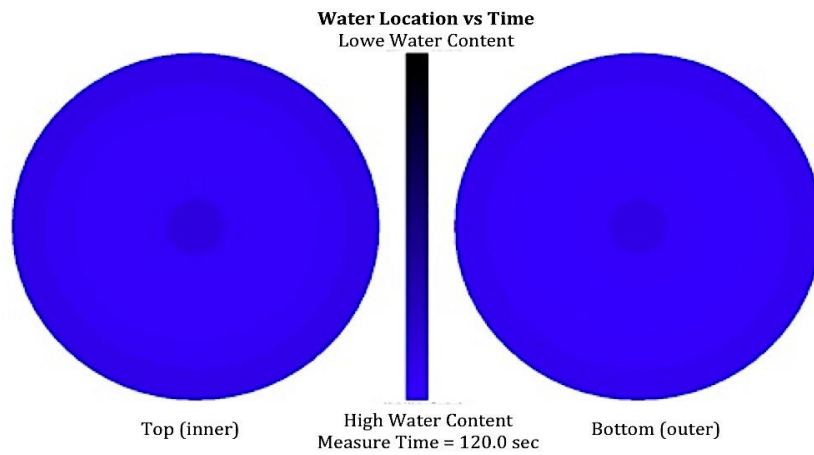


Figure 5.12 Water content of fabric P65C35.

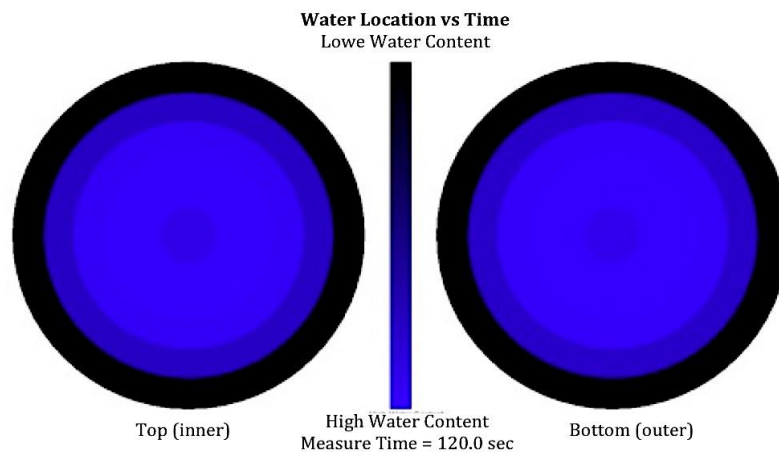


Figure 5.13 Water content of fabric W100.

Based on the MMT results, fabrics P65C35, W100 and W50N50 can be classified as fabrics having good moisture management properties, since they had fast rates of water absorption, large spreading speeds and good transportation. These fabrics therefore would be expected to be more comfortable to wear in hot climates than fabrics P96E4 and N100.

From the fabric properties ascertained in this chapter, it appeared that fabric P96E4 was better in terms of thermal comfort management as measured by air permeability and thermal and vapour resistance. Therefore P96E4 was used to design an abaya garment and evaluated with multiple layers of clothing by using a thermal manikin, as explained in Chapter 6. The negative aspect is that P96E4 cannot effectively transport moisture away from the body and thereby leads to a possible feeling of discomfort. Although thermal comfort is very important to abayas, other factors such as drapeability and stretch and recovery also influence the choice of abaya fabrics.

## **5.4 Summary**

The investigations in this chapter were aimed at analysing five knitted fabrics presently being used for abayas and evaluating their thermal comfort properties. The results highlight the importance of knit structure, fibre composition and other fabric properties in affecting the thermal comfort performance. The polyester/elastane (96/4) single jersey knit fabric showed better air permeability, and stretch and recovery properties, and lower thermal and water vapour resistance compared to the other fabrics studied. However, polyester/elastane fabric could not effectively evaporate water into the environment as it kept the sweat between the skin and the adjacent surface of the fabric. Overall, different knit structures studied such as interlock, single jersey and double jersey appear to be suitable for abayas. It should be kept in mind that knitted fabrics are normally not as dimensionally stable as woven fabrics, hence knitted abayas could reveal body contour. This could be avoided by using thicker fabrics with a heavier mass per unit area. Alternate knit structures and fibre blends may also be investigated.

## **Chapter 6 Evaluation of abaya designs for comfort using a thermal manikin**

Significant portions of this chapter have been published in *Advanced Materials Research* as “Evaluation of abaya design using thermal manikin” [190], *Journal of Fiber Bioengineering & Informatics* as “Effect of abaya designs and daily wear clothing on thermal comfort measured with a female thermal manikin” [143] and in *Textile Bioengineering and Informatics Symposium Proceedings* “ Evaluation of heat loss in abaya and daily wear clothing using a heated thermal manikin” [191]. Based on the findings from Chapter 4 and Chapter 5, a 100% polyester woven abaya fabric and a 96/4% polyester/elastane knitted abaya fabric were selected, based on their comfort properties as determined earlier, to produce abayas and investigate its thermal comfort using a thermal manikin.

### **6.1 Introduction**

The aim of this chapter is to determine the physical values related to the heat transfer and moisture management properties of the abaya-scarf-daily-wear combination as worn in Saudi Arabia, by using a female sweating thermal manikin. The daily-wear consists of underwear, skirt/slacks and shirt. The thermal and evaporative resistances of clothing worn within the abaya were measured. All clothing and abaya combinations were also tested in accordance with ASTM F-1291-05 and ASTM 2370-05. The results could contribute to the improvement of the design of the abaya worn in a hot environment by minimising thermal and evaporative resistance.

### **6.2 Materials and methods**

The below sections describe the effect of two daily wear clothing (DWC) (underwear and long-sleeved shirts, with a skirt or slacks and shoes), three abaya designs (abaya worn from the shoulder with either tight sleeves (TS) or loose sleeves (LS) and an abaya worn



from the top of the head with tight sleeves (OH)) and two fabrics (woven and knitted fabrics) that were evaluated on the thermal manikin. Both stationary and walking modes were utilized to obtain realistic results.

## 6.2.1 Clothing ensembles

### 6.2.1.1 Daily wear garments (worn inside)

The most common daily-wear clothing (DWC) combination which consists of underwear and long-sleeved shirts, with a skirt or slacks and shoes; there evaluated. The shirt fitted to the manikin was size 12 with a typical design with buttons, woven fabric, long sleeves and a shirt collar. The fabric was made of 66% cotton/30% polyester/4% elastane. The skirt was a size 12, A-line, ankle-length, knitted-fabric skirt constructed of 95% viscose/5% elastane. Figure 6.1 shows the shirt and skirt designs. The slacks were size 12, straight-fitted, zipper-fly, constructed of 40% cotton/30% viscose/25% polyester/5% elastane woven-fabric.

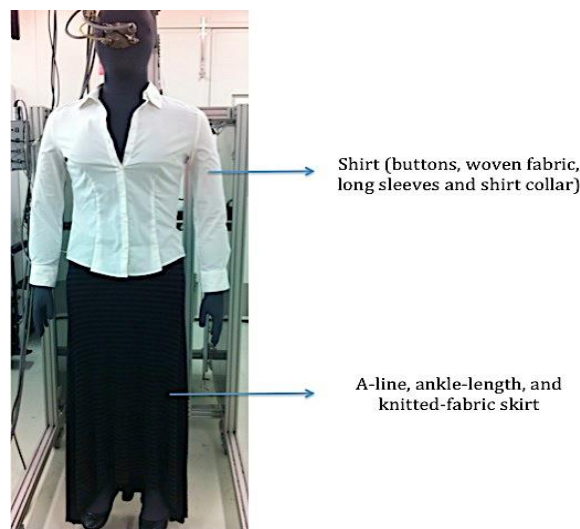


Figure 6.1 Manikin with the shirt and skirt design

### 6.2.1.2 Outer garment (abaya)

Three abaya designs, that is, an abaya worn from the shoulder with either tight sleeves (TS) or loose sleeves (LS) and an abaya worn from the top of the head with tight sleeves (OH), were assessed. These designs were made of both woven and knitted fabrics. The

abayas fitted to the manikin were of medium (M) size (8–10). Each abaya, along with a scarf, was worn in an individual combination with each of the two dress ensembles, as shown in Figure 6.2. The scarf was made of 100% polyester. Daily-wear clothing and abaya fabrics were given codes for ease of identification. The clothing codes and their meanings are given in Table 6.1. The particulars of the clothing ensembles and abaya fabrics are presented

Table 6.2.

Table 6.1 Daily wear clothing, abaya fabrics and abaya design codes

Description of clothing	Sample code
Underwear (bra and panties)	U
Shirt (long sleeves)	SH
Daily wear clothing (underwear + shirt (long sleeves)+ skirt + shoes)	SH+SK
Daily wear clothing (underwear + shirt (long sleeves)+ slacks + shoes)	SH+SL
Scarf	SC
Abaya only (no daily-wear clothing underneath abaya)	AO
Abaya worn from shoulder with tight sleeves and scarf	TS
Abaya worn from shoulder with loose sleeves and scarf	LS
Abaya fabric worn from top of head and scarf	OH
Woven abaya fabric	WA
Knitted abaya fabric	KA

Table 6.2 Fabric particulars of clothing ensembles

Clothing Code	Garment mass (g)	Thickness (mm)
Bra	87	0.64
Panties	17	0.52
SH	157	0.26
SK	349	0.51
SL	443	0.79
SC	121	0.22
WAOH	349	0.17
WATS	276	0.17
WALS	250	0.17

KAOH	802	0.50
KATS	587	0.50
KALS	652	0.50

**Inner garment (daily wear clothing (DWC))**



**Manikin wearing underwear (U)**



**Long sleeve shirt with skirt (SH+SK)**



**Long sleeve shirt with slacks (SH+SL)**

**Outer garment (abaya)**

**Woven (WA) and knitted (KA) fabrics**



**Abaya worn from shoulder with tight sleeve (TS)**



**Abaya worn from shoulder with loose sleeve (LS)**



**Abaya worn from top of the head with tight sleeve (OH)**

Figure 6.2 Daily-wear clothes with the combination of three abaya designs produced from either woven or knitted fabrics with scarf.

## 6.2.2 Three-dimensional (3D) body scanning

Three-dimensional (3D) body scanning technology was applied to measure the air gap layers between the outmost clothing and a clothed manikin as described in Section 3.6.5.

After superimposing the data from two scans, the data were processed by evenly slicing the surface of the scanning body from the head to ankle in cross-section. The distance between each slice was 7.50 cm. Figure 6.3 shows the body separation according to the slices. The next step was to import the data from the KX-16 scan system into the Rhino software to extract the cross-section of the body, and to compare it with the cross-section of the clothing within the abaya. In this study, two cross-section pairs in the slice positions 7 and 20 (bust and calves), as shown in Figure 6.3, were taken to investigate the distribution of air gaps. The normal distance between two contour lines of cross-section pairs is the air gap. The thickness of the air gap was calculated by the average of the air gaps between each layer.



Figure 6.3 Schematic of body separation.

## **6.2.3 Temperature logging**

The temperature logging was used to measure the temperature on the inner surface of the DWC and in between the DWC and the abaya, and then at the outer surface of the abaya under dry conditions as described in Section 3.6.6. The sensors were applied to the unclothed manikin and then U, after that with DWC (SH+SK/SH+SL) and finally to an abaya with DWC. Temperatures were taken at 10 to 12 locations on the body, allowing differentiation between the front and the back. Temperatures of the sensors were recorded every 30 seconds. The length of each experiment was typically 45 min. The 45 min duration was set to allow sufficient time for the manikin within the abaya combination to reach a steady-state condition.

## **6.2.4 Sweating thermal manikin**

### **6.2.4.1 Manikin testing procedure**

The thermal properties of the clothing were determined using the sweating thermal manikin as described in Section 3.6.4. Dry thermal and evaporative resistances are the two most important parameters for thermal comfort. Figure 6.4 shows the experimental design of the manikin procedure with the DWC and abaya combination.

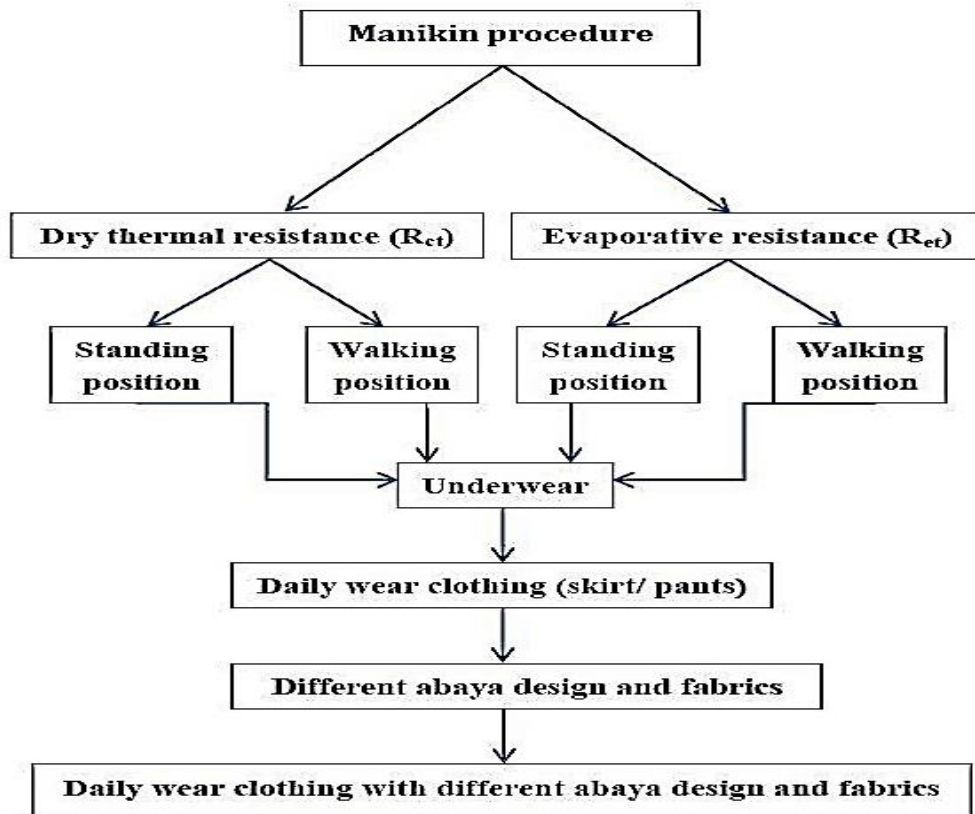


Figure 6.4 Design outline for manikin testing.

In order to simulate the real situations of daily life, tests were conducted using clothing ensembles within the abaya under both the stationary (standing) and the motion (walking) modes (Figure 6.5). The manikin used can generate smooth, realistic walking movements in compliance with EN 342.



Figure 6.5 Female thermal manikin in walking mode.

### **6.2.5 Dry thermal resistance $R_{ct}$**

The mean skin temperature of the unclothed manikin was maintained at  $35 \pm 0.3^\circ \text{C}$ . The manikin testing was done at ambient conditions of  $23^\circ \text{C}$  and 50% RH with a room air velocity of  $0.4 \pm 0.1 \text{ m/s}$ . The manikin used could not operate at ambient temperature of  $35^\circ \text{C}$  or above. Also, the manikin was tested without the presence of wind blowing across its body. All garments were preconditioned in the environmental chamber at the conditions they were to be tested in for a minimum of 12 hours before testing. This ensured that the manikin temperatures stabilised more quickly. During the experiment, the computer software (ThermDAC8) recorded the skin temperature and the power requirement for each manikin zone as well as the ambient temperature around the manikin.

### **6.2.6 Evaporative resistance $R_{et}$**

Wet tests were conducted under isothermal conditions, that is, the ambient temperature of the climate chamber, and the mean skin temperature of the manikin were set to  $35 \pm 0.5^\circ \text{C}$  and the RH to  $40 \pm 2\%$ . An attempt to test the manikin in the actual conditions in Saudi Arabia (e.g.  $45^\circ \text{C}$ , 70% RH) was unsuccessful because the manikin was unable to evaporate enough water from some zones of its body to keep it from rising above  $35^\circ \text{C}$ . The tests were repeated without the presence of wind blowing across the manikin body.

In order to provide an evaporative surface, the manikin skin consisted of a thin stretch cotton layer on top of the heating layer. The skin was wetted before dressing and acted as a 'sweating skin layer'. The skin suit was pre-wetted by spraying distilled water to simulate skin saturated with sweat. In addition to this pre-wetting procedure, the wet-unclothed test, without clothing, was run for about one hour with a different perspiration rate of each zone according to the method supplied by Measurement Technology Northwest [108] (Table 6.3).



During the wet test, the total perspiration rate of the manikin was set to 440 ml/ (hr.m<sup>2</sup>) to keep the surface of the manikin moist. The wet-unclothed tests were performed before the wet-test in order to evenly distribute the moisture over the skin to simulate skin saturated with sweat.

Table 6.3. Perspiration rate of the manikin zone.\*

<b>Region</b>	<b>Flow Rate ml/(hr.m<sup>2</sup>)</b>
Head/face	1100
Upper torso	400
Lower torso	300
Upper arms	400
Forearms	300
Hands	900
Upper thighs	400
Lower thighs	300
Calves	300
<b>Total</b>	<b>440</b>

Note 1: \* Data in Table 6.3 were supplied by Measurement Technology Northwest.

The experiment duration varied depending on how long it took for the temperature and heating power of each zone to stabilise. Measurements were taken for 45 min after dressing the manikin with the clothing ensemble underneath the abaya. Before and after each test, the DWC and abaya were weighed on a digital scale (accurate to 0.01 g). This was performed for every test, since the accumulation of moisture in the garments is an important variable in wet testing. During the experiment, the computer software recorded the skin temperature and power requirement for each manikin section, as well as the ambient temperature around the manikin.

### **6.2.7 Data analysis**

Data analysis was performed using SPSS 21. A three-way factorial analysis of variance (ANOVA) was performed to test the effect of fabrics. DWC and different design of the

abaya on mean thermal and evaporative resistance in the stationary and motion modes. The first factor, fabric, had two levels: woven and knitted. The second factor, DWC, had three levels: AO, SK and SL. The design of abaya factor also had three different types: TS, OH and LS. In addition, Sperman's correlation coefficient was used to evaluate the correlation between air gap and  $R_{ct}$  and  $R_{et}$  in the abaya combinations to examine whether the differences between the abaya combinations with clothing in the manikin test were significant at  $p > 0.001$ .

## **6.3 Results and discussion**

### **6.3.1 Thermal and evaporative resistance in the stationary and the motion modes**

The results of the total thermal and evaporative resistance within the clothing of U, manikins covered with DWC and different abaya combinations, when stationary and in motion in the conditioned surroundings, are given in Figure 6.6 to Figure 6.32. The Table result  $R_{ct}$  and  $R_{et}$  of DWC and DWC (U+SH+SK/ U+SH+SL) with the different designs (TS, OH and LS) of the woven and knitted fabrics of were given in (Appendix E) in (Table E 1 to Table E 3). The coefficients of variation of values from repeated tests were generally less than 4%.

#### **6.3.1.1 Head group**

Figure 6.6 shows the head group, which covered only the head and not the face. The head  $R_{ct}$  and  $R_{et}$  of DWC and DWC (U+SH+SK/ U+SH+SL) with the different designs (TS, OH and LS) of the woven and knitted fabrics were measured. Figure 6.7 to Figure 6.10 illustrate the  $R_{ct}$  and  $R_{et}$  values of the DWC, AO and abaya combinations in the stationary and walking modes. The surface temperature of the skin fabric and the daily-wear clothing (U +SH+ SK/ U +SH+ SL) and abaya combinations, temperatures logging and thermal imaging were used as shown in Figure 6.11 and Figure 6.12.

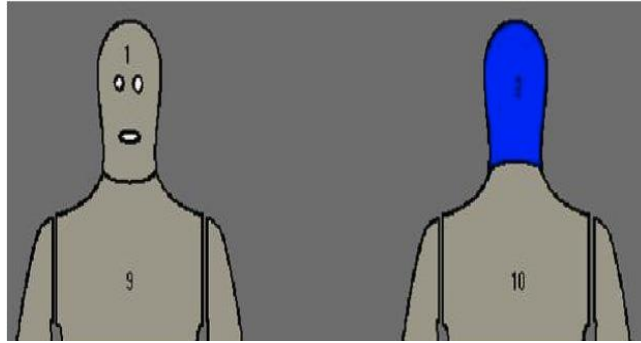


Figure 6.6 Head group.

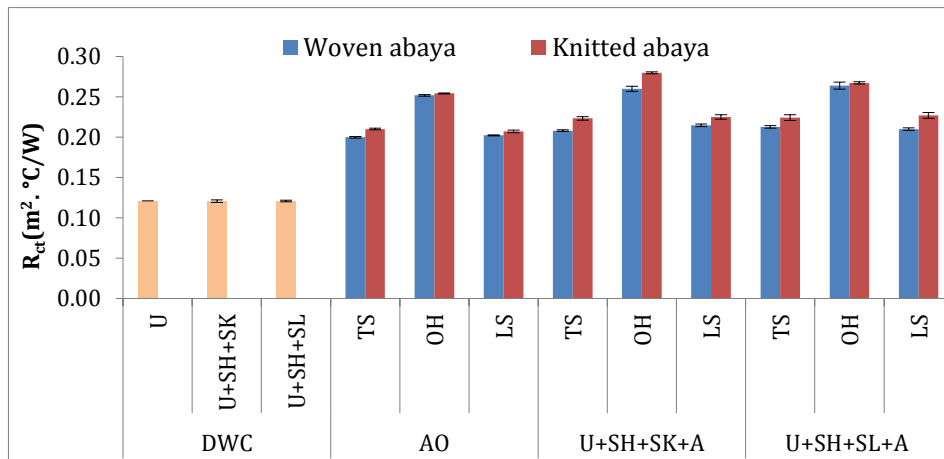


Figure 6.7 Thermal resistance of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the head group and in the stationary mode.

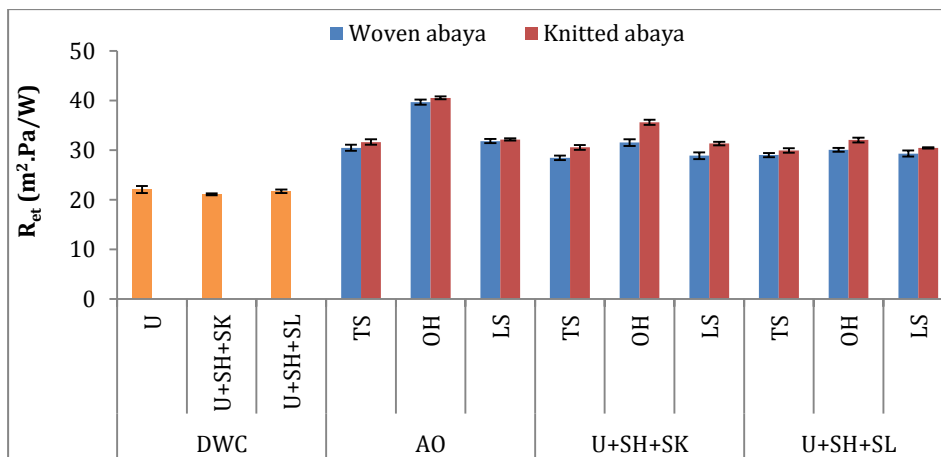


Figure 6.8 Evaporative resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the head group and in the stationary mode.

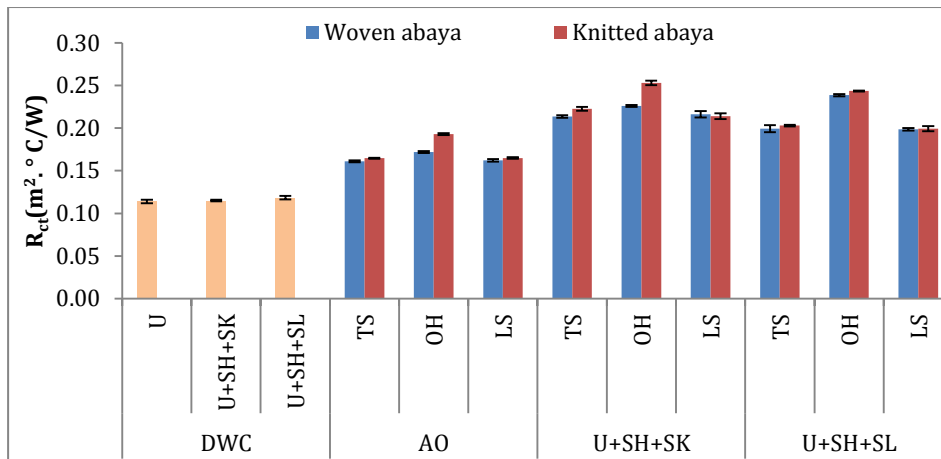


Figure 6.9 Thermal resistance of DWC, abaya only and DWC with different abaya designs of woven abaya fabric and knitted abaya fabric head group and in the motion mode.

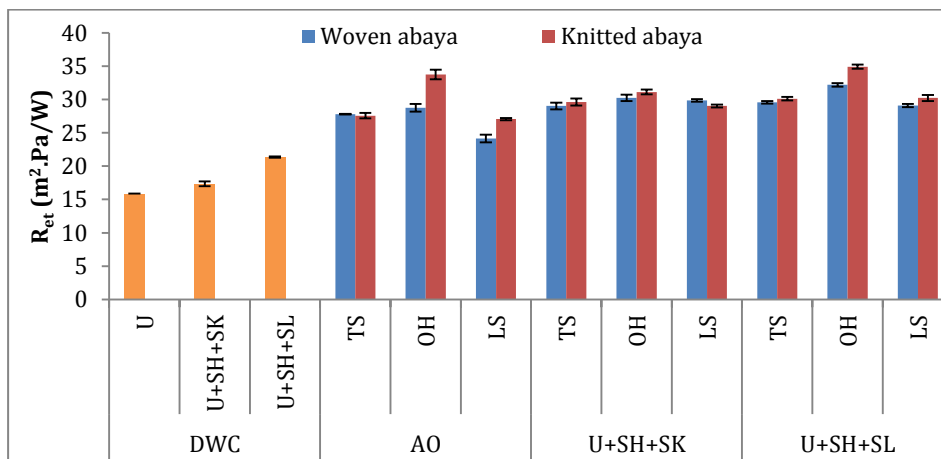


Figure 6.10 Evaporative resistance values of DWC, abaya only and DWC with different design of woven abaya fabric and knitted abaya fabric in head group in the motion mode.

### Stationary mode

The total values of  $R_{ct}$  and  $R_{et}$  increased as the layers increased. The overall test of the factorial ANOVA analysis was statistically significant in  $R_{ct}$ ,  $F(4, 36) = 40.88$ ,  $p < 0.001$ . The triple interaction effect for fabric by clothing design was statistically significant,  $F(4, 36) = 40.88$ ,  $p < 0.001$ . This means that the abaya combination with DWC (U, U+SH+SK and U+SH+SL) and abaya only (AO) had a higher  $R_{ct}$  and  $R_{et}$  than the DWC (U, U+SH+SK and U+SH+PA) by itself, as can be seen from Figure 6.7 and Figure 6.8.

The reason for increased the values of  $R_{ct}$  and  $R_{et}$  in head and abaya group were that the scarf was wrapped in two layers around the head while there was no scarf in the DWC. In addition, the abaya worn on head (OH) gave significantly higher  $R_{ct}$  and  $R_{et}$  values when compared to that worn from the shoulder with tight sleeves (TS) or lose sleeves (LS), because the former has three layers, two from the scarf and the third one from the abaya worn on head (OH). This result confirmed with the surface temperature of the manikin head measured first unclothed, then the scarf was added, and the temperature was measured between the scarf and the abaya worn on top of the head. Figure 6.11 and Figure 6.12 shows that the surface temperature of the manikin head without the abaya was 34° C and when the scarf was present, the temperature decreased to 28.7° C. It is clear that the skin surface temperature decreased when the layers of clothing increased. Due to the multiple layers of scarf and abaya, 34% of women feel heat stress in the neck area of the body, as described in Chapter 2. This means that the scarf worn with the abaya from the top of the head (three layers) led to decreased skin temperatures. This is because there was more thermal insulation from the head to the outside due to the multiple layers of fabric and the air gaps between the layers.

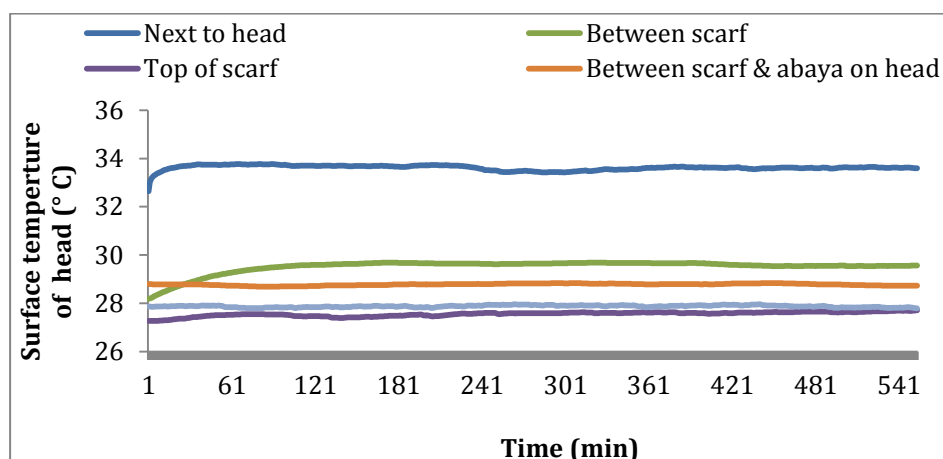


Figure 6.11 Surface temperatures of the manikin head.

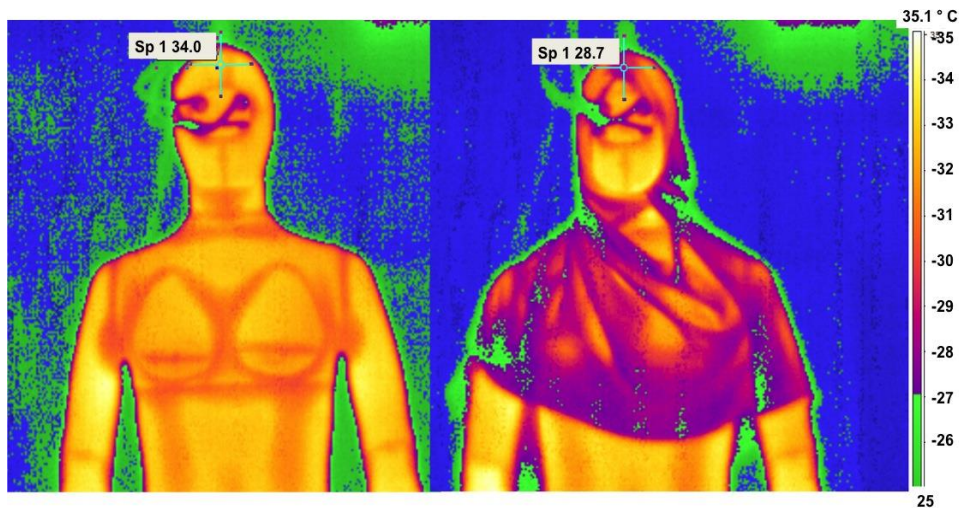


Figure 6.12 Thermal imaging on the unclothed manikin head: a) without scarf; b) with scarf.

The  $R_{ct}$  value ranged from  $0.12 \text{ m}^2 \cdot ^\circ \text{C}/\text{W}$  on the unclothed head to  $0.25 \text{ m}^2 \cdot ^\circ \text{C}/\text{W}$  in the presence of the scarf, which was similar to the scope of  $R_{ct}$  ranging from  $0.1 \text{ m}^2 \cdot ^\circ \text{C}/\text{W}$  for the surface of the unclothed body (head) to  $0.2 \text{ m}^2 \cdot ^\circ \text{C}/\text{W}$  for the helmet test as reported by Pang et al. [45]. In addition, Al-ajmi et al. [11] found that the  $R_{ct}$  values ranged between  $0.12 \text{ m}^2 \cdot ^\circ \text{C}/\text{W}$  without covering the head, to  $0.21 \text{ m}^2 \cdot ^\circ \text{C}/\text{W}$  when covering the head with a scarf. Moreover, McCullough et al. [192] reported that adding a hat to a relatively warm ensemble has a major effect on  $R_{ct}$ . Since the rest of the body is well insulated, much of the heat loss is from the head and the hat blocks the heat loss.

### **Motion mode**

The  $R_{ct}$  values for the head in the motion mode (Figure 6.9) decreased significantly compared to the stationary mode for DWC, abaya only (AO) and DWC with different abaya designs and fabrics. The triple interaction effect for fabrics by DWC and different abaya design was statistically significant,  $F(4, 36) = 15.66, p < 0.001$ . This could be because the scarf was thin and the fabric was breathable, which can enable transfer of heat from the inside to the outside easily when walking.

In contrast, the  $R_{et}$  value in the motion mode was slightly lower than that in the stationary mode, in the head group, as shown in Figure 6.10. A possible reason is that the water captured within the 'skin' suit can either diffuse through the scarf or escape through the scarf as vapour condensation within the abaya.

### 6.3.1.2 Torso group

Figure 6.13 shows the torso group, which consists of the chest, back and arms without hands. The cross-section of the bust as presented in Figure 6.14 and Table 6.4 shows the air gap thickness between the three layers, which were bra, shirt and abaya. Figure 6.15 to Figure 6.18 shows the  $R_{ct}$  and  $R_{et}$  values of the DWC, abaya only (AO) and abaya combination with the clothing in the stationary and the motion modes.

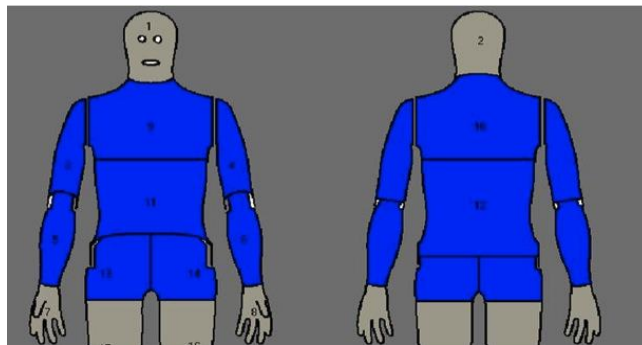


Figure 6.13 The torso group.

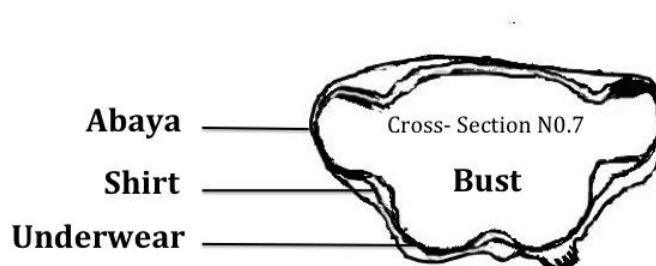


Figure 6.14 Air gap thickness in the torso (bust) area of the body cross-section.

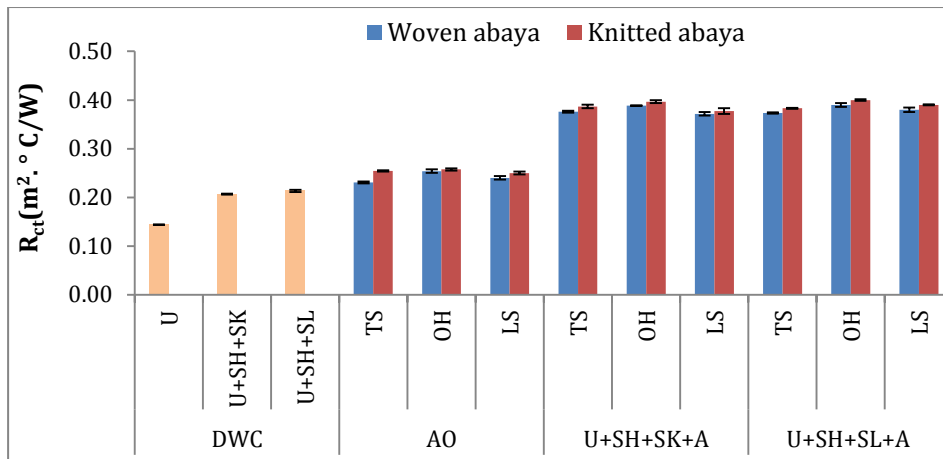


Figure 6.15 Thermal resistance values of DWC, abaya only and DWC with different abaya designs of the woven and knitted fabrics in the torso group in the stationary mode.

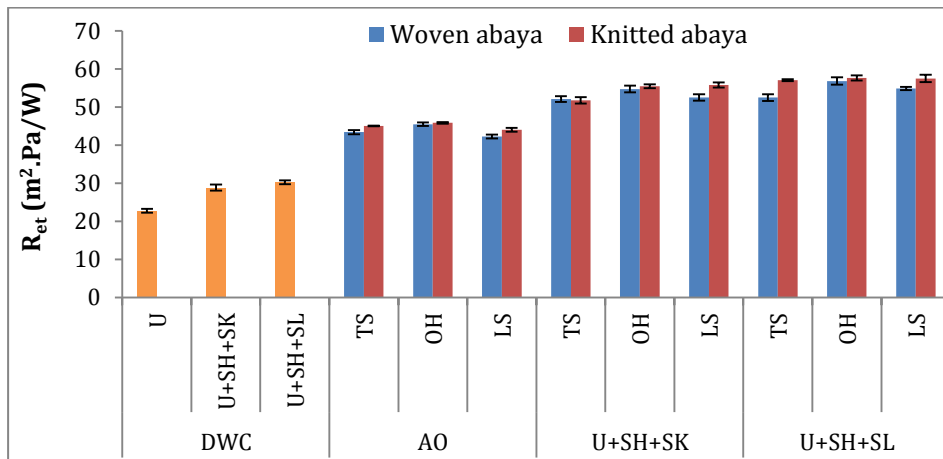


Figure 6.16 Evaporative resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the torso group in the stationary mode.

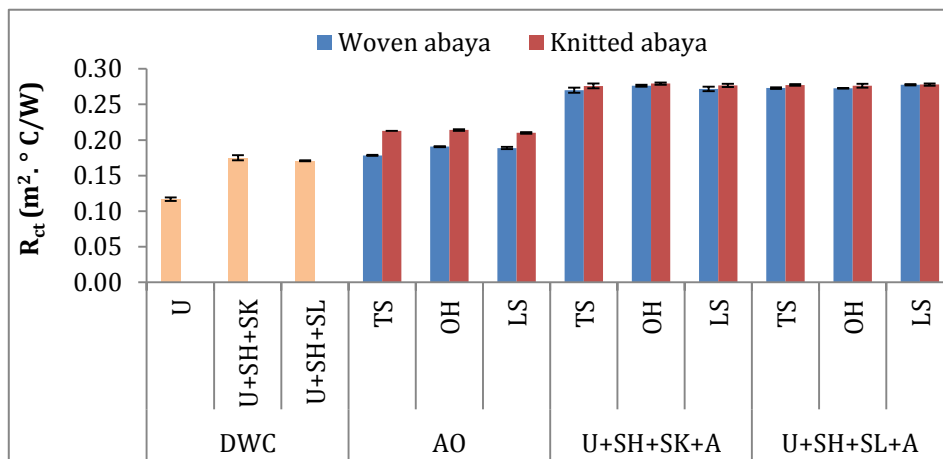


Figure 6.17 Thermal resistance values of DWC, AO and DWC with different abaya designs of the woven and knitted fabrics in the torso group in the motion mode.



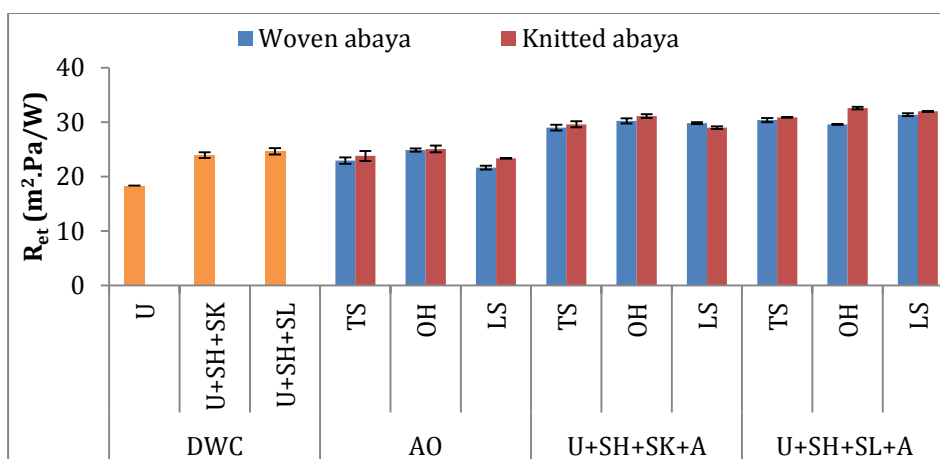


Figure 6.18 Evaporative resistance values of DWC, AO and DWC with different designs of the woven and knitted fabrics in the torso group and in the motion mode.

### Stationary mode

The estimated marginal means of  $R_{ct}$  and  $R_{et}$  values and the 95% confidence interval (CI) shown in Figure 6.15 and in (Appendix E) indicate that the abaya combination with U+SH+SK and U+SH+SL had statistically significantly higher  $R_{ct}$  values,  $F(4, 36) = 37.71$ ,  $p < 0.001$  and  $R_{et}$  values,  $F(4, 36) = 35.82$ ,  $p < 0.001$ , compared with abaya only (AO) and DWC. This is because the torso was covered with three layers or more in some parts of the body, especially the chest area (bra, shirt, abaya and scarf). In addition, the thickness of the bra was greater than those of the shirt and the woven abaya fabric (

Table 6.2).

The higher  $R_{ct}$  value in the abaya combinations agree with the survey results in that 30% of women complained about heat stress in the chest area (Chapter 2). The distance between each layer was the average of the air gap thickness as presented in Table 6.4. It was found that the air gap thickness between each layer was small (Figure 6.14). This might be due to the fact that the chest and upper part of the back are the areas of the body that tend to be touched by the clothing. This result is similar to those reported by Lu et al. [193] and Zhang et al. [194], that the smaller air gap thickness at the bust might be related to convex body geometry. Clothing normally hangs from the shoulders, and this might

block the air ventilation between the garment and the body [36]. The multilayers of fabric in the chest area create a high  $R_{ct}$  and  $R_{et}$  hence more heat stress. In addition, more layers create additional pockets of still air, resulting in high thermal insulation compared to a single layer of fabric [195]. As suggested by McCullough [100], adding clothing to a particular area of the body will reduce the heat loss only from that area and will have no effect on the other areas. Therefore, the torso group shows a generally higher  $R_{ct}$  and  $R_{et}$  values than those of the other groups.

Table 6.4 Air gap thickness in bust and calves cross- section

Clothing	Air gap thickness (mm)	
	Bust $\pm$ std	Calves $\pm$ std
U+SH+ SK	26.04 $\pm$ 1.12	53.49 $\pm$ 4.42
U+SH+ SL	26.04 $\pm$ 1.12	29.69 $\pm$ 0.99
U+SH+SK+A	31.71 $\pm$ 0.66	64.57 $\pm$ 1.81
U+SH+SL+A	32.03 $\pm$ 1.40	84.55 $\pm$ 2.76

The interaction effect of DWC and AO decreases significantly in  $R_{ct}$ ,  $F(2, 36) = 12897.91$ ,  $p < 0.001$  compared with the abaya combination with U+SH+SK and U+SH+SL, as shown in Figure 6.15. This could be because the abaya was shaped to fit loosely in the chest area, which creates an air gap in addition to the female convex body geometry [193]. Natural convection appears to exist even within the smallest air gaps of the standing mode of the manikin [196]. Moreover, when fabrics are made into clothing, the air gaps between the skin and clothing influence the  $R_{ct}$  value more than the intrinsic thermal insulation of the fabrics [197]. From this point of view, the fabric selection for abayas appears less important than abaya design.

In comparison, the higher the  $R_{et}$ , the less permeable the clothing is to transfer moisture. In DWC, the  $R_{et}$  interaction value shows significantly lower  $F(2,36) = 1538.385$ ,  $p < 0.001$ , compared with the abaya combination  $F(2, 36) = 17.89$ ,  $p < 0.001$ . The main reason for this difference between  $R_{et}$  values in DWC and abaya combinations is that DWC had two

layers, both clothing layers (U and SH) had a higher content of cotton (being very hygroscopic), which absorbs more moisture as everyday clothing worn for normal wear, when compared to polyester fabrics, which have very poor moisture-absorbing capability. AO had slightly higher  $R_{et}$  values than DWC even though DWC had two layers. AO had one layer and some part of the scarf covered the chest area. As a result, air gaps were large due to the drape of the fabric, which hung the fabric away from the body and slowed the moisture evaporation through the fabric to the environment.

### **Motion mode**

The  $R_{ct}$  and  $R_{et}$  values of DWC, abaya only (AO) and DWC with different designs of the woven and knitted fabrics in the torso group, in the motion mode are shown in Figure 6.17 and in Appendix E. The triple interaction effect for DWC with the different designs of the woven and knitted fabrics were statistically significant,  $F(4, 36) = 11.25, p < 0.001$ . It is obvious that  $R_{ct}$  and  $R_{et}$  values decrease significantly for around 16- 19% of DWC and 30 to 45% of DWC with different designs of the woven and knitted fabrics when compared with the stationary mode. This might be because many openings (Figure 6.19) in the front area of the shirt and abaya enhance ventilation of the enclosed air that is in contact with the human body surface, thereby contributing to the wearer feeling slightly more comfortable [11].

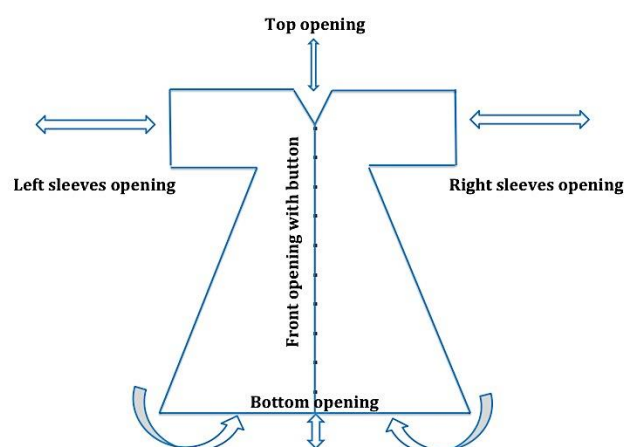


Figure 6.19 Sketch of an abaya showing openings

The correlation analysis results show that the correlation between the  $R_{ct}$  of the torso and the air gap thickness in the stationary and the motion modes was significant,  $r = -0.58$ ,  $p < 0.001$ . The experimental results demonstrate that the  $R_{ct}$  of the torso area with clothing and an abaya decreased with increased air gap thickness. However, there was no correlation between the  $R_{et}$  values of the torso and the air gap thickness in the stationary mode  $r = 0.63$ , ( $p < 0.001$ ), whereas in the motion mode there was a significant relation between the air gap and  $R_{et}$ .

### 6.3.1.3 Lower torso group

Figure 6.20 shows the lower torso group, which consists of the hips and legs. The cross-section of the lower torso as presented in Figure 6.21 and Table 6.4 shows the air gap thickness between the calves and DWC inside the abaya. Figure 6.22 to Figure 6.25 and Appendix E illustrate the  $R_{ct}$  and  $R_{et}$  values of DWC, AO and abaya combinations with the clothing in the stationary and the motion modes. Figure 6.26 shows the skin surface temperature of the lower torso with different layers of clothing and Figure 6.27 shows the thermal imaging on manikin: a) skirt, b) slacks, c) abaya.

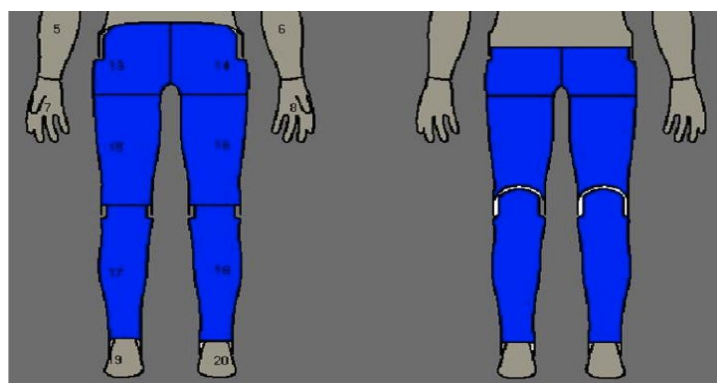


Figure 6.20 Lower torso group.

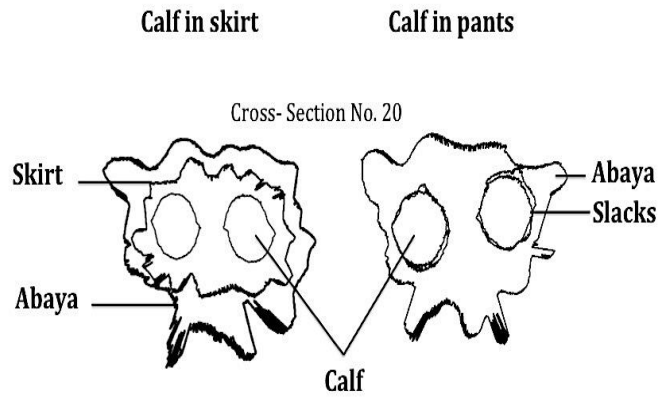


Figure 6.21 Air gap thickness in the lower torso (calf) area of the body cross-section.

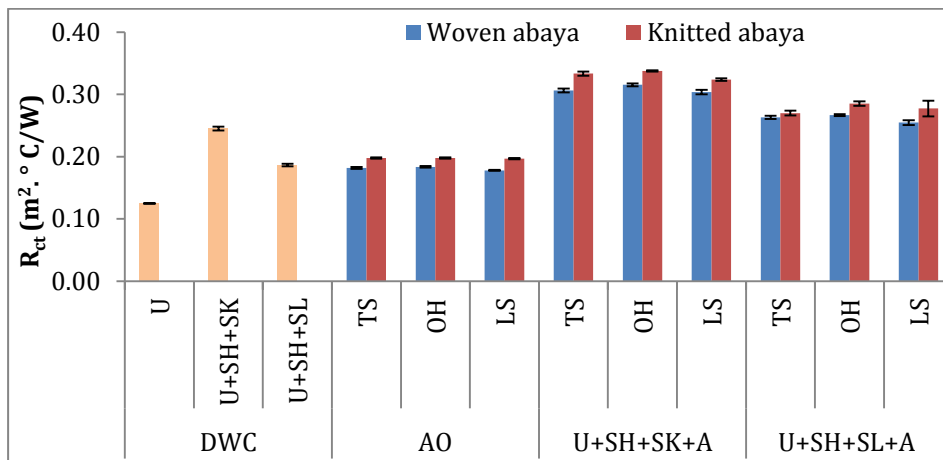


Figure 6.22 Thermal resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the lower torso group and in the stationary mode.

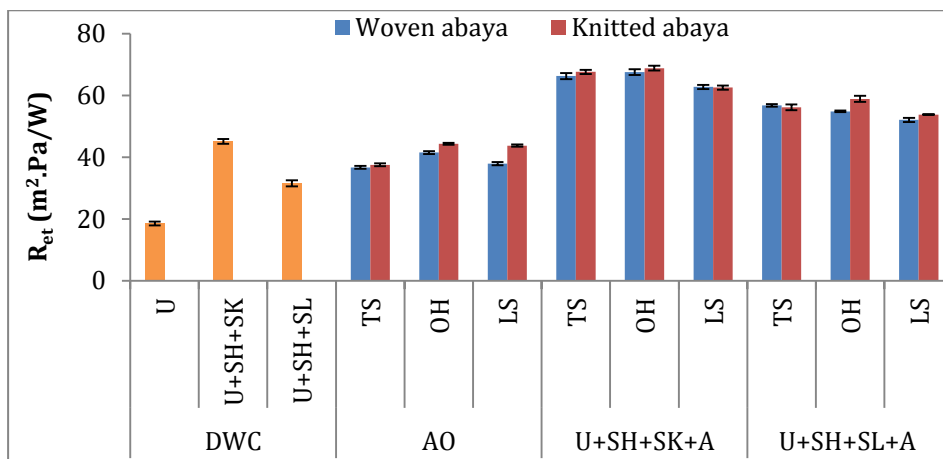


Figure 6.23 Evaporative resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the lower torso group and in the stationary mode.

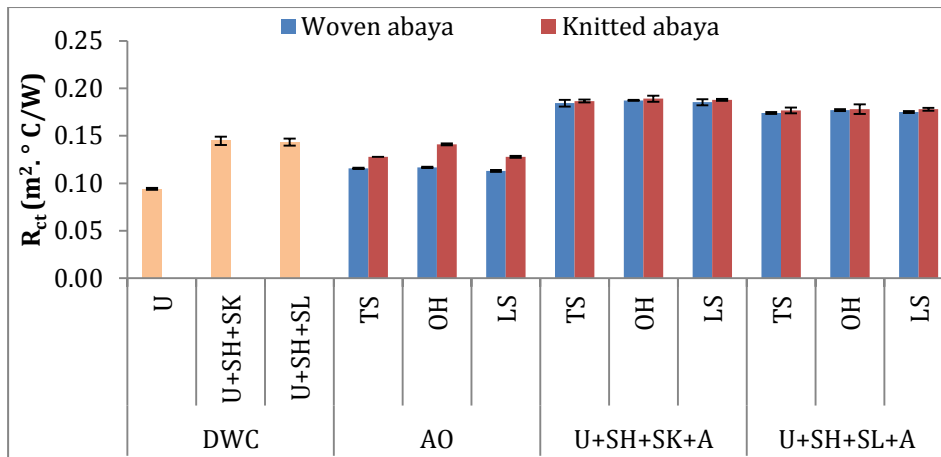


Figure 6.24 Thermal resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the lower torso group and in the motion mode.

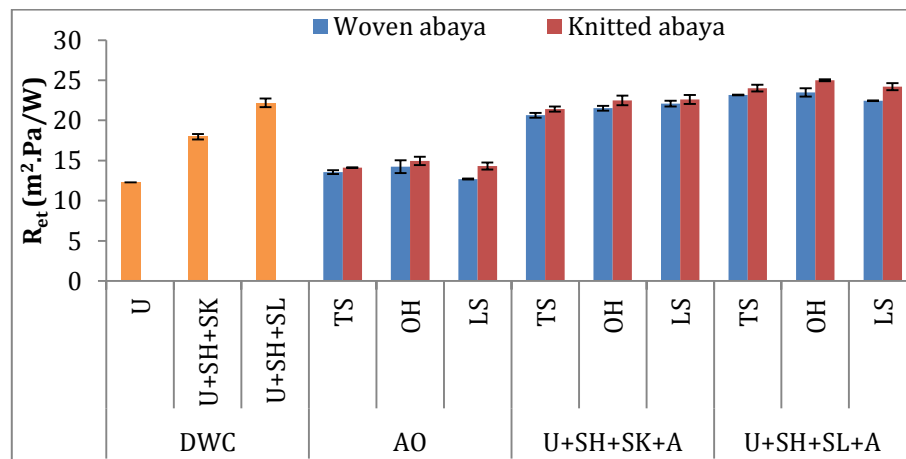


Figure 6.25 Evaporative resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the lower torso group and in the motion mode.

### Stationary mode

The  $R_{ct}$  and  $R_{et}$  values in the lower torso with U+SH+SK and U+SH+SK+A interactions were statistically significantly higher  $R_{ct}$ ,  $F(4, 36) = 4.05$ ,  $p < 0.001$ , and higher  $R_{et}$   $F(2, 36) = 78.67$ ,  $p < 0.001$ , than with abaya only (AO) and U+SH+SL+A, as presented in Figure 6.22 and Figure 6.23. This could be because the thickness of SL was higher compared to SK, with the woven and knitted fabrics (

Table 6.2), although slacks were held tight to the thigh and therefore there was high radiation loss. Garment fit has always been considered one of the elements that influences

thermal insulation [2]. McCullough et al. [144] found that loose garments provide more insulation in static conditions because of the large air gaps between the body and garment layers. From this study, the skirt was not in contact with the body, which provided a high  $R_{ct}$  and  $R_{et}$  because the air gap was large. The amount of body surface area covered in the skirt worn with an abaya was small compared with the slacks. This indicates that adding layers decreased fabric drape and clothing folds, resulting in an increase in the average air gap within the abaya [193]. The slacks had a small air gap with the skin but the SL and the abaya had a large air gap in between them (Figure 6.21). These results agree with McCullough et al. [192] who found that loose-fit trousers provided higher insulation than tight-fit trousers (0.34 clo and 0.24 clo respectively) by comparing tight-fit and relatively loose-fit long trousers. In the loose garment, which is the skirt, the  $R_{ct}$  has 0.25 clo and in the tight fit, which is the slacks, the  $R_{ct}$  has 0.19 clo. By comparing each DWC with an abaya, the  $R_{ct}$  was found to be 0.30 clo and 0.27 clo, respectively.

In addition, the lower torso (hip, thigh and calf) showed large air gaps in SK and U+SH+SK+A and U+SH+SL combinations because the abaya creates large air gaps, as presented in Figure 6.21 and Table 6.4. In fact, a large air gap was observed at the legs and abdomen, a result that agrees with that of Lu et al. [193], who found that the air gaps on the right posterior thigh and both anterior calves were obviously higher than those on other parts. The air gap of the convex area where the clothing closely fits to the body was smaller than that of the concave area (Figure 6.14 and Figure 6.21). An increase in garment size will increase the air gap; hence the abaya size could be considered in order to manage thermal comfort in future research. For fabrics, the  $R_{et}$  value is dependent on the enclosed air and the density of the construction [41]. Additionally, tight fitting minimises air circulation between skin and clothing. Also, because the pants were worn next to the skin, they absorbed more moisture and had a higher content of cotton (being very hygroscopic). Therefore, the slacks had a lower  $R_{et}$  value than skirt.

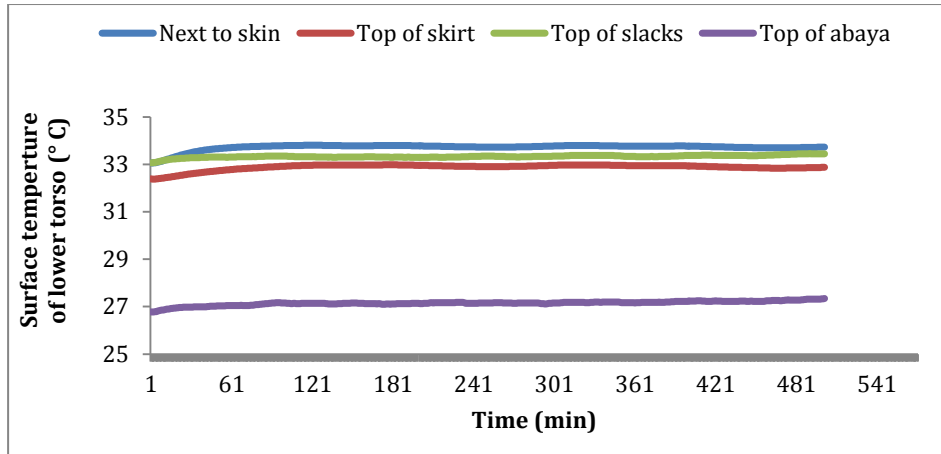


Figure 6.26 Skin surface temperature of the lower torso with different layers of clothing.

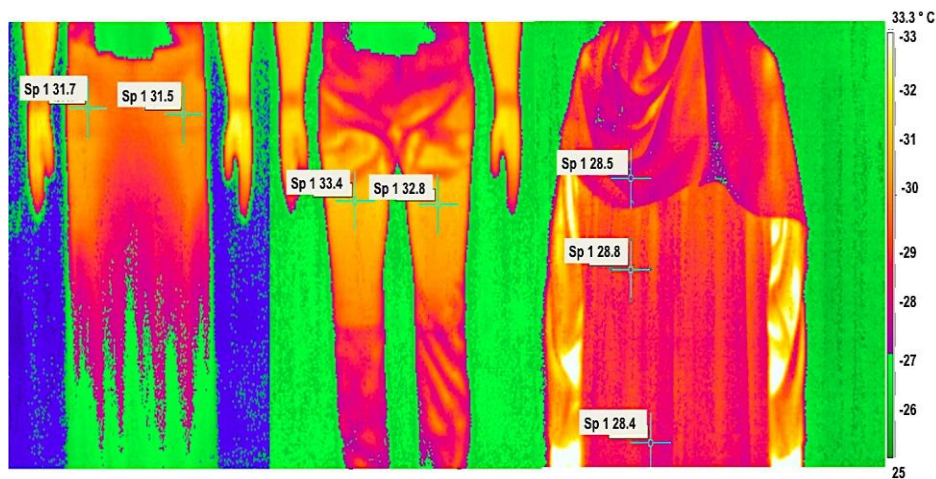


Figure 6.27 Thermal imaging on manikin: a) skirt, b) slacks, c) abaya.

In Figure 6.26 the clothing surface temperature of the lower torso in the abaya combinations with DWC decreased with more clothing items. This result conforms with the thermal imaging of the manikin when dressed with skirt, slacks and then abaya as illustrated in Figure 6.27. On the lower torso, the slacks had a slightly lower temperature. This could have been because the slacks were very close to the thigh, so the heat transfer from the thigh (skin) was similar to the heat transfer from the slacks (Figure 6.27 b), whereas the surface temperature on the skirt was lower than that on the slacks. This indicates that the lower surface temperature might be explained by the large air gap between the thigh and the skirt as shown in Figure 6.27 a. The lowest apparent



temperatures among all garments were found in the presence of the abayas (Figure 6.27 c). This was probably because the large air gaps between the clothing and the abaya blocked the heat transfer from the skin to the clothing surface and to the abaya. This result agrees with that of Zhang and Li [198], who found that the clothing temperature and heat flux decreased with garment size, while the thermal insulation increased as the air blocked the heat transfer from skin to a clothing surface.

### **Motion mode**

The  $R_{ct}$  values in the motion mode were significantly decreased compared with the stationary mode, which was around 43% in U+SH+SK and U+SH+SK with the woven and knitted abaya fabrics, and around 36% in U+SL and U+SL with the woven and knitted fabrics respectively, as illustrated in Figure 6.24;  $F(4, 36) = 11.25, p < 0.001$ . It is obvious that the  $R_{et}$  values in the motion mode were lower than in the stationary mode (Figure 6.25). In addition, U+SH+SL and U+SH+SL with abaya combination had lower  $R_{et}$  values, around 30% for U+SH+SL and around 55 to 59.19% in abaya combination (the woven abaya fabric and knitted abaya fabric) than U+SH+SK around 60% and abaya combination with U+SH+SK, around 64.0 to 68.9%.

During movement of the lower torso, the thigh or calf had a lower  $R_{ct}$  and  $R_{et}$  than other parts of the body. The SK and the abaya had a large air gap and loosely fitted to the body; as a result, the air would be pumped during walking to circulate between the body and the garment layers, through pores in the fabrics and through garment openings (bottom opening), causing convection losses compared to U+SH+SL. These openings are: in the front from chest opening between buttons/snaps, to the sides from both hands and a downward opening, as shown in Figure 6.19. The  $R_{ct}$  can be dramatically decreased by body motion due to air being forced in and out of the microenvironment. This becomes more critical as the air permeability of the clothing decreases. Clothing movement helps to move stagnant air out of the microenvironment, allowing ambient air to circulate [199,

200]. The air movement between the body and clothing within the abaya allowed more air to release heat from the body to the environment. This agrees with McCullough [100, 192], who proposed that the effect of clothing fit on heat transfer depends on body modes and movement.

The correlation analysis results show that the correlation between the  $R_{ct}$  of the lower torso and the air gap thickness in the stationary and the motion modes was significant,  $p < 0.001$ . The experimental results demonstrate that the  $R_{ct}$  of the torso area with clothing and an abaya decreased with increased air gap thickness. However, the  $R_{et}$  values of the torso and the air gap thickness in the stationary mode were not significant,  $p < 0.001$ , whereas in the motion mode there was a significant relation between the air gap and the  $R_{et}$ .

#### 6.3.1.4 The abaya group

Figure 6.28 shows the abaya group, which consisted of the entire manikin except the face and hands (body fully covered with the abaya). This group relates to the  $R_{ct}$  and  $R_{et}$  of daily-wear clothing with an abaya in combination Figure 6.29 to Figure 6.32 and (Appendix E) shows the  $R_{ct}$  and  $R_{et}$  of DWC, abaya only and abaya combinations with the clothing in the stationary and the motion modes.

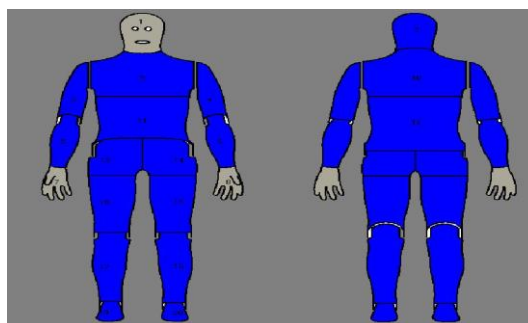


Figure 6.28 The abaya group (body fully covered with abaya).

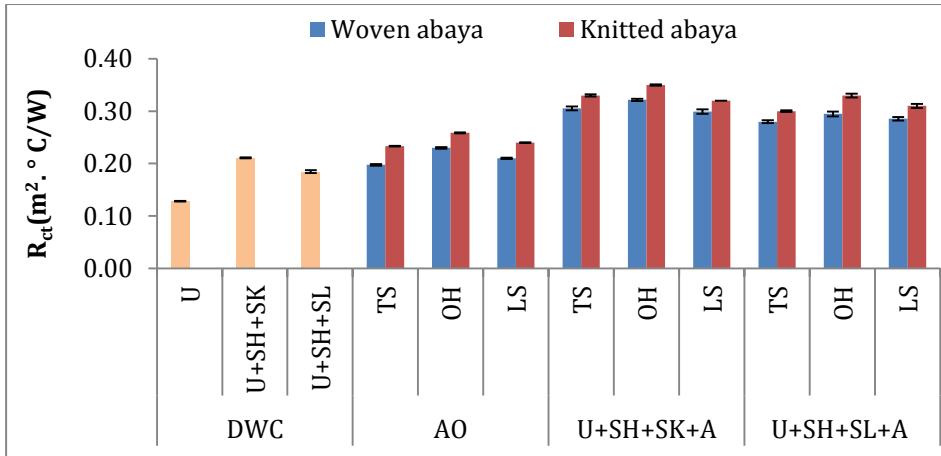


Figure 6.29 Thermal resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the abaya group in the stationary mode.

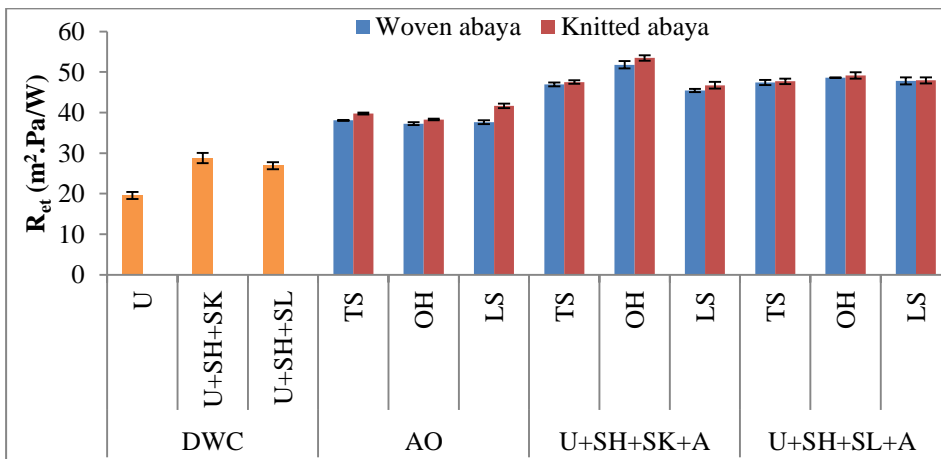


Figure 6.30 Evaporative resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in the abaya group and in the stationary mode.

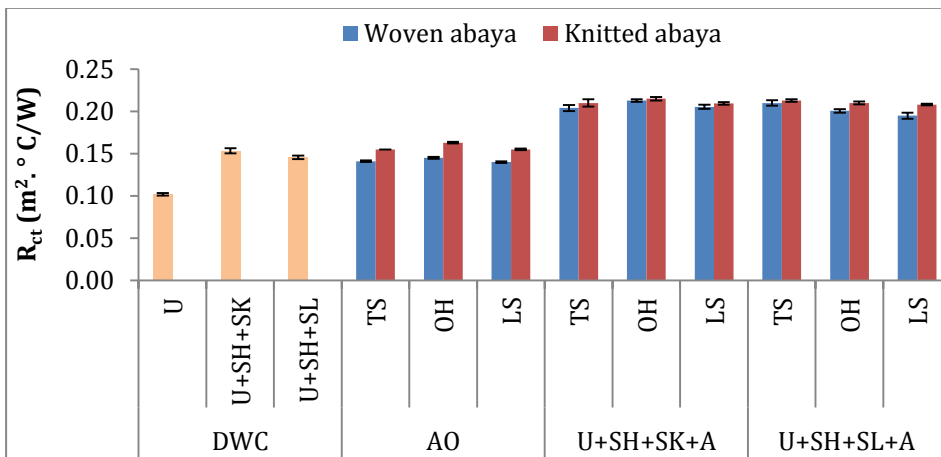


Figure 6.31 Thermal resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in abaya group in the motion mode.

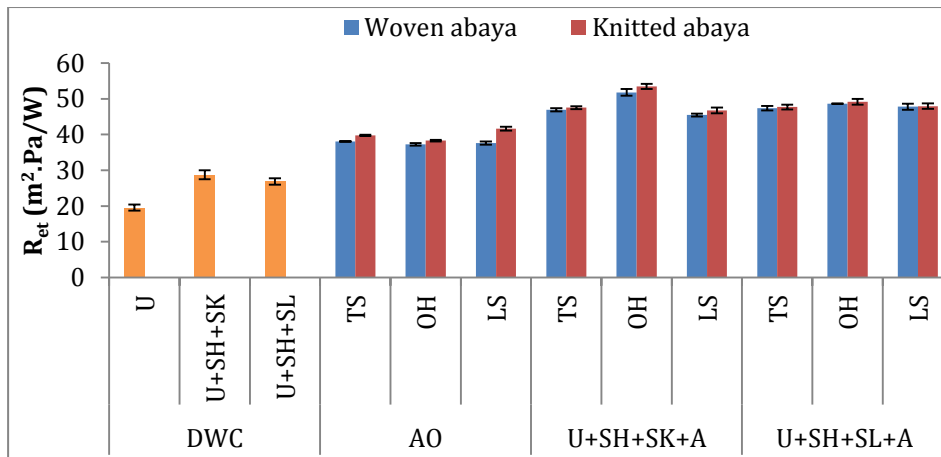


Figure 6.32 Evaporative resistance values of DWC, abaya only and DWC with different designs of the woven and knitted fabrics in abaya group in the motion mode.

### Stationary mode

The effect of the design and the abaya fabric (woven and knitted) interaction was statically significant in  $R_{ct}$ ,  $F(2, 36) = 17.32$ ,  $p < 0.001$ , and  $R_{et}$ ,  $F(2, 36) = 35.09$ ,  $p < .001$ . It can be observed from Figure 6.29 that when comparing the designs and fabrics for an abaya, wearing abaya only shows slightly, but significantly higher  $R_{ct}$  values  $F(2, 36) = 46.36$ ,  $p < 0.001$ , than wearing the abaya from the shoulder with tight and loose sleeves (Figure 6.29). According to the survey results (Chapter 2) 37% and 36% of women would like to wear an abaya from the shoulder with tight sleeves or loose sleeves, respectively. In contrast, none of the respondents liked to wear the abaya from the top of the head. This again may be due to having more layers on the head than with the abaya worn from the shoulder, as discussed earlier. Furthermore, the abaya made from the woven fabric had a significantly lower mean  $R_{ct}$  value  $F(1, 36) = 355.07$ ,  $p < 0.001$ , and  $R_{et}$  values than that made from knitted fabric. The structure of the woven fabric was satin weave and it was thin (thickness 0.17 mm) (

Table 6.2) which allowed more air and heat to pass through the fabric. The woven abaya fabric had a lower  $R_{ct}$  ( $0.0005 \text{ m}^2 \cdot \text{°C/W}$ ) and  $R_{et}$  ( $0.6725 \text{ m}^2\text{Pa/W}$ ) [137] according to the findings reported in Chapter 4.

In addition, the  $R_{ct}$  of the knitted fabric was high ( $0.0075 \text{ m}^2 \cdot \text{°C/W}$ ) and  $R_{et}$  ( $1.8597 \text{ m}^2\text{Pa/W}$ ) [138] and it had a single jersey structure with the thickness of the fabric  $0.8 \text{ mm}$ , as reported in Chapter 5. Moreover, an abaya covers about 86% of the body surface area and a scarf about 12%, when compared with the DWC, which covers only 82%, according to ISO 9920. When a fabric is made into clothing, the thermal insulation is influenced more by the air gaps between the skin and clothing than by the intrinsic thermal insulation of the fabric [197]. In this context, the abaya creates large air gaps, which provide more insulation. Therefore, an abaya contributes a significant amount to an  $R_{ct}$  and  $R_{et}$  values.

Moreover, the main effect for fabrics was not statistically significant,  $F(1, 36) = 0.4$ ,  $p = 0.531$ . The results show that knitted fabric had slightly higher  $R_{et}$  values than the woven fabric. This is due to the fact that the knitted fabric had a higher  $R_{et}$  value than the woven fabric. Also, of course, the knitted fabric had a different structure to the woven fabric.

The  $R_{et}$  of an ensemble depends on the moisture permeability characteristics and wicking properties of the component materials, in addition to the amount of skin surface covered. Fibre content has little to do with the moisture permeability of textiles as compared to their openness and the type of surface treatment [201]. According to Dlugosch et al. [202], the higher the  $R_{et}$ , the higher the resistance of the material to water vapour transmission and thermal insulation ( $R_{ct}$ ) acts to reduce the transmission, of heat. Therefore, a knitted abaya fabric is not preferred to be worn in summer but it could be preferred to be worn in cold weather.

### **Motion mode**

Figure 6.31 shows the  $R_{ct}$  and  $R_{et}$  values of DWC, abaya only (AO) and DWC with different designs of the woven and knitted fabrics during movement. The triple interaction effect for AO, U+SH+SK+A and U+SH+SL+A was statistically significant,  $F(4, 36) = 5.30$ ,  $p < 0.001$ . It can be observed that the  $R_{ct}$  and  $R_{et}$  values in AO, U+SH+SK+A and U+SH+SL+A were significantly lower, around 34 % to 53% in walking mode compared to the

stationary mode. In addition, wearing AO in both the woven and knitted fabrics has a lower  $R_{ct}$  than the combination of DWC with the woven or knitted fabric. This might be because AO has a single layer compared with multiple layers of DWC with the woven or knitted fabric. Also, the abaya is worn loosely on the body and has many openings, as shown in Figure 6.19, that enhance ventilation of enclosed still air in contact with the human body surface, thereby contributing to comfort more while walking than standing. It has been reported that as much as 75% of the total heat can be lost through openings in places like the neck, waist, wrists and ankles by bellows action when the body is moving in windy conditions [2].

In comparison, the abaya design with LS in the woven and knitted fabrics showed a lower  $R_{et}$  value in the walking mode when compared with other abaya designs. A lower value of  $R_{et}$  indicates that the design of the abaya has greater influence on the ability to release liquid and moisture through the garment. It means that the air movement between the body and clothing allows more air to transfer the moisture out into the environment.

In addition, the abaya design with LS shows slightly lower  $R_{ct}$  and  $R_{et}$  values in both U+SH+SK+A and U+SH+SL+A in the walking mode when compared with other abaya designs. This could be because moving the hands towards the body allowed air to circulate between the abaya and clothing.

Thermal insulation can be dramatically decreased by body motion due to air being forced in and out of the microenvironment [199]. It means that air movement between the body and clothing can be created and allows more air to release dry heat from the body. From Figure 6.29 to Figure 6.32, the results indicate that the woven fabrics with U+SH+SK+A were better than the knitted fabric in terms of releasing body heat to the environment. This agrees with Dlugosch et al. [202], who proposed that lower thermal insulation and lower moisture vapour resistance values indicate more heat and vapour transmission

through the garment, enhancing the heat exchange between the wearer and the environment.

### 6.3.1.5 Permeability index

The moisture vapour permeability of apparel textiles is directly related to the thermal comfort of clothing ensembles made from the textiles. [45]. A higher permeability index ( $i_m$  value) indicates greater moisture permeability of the clothing and hence is desirable for heat transfer and thermal comfort. The  $i_m$  value does not provide a value intrinsic to clothing as it is affected by external environmental conditions. A value of 0 is total impermeability 1 and total is permeability, so a value of 0.5 is a typical value for a unclothed subject, 0.4 for normal clothing and 0.2 for impermeable-type clothing [142, 201]. The  $i_m$  value indicates the evaporative heat transfer permitted by a clothing system [30, 203, 204].

In the DWC with abaya combination, with the most body surface coverage,  $i_m$  ranged from 0.19 to 0.28 (Table 6.5) and had the lowest permeability index values, which means the abaya can be described as impermeable; lower permeability keeps the wearer warm by preventing the escape of body heat and/or water vapour.

Table 6.5 Permeability index ( $i_m$ ) and moisture accumulation ( $M_a$ ) in percentage of clothing weight.

Clothing system layer	Permeability index ( $i_m$ )	Before wetting ( $w_b$ )	After wetting ( $w_a$ )	$M_a$ (%)
U	0.38	53	78	47.2
SH	0.40	169	243	43.8
SK	0.29	347	431	24.3
SL	0.28	442	621	40.5
WATS	0.20	276	284	2.9
WAOH	0.19	349	354	1.4
WALS	0.20	250	259	3.6
KATS	0.28	587	590	0.5
KAOH	0.19	802	803	0.1
KALS	0.19	652	654	0.3

Skin	0.38	246	448	82.1
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Davis and Bishop [199] reported that the permeability index is affected by the amount of air trapped within and between the fibres and layers of clothing. This is the case for multiple layers of clothing, where the  $i_m$  is increased due to the amount of stagnant air trapped within and between the layers of clothing. The DWC (U+SH+SK and U+SH+SL) combinations provided the highest  $i_m$  values and are typical of normal clothing, because they had the highest exposed body surface area for the unimpeded evaporation of sweat. The  $i_m$  of DWC ranged value from 0.28 to 0.4%, which is between impermeable and normal clothing. The higher the values of  $i_m$ , the easier it is for the heat to dissipate through the clothing by means of evaporative cooling.

### 6.3.1.6 Moisture accumulation ( $M_a$ ) within clothing

The total moisture accumulation of the DWC and DWC inside the abayas was measured and the results are shown in Table 6.5. The amount of  $M_a$  depends on the properties of both the inner garments (U+SH+SK and U+SH+SL) and the outer garment (abaya) of the ensembles. As can be seen from Table 6.5, the water content in the outer garment (abaya) was much lower than that of the inner garment. Inner garments like underwear had the greatest amount of moisture accumulation of 47%, followed with SH and SL, which had approximately similar  $M_a$  of 44% and 40.5% of the clothing weight. This is due to the fact that inner clothing (U, SH and SL) had a higher content of cotton (being very hygroscopic), which absorbed more moisture compared with the other fabrics used for the abayas. Polyester (being hydrophobic) resulted in a relatively less water vapour permeable outer garment.

It can also be seen from Table 6.5 that SK took less moisture (24.3%) than SL (40.5%). In addition, the air gap within the skirt was large, and this kept perspiration on the surface of



the body. Therefore, the SK combination shows that high moisture accumulated in the skin of the manikin, which is likely to make the wearer feel uncomfortable.

Most women felt discomfort while wearing a skirt with an abaya as, discussed earlier in Chapter 2. Fan and Chen [46] observed that some moisture vapour that dissipated from the skin surface of a manikin would be accumulated (absorbed or condensed) within the clothing ensembles. The total moisture accumulation thus depends on the absorption of the clothing materials, as well as the permeability of the outer garment.

## **6.4 Summary**

As a pioneering effort, a sweating thermal manikin (female form) was utilised to assess the thermal comfort of the abaya in combination with common daily-wear clothing ensembles. Results were obtained for both the stationary and walking modes of the manikin. Analysis of data was carried out on the basis of key locations on the body such as head, torso, lower torso and the body fully covered with abaya. The surface temperature between daily wear clothing and abayas were measured by using temperature logging and an infra-red camera.

Three designs of abaya (worn from the shoulder with either tight sleeves or loose sleeves and worn from the top of the head with tight sleeves), in combination with two clothing ensembles - underwear and long-sleeved shirts, in combination with a skirt, slacks and shoes were studied. Abayas were made from a knitted and a woven fabric.

IR thermography results concurred with established findings that the outer surface temperature decreased when the layers of clothing increased. The air gaps between the body (manikin) and clothing and multiple layers of clothing affected heat loss as they served as excellent insulators. This signifies that wearing an abaya as an outer layer reduces heat loss from the body and can lead to discomfort in hot environments.

Thermal manikin results identify that the skirt ensemble had higher thermal and evaporative resistance than the slacks ensemble in standing mode. However, this trend was reversed in walking mode. These results highlight the importance of the air trapped in the microclimate between the body and garments for thermal comfort properties. Irrespective of the type of clothing, the thermal resistance and evaporative resistance in the abaya combinations are higher than for the clothing ensemble by itself. This is in agreement with the IR thermography results and indicates a sizable air gap thickness between clothing and abaya. Among the types of abaya design evaluated, those worn on the head offered slightly higher thermal and evaporative resistance than those worn from the shoulder with tight or loose sleeves.

Wearing an abaya on the head results in three layers, two from the scarf wrapped around the head and the third layer from the abaya. The abaya made from the woven fabric seemed to be more comfortable than the abaya made from the knitted fabric. Based on the results for the woven and knitted fabric with clothing, the woven fabric had lower thickness, weight, thermal resistance and evaporative resistance than the knitted fabric. Therefore, abaya combinations with knitted fabric are not recommended to be worn in summer but could be comfortable in winter.

Any developments aimed at reducing the thermal resistance of the abaya will be important in areas such as the Arabian Gulf.

## **Chapter 7 Improvement in thermal comfort of wool and polyester/wool woven fabrics dyed in black**

Significant portions of this chapter have been published in the *Journal of Fibre Bioengineering & Informatics* [205] as “Thermal comfort properties of wool and polyester/wool woven fabrics dyed in black” and in *Textile Bioengineering and Informatics Symposium Proceedings* [206] as “Investigation of thermal comfort properties of black fabrics for abaya” . This chapter investigates the thermal comfort properties of plain-weave fabrics dyed black and treated chemically to reflect a proportion of the sunlight’s energy in order to reduce the heat absorption so that the wearer will feel more comfortable. The fabrics were 100% wool, 100% polyester and two polyester/wool blends.

### **7.1 Introduction**

The absorption of sunlight or infra-red by textiles is a very important property needing to be thoroughly studied. This is because almost all textiles will absorb infra-red energy with a consequent increase in temperature [207]. The solar energy absorbing and retaining behaviour may be modified by incorporating a special energy-reflecting chemical (ERC) in the fibre [208]. The ERC-treated textiles reflect solar energy without altering the colour or feel of the fabric, and this could be an effective solution for reducing the thermal discomfort caused by wearing a black garment.

Since the purpose of ERC treatment is to reflect heat radiation, tests quantifying material infra-red (IR) radiation characteristics should provide useful information on the effectiveness of such treatments. IR thermography or thermal imaging is rapidly gaining popularity among researchers in diverse fields such as medicine, biology, material science and civil engineering [209]. Researchers in textiles have tried to utilise the potential of IR

thermography in fibre spinning, clothing comfort and fabric insulation [209]. Hu et al. [210] developed an instrument for measuring the thermal radiation properties of polymeric materials. Pang et al. [211] investigated the distribution of radiant heat in helmets by using a thermal imaging camera. Qi et al. [131] used a similar IR camera to measure the temperature on the back surface of the thermal protective performance of aerogel-embedded protective clothing for firefighters.

The present chapter discusses experiments aimed at improving the thermal comfort properties of the abaya by giving the constituent black abaya fabrics an energy-reflecting treatment.

## **7.2 Experimental design**

### **7.2.1 Materials**

This research evaluated four types of plain-woven fabrics, pure wool (W), pure polyester (P) and two different polyester/wool (P/W) blends in the ratios of 63/37 and 50/50, respectively. The fabric particulars are given in Table 3.3 and described in Chapter 3 (Section 3.3.2). After being dyed a black colour, the fabrics were given an energy-reflecting chemical treatment as described in Section 3.4.1. Fabric performance was then evaluated against non-ERC-treated fabrics.

## **7.3 Testing of fabrics**

All fabric specimens were conditioned in the standard atmosphere of  $20 \pm 2^\circ \text{C}$  and  $65 \pm 2\% \text{RH}$  for at least 24 hours prior to testing.

### **7.3.1 Physical properties**

The physical properties of both untreated and ERC-treated fabrics were assessed according to relevant standards described under Section 3.5. The properties evaluated were weight per unit area, thickness, thread count and cover factor (Table 7.1).

Table 7.1 Physical properties of plain woven fabrics.

Fabric composition	Sample	Ends/cm	Picks/cm	Fabric weight (g/m <sup>2</sup> ) ±std	Thickness (mm) ±std	Fabric Cover factor
W100	Greige	25	22	148.4±0.9	0.35±0.01	19.74
	Dyed Black	26	23	164.8±0.8	0.43±0.01	20.32
	ERC Treated	26	23	165.2±0.8	0.43±0.01	20.32
P63W37	Greige	23	21	132.0±0.7	0.34±0.01	18.68
	Dyed Black	24	22	146.4±0.6	0.37±0.01	19.30
	ERC Treated	24	22	145.8±1.5	0.37±0.01	19.30
P50W50	Greige	22	20	130.6±1.1	0.34±0.01	17.95
	Dyed Black	23	21	146.8±1.3	0.36±0.00	18.58
	ERC Treated	23	21	145.0±0.0	0.36±0.01	18.58
P100	Greige	40	54	78±0.0	0.19±0.00	19.90
	Dyed Black	41	55	83±0.01	0.20±0.00	20.20
	ERC Treated	42	56	82±0.00	0.20±0.00	20.49

### 7.3.2 Comfort properties

The thermal comfort properties (air permeability, thermal resistance, water vapour resistance and moisture management) of the fabrics were evaluated. All testing was carried out using appropriate instruments and according to relevant standards described in Chapter 3 under Section 3.6.

### 7.3.3 Thermal imaging camera (IR)

The surface temperature of the fabric samples was recorded by using thermal imaging camera as described in Chapter 3. The values selected are presented in Table 7.2. Relative temperature changes were used for all main results of this study. This avoided inaccuracies in absolute temperature, due to dependence on emissivity or any other parameter settings. The thermal images were analysed using FLIR Software [212].

Table 7.2 Selected values of adjustable imaging parameters.

	Method 1: controlled indoor	Method 2: natural outdoor
Emissivity	0.98	0.98
Distance	1.0 m	1.0 m
Temperature	35° C	40° C
Relative humidity	40%	40%

Two methods (controlled indoor and natural outdoor) were followed in this study. In the first method: the experiment was carried out in controlled indoor conditions at  $35 \pm 0.5^\circ \text{C}$  and RH 40%. A constantly induced airflow through a ducted air-conditioning system was maintained at an air velocity under  $0.8 \text{ ms}^{-1}$  (Table 7.2). An infra-red lamp of 150 watt (heat source) was placed in front of the fabric as a heat source, and the distance between the camera and the fabric was one meter as shown in Figure 7.1. The second method (Figure 7.2): the experiments were carried out in natural outdoor conditions (direct sunlight) to measure the surface temperature of the fabric, The AccuWeather application from the App store was used to measure the air temperature of the environment, the air temperature was  $40^\circ \text{C}$ , and the RH 40% (Table 7.2) and the wind speed was 15 km/h. The distance between the fabric and camera was kept the same as for the indoor method.

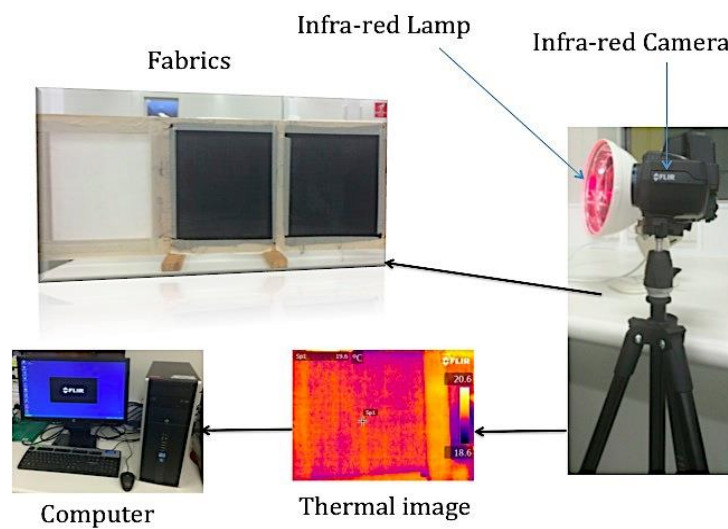


Figure 7.1 Thermal imaging experimental setup in controlled indoor (method 1).

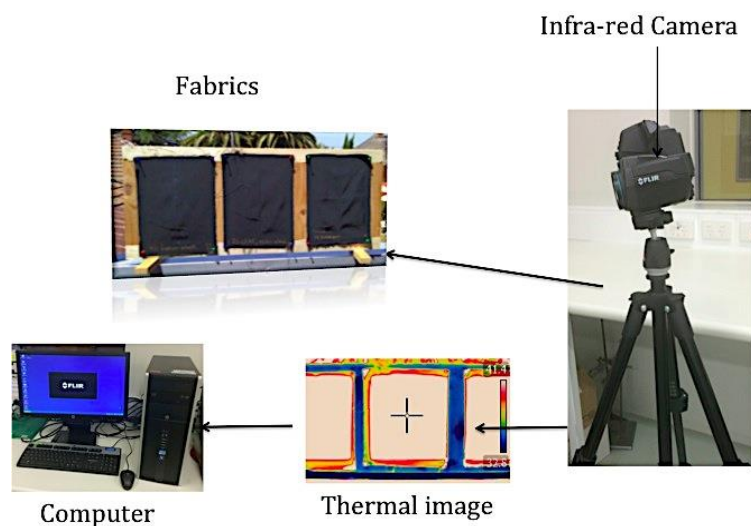


Figure 7.2 Thermal imaging experimental setup in natural outdoor (method 2).

## 7.4 Results and discussion

The results in Table 7.1 indicate an increase in the fabric weight and thickness after dyeing and ERC treatment. This may be attributed to shrinkage during wet processing. In the case of the W100 fabric, treatment with the ERC increased the fabric weight and thickness when compared to the dyed fabric although the fabric cover factor remained the same. In the case of the two blends, the dyed and ERC-treated samples had approximately similar weight, thickness and cover factor. With the P100 fabric, on the other hand, although treatment with the ERC increased the fabric weight and thickness when compared to the dyed fabric, the fabric cover factor increased slightly when the fabric was treated with the ERC. Overall, the ERC treatment did not significantly affect the physical properties of the dyed fabrics. To a less extent, the fibre fineness and cross-sectional shapes may affect the thermophysiological comfort properties of fabrics [168, 180]. This could be further investigated in the future.

### 7.4.1 Air permeability

Air permeability is the measure of airflow per unit area through a fabric perpendicular to the fabric plain. This parameter to a large extent influences the thermal comfort properties of the fabric. The air permeability values in Figure 7.3 show that the greige fabrics had a higher air permeability value than the dyed fabrics with or without ERC-treatment. This could be because the structure of the greige fabric was more open and there was nothing to apply in the fabric and it had a lower cover factor (Table 7.2).

Significant changes are seen primarily in the blended fabrics (P63W37 and P50W50), which were dyed at 110° C and had more compact structures due to relaxation shrinkage as compared with the W100 or P100 fabrics. The main reason would be the differential behaviour of the constituent materials on wet processing. Overall, air permeability differences between each of the dyed fabrics treated with and without the ERC were not statistically significant at 95% confidence interval.

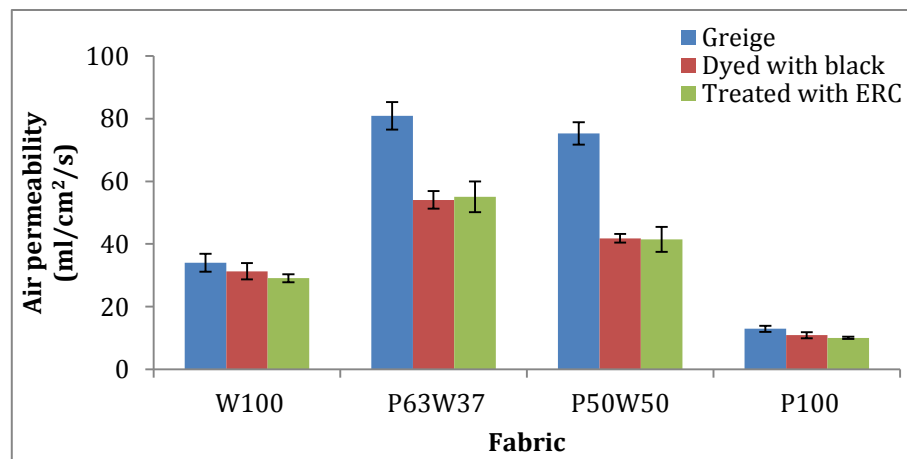


Figure 7.3 Comparison of air permeability values.

### 7.4.2 Thermal resistance ( $R_{ct}$ )

Thermal resistance is a measure of the material's ability to prevent heat from flowing through it [175]. Thermal resistance results are graphically shown in Figure 7.4. The fabrics with  $R_{ct}$  values less than 0.055 are considered to be very comfortable [171]. Hence,



all fabrics examined were considered to be comfortable. The higher value of  $R_{ct}$  for P63W37 can be attributed to the higher amount of spun polyester content in the fabric. The  $R_{ct}$  values of all the greige fabrics lie in a close range. It can be observed that all greige fabrics had a similar level of  $R_{ct}$  except fabric P100, which had the lowest  $R_{ct}$  among the four greige fabrics. This could be because P100 is made of filament yarn, which has higher thermal conductivity of 0.14 W/mK [167] than wool-spun yarn (0.039 W/mK) [63]. Fabric P100 was thinner and lighter than W100 and the blended fabrics. The fabric containing P50W50 and P63W37, after ERC-treatment, had the lowest  $R_{ct}$  value among all the dyed fabric. This may have been due to the composition of the fabric, which resulted in different physical properties between the fabrics.

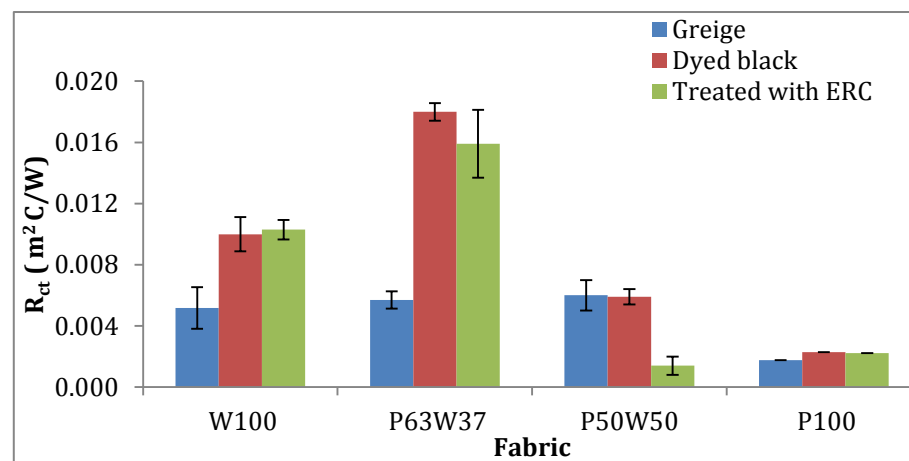


Figure 7.4 Comparison of thermal resistance values.

The increase in the  $R_{ct}$  values of W100 after dyeing and ERC treatment can be attributed to the increase in fabric thickness. This supports previous studies that the thermal resistance of the fabrics increased with an increase in fabric thickness [120, 213]. For a hot environment, low thermal resistance is necessary to allow the heat from the body to flow outside to the environment [170]. On the other hand, high thermal resistance may help by reducing the amount of energy from sunlight, which is transferred to the body in an extremely hot environment.

### 7.4.3 Water vapour resistance ( $R_{et}$ )

A lower water vapour resistance value is desirable for better moisture transport properties of the fabric, leading to improvement in thermal comfort [99]. The  $R_{et}$  values for all fabrics are in the range 0–4, which is considered to be very good or extremely breathable and comfortable according to the Hohenstein Institute [171]. Hence, these fabrics may be considered comfortable. As far as water vapour resistance was concerned, there was no statistically significant change between the dyed fabrics with and without the ERC-treatment. A higher value of water vapour resistance indicated that the fabric would have a lower rate of water vapour transmission from the body to the outside atmosphere. For this reason, the fabrics used in abayas should have low water vapour resistance if they are to be comfortable to wear.

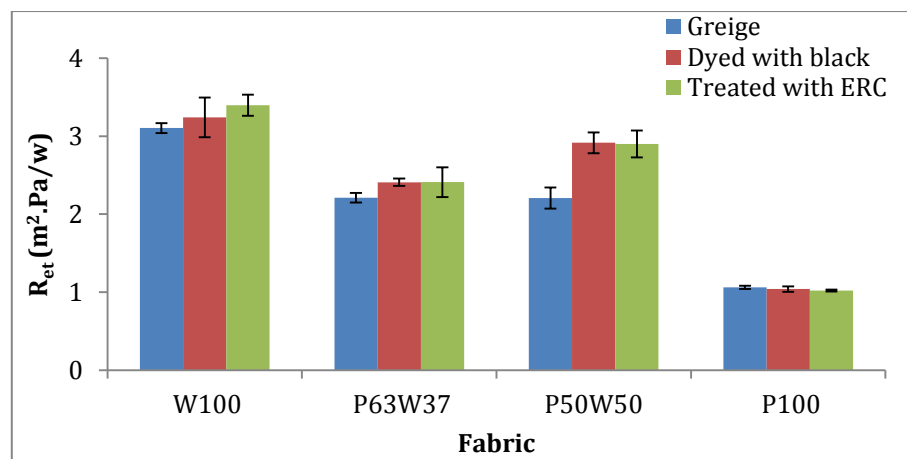


Figure 7.5 Comparison of water vapour resistance values.

It can be observed in Figure 7.5 that the  $R_{et}$  of fabric P100 was the lowest among the fabrics examined because of its low thickness and weight. The most important factors directly affecting water vapour resistance are thickness and weight of the fabric [214]. This is confirmed by the high  $R_{et}$  of W100 fabric and the fact that it was the thickest and heaviest among the fabrics studied. The increased thickness may be attributed to the hairiness of woollen yarns and the inherent bulkiness of wool fibres. When the water

vapour resistance is high, it can be difficult to release sweat from the body in the form of water vapour [120, 214].

#### **7.4.4 Moisture management properties**

The moisture management values of the fabrics are given in Table 7.3. The results show that all samples exhibited similar moisture management performance irrespective of having been dyed or given an energy reflective treatment. The W100 fabric, after being dyed, had a lower top surface absorption rate than the ERC treatment, although the maximum wetted radii for top and bottom surfaces were the same. The small maximum wetted radius indicates that the testing solution did not spread much during the two minute testing duration.

The W100 in greige, dyed and ERC-treated forms had poor OMMC and AOTI. These fabrics had a very slow spreading rate and did not get wet on their top or bottom surfaces. This was due to the special structure of the wool fibre. Wool is hydrophilic because water is absorbed by the fibres but the surfaces of unmodified wool fibres are hydrophobic because of a lipid layer on the outside of the scale cells. So wool fibres can absorb moisture without feeling wet. Water tends to be retained in hydrophilic fibres, which have poor moisture transportation and release [215]. There was a medium wetting time observed on the top surface but a slow wetting time on the bottom surface. This may be because fabric W100 was thicker and had a higher cover factor. Therefore, it took a long time for liquid moisture to spread on the outer fabric surface. The higher indices on the top surface than the bottom surface mean that the moisture remained at the top of the fabric surface near the skin but was not transported to the bottom of the fabric surface.

According to the results, fabric W100 was consequently designated as being a relatively waterproof fabric, since the fabric had a very slow rate of water absorption, a low spreading speed, no one way transport, and no water penetration. Though wool retains up to around 30% by weight of moisture without feeling wet, wool tends to keep water

within the fibre structure and was slow to release it to the environment [38]. Hence, the fabric W100 may not be suitable for abayas.

The larger the OMMC, the higher the overall moisture management capability of the fabric. The blended fabrics (P50W50 and P63W37) had higher OMMC values compared with the W100 and P100 fabrics. The OMMC values of the blended fabrics were found to be in the range 0.7–0.65, which means that the liquid moisture management capacity was very good [116, 216]. These results indicate that liquid sweat can be easily and quickly transferred from next to the skin to the outer surface to keep the skin dry. In addition, the blended fabrics had an excellent AOTI, a value higher than 400, so one-way transport was assessed as excellent [116, 216]. This means that the moisture content of the bottom surface was higher than that of the top surface, and the difference in the accumulative moisture content between the two surfaces of the fabric was high.

The wetting time and absorption rate were slow on the top surface and fast on the bottom surface. This also suggests that the bottom surface of the fabric would start to get wet faster than the top surface.

As the bottom surface absorbed more moisture than the top surface, the top surface remained drier than the bottom surface. Because the wetting time and absorption on the bottom surface were higher than on the top, the water was transported from the top to the bottom surface and the top surface remained dry. Based on these results, the blended fabrics were rated as fabrics, which enable moisture management to occur because they have fast wetting times, fast absorption rates and excellent one-way transport indices. ERC-treatment resulted in improvement of the moisture management of the blended fabrics.

Table 7.3 Moisture management data.

Fabrics			Wetting time (sec)		Absorption rate (%/sec)		Max wetted radius (mm)		Spreading speed (mm/sec)		Accumulative one-way transport index (%)	OMMC
			Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom		
W100	Greige	Mean	<b>6.89</b>	<b>120,0</b>	<b>185.82</b>	<b>0.00</b>	<b>6.0</b>	<b>0.0</b>	<b>0.93</b>	<b>0.00</b>	<b>-832.8</b>	<b>0.00</b>
		SD	0.38	0.00	157.87	0.00	2.2	0.0	0.50	0.00	94.3	0.00
	Dyed black	Mean	<b>7.03</b>	<b>119.95</b>	<b>70.50</b>	<b>0.00</b>	<b>5.0</b>	<b>0.0</b>	<b>0.70</b>	<b>0.00</b>	<b>-944.3</b>	<b>0.00</b>
		SD	0.33	0.00	13.76	0.00	0.0	0.0	0.03	0.00	53.9	0.00
	ERC-treated	Mean	<b>7.56</b>	<b>119.95</b>	<b>199.98</b>	<b>0.00</b>	<b>5.0</b>	<b>0.0</b>	<b>0.66</b>	<b>0.00</b>	<b>-819.3</b>	<b>0.00</b>
		SD	1.23	0.00	120.75	0.00	0.0	0.0	0.09	0.00	31.8	0.00
P63W37	Greige	Mean	<b>119.95</b>	<b>7.18</b>	<b>0.00</b>	<b>74.93</b>	<b>0.0</b>	<b>5.0</b>	<b>0.00</b>	<b>0.68</b>	<b>1128.3</b>	<b>0.68</b>
		SD	0.00	0.25	0.00	5.04	0.0	0.0	0.00	0.02	14.7	0.01
	Dyed black	Mean	<b>119.95</b>	<b>6.31</b>	<b>0.00</b>	<b>74.97</b>	<b>0.0</b>	<b>5.0</b>	<b>0.00</b>	<b>0.64</b>	<b>1125.4</b>	<b>0.68</b>
		SD	0.00	0.49	0.00	7.29	0.0	0.0	0.00	0.04	14.2	0.02
	ERC-treated	Mean	<b>119.95</b>	<b>7.70</b>	<b>0.00</b>	<b>80.69</b>	<b>0.0</b>	<b>5.0</b>	<b>0.00</b>	<b>0.78</b>	<b>1290.4</b>	<b>0.70</b>
		SD	0.00	0.52	0.00	8.60	0.0	0.0	0.00	0.06	14.0	0.02
P50W50	Greige	Mean	<b>119.95</b>	<b>6.92</b>	<b>0.00</b>	<b>65.56</b>	<b>0.0</b>	<b>5.0</b>	<b>0.00</b>	<b>0.71</b>	<b>1008.1</b>	<b>0.65</b>
		SD	0.00	0.11	0.00	21.63	0.0	0.0	0.00	0.01	301.8	0.06
	Dyed black	Mean	<b>119.95</b>	<b>6.73</b>	<b>0.00</b>	<b>70.43</b>	<b>0.0</b>	<b>5.0</b>	<b>0.00</b>	<b>0.70</b>	<b>1097.7</b>	<b>0.67</b>
		SD	0.00	0.46	0.00	4.10	0.0	0.0	0.00	0.03	26.1	0.01
	ERC-treated	Mean	<b>119.95</b>	<b>7.00</b>	<b>0.00</b>	<b>72.70</b>	<b>0.0</b>	<b>5.0</b>	<b>0.00</b>	<b>0.73</b>	<b>1131.6</b>	<b>0.67</b>
		SD	0.00	0.29	0.00	3.69	0.0	0.0	0.00	0.05	21.4	0.01
P100	Greige	Mean	<b>3.38</b>	<b>3.43</b>	<b>23.30</b>	<b>49.45</b>	<b>19.00</b>	<b>24.00</b>	<b>4.83</b>	<b>5.43</b>	<b>212.92</b>	<b>0.65</b>
		SD	0.31	0.22	9.43	5.18	2.24	5.48	0.41	0.73	63.98	0.08
	Dyed black	Mean	<b>5.98</b>	<b>22.68</b>	<b>81.76</b>	<b>10.42</b>	<b>6.00</b>	<b>5.00</b>	<b>0.85</b>	<b>0.46</b>	<b>-658.82</b>	<b>0.01</b>
		SD	1.00	17.76	51.32	5.51	2.24	0.00	0.19	0.43	272.40	0.01
	ERC-treated	Mean	<b>26.06</b>	<b>10.58</b>	<b>34.68</b>	<b>44.59</b>	<b>16.00</b>	<b>17.00</b>	<b>3.74</b>	<b>3.37</b>	<b>264.25</b>	<b>0.46</b>
		SD	52.51	17.54	22.62	22.84	10.84	9.08	2.19	1.88	193.03	0.14

Note: SD = Standard Deviation

The greige and ERC treated P100 possessed good OMMC moisture management properties ranging from 0.46–0.65 and very good AOTI values ranging from 200–400, showing that liquid sweat can be absorbed from the skin surface to the fabric and spread quickly on both surfaces of the fabric with a large wetted area. Therefore, fabric P100 was expected to be a fast-absorbing and quick-drying fabric. Synthetic fibres such as polyester are hydrophobic, meaning that their surface (and internal structure) has few bonding sites for water molecules. Hence, they tend to remain dry and have good moisture transportation and release [213].

In comparison, P100 after being dyed black had poor liquid moisture management capacity and AOTI with no wetted radius and very slow spreading speed, indicating that liquid can transfer from the surface next to skin to the opposite surface but cannot easily evaporate into the environment. P100 after treated with the ERC, on the other hand, had a good moisture management property and fair AOTI with fast spreading speed on both sides, a medium absorption rate and a medium wetting time on the bottom surface. This indicates that liquid sweat could be easily and quickly transferred from next to the skin to the outer surface to keep the skin dry. That means that the ERC-treatment improved the moisture management when applied to black fabric. According to the chemical supplier, the ERC chemical had hydrophilic end groups that assist in increasing moisture management properties. Based on the MMT results, the pure polyester fabric with the ERC treatment was a fast-absorbing and quick-drying fabric.

Fibre blending plays an important role in the moisture-related comfort properties of clothing. These results from MMT are consistent with those from Namligöz et al. [119], who reported that both synthetic fibres of 100% polyester (212.92%) and 100% natural fibres (-832.8) have limited moisture management capability. However polyester blended fabrics allow liquid absorption and transportation sensitively. Therefore, from the MMT results, it can be concluded that blended fabrics had better moisture management

performance than P100 and W100 and should be more comfortable to wear in hot climates because they have an excellent one-way moisture transport properties.

## 7.4.5 Thermal camera measurements of fabric surface temperature distributions

Table 7.4 and Figure 7.6 and Figure 7.7, show the infra-red images of the surface temperature distributions on the tested fabrics (greige, black dyed and black treated with the ERC) inside and outside the laboratory. The temperatures were recorded first without the heat source in the conditioned room and then the temperature of the surface fabric was recorded after the heat source was switched on for 10 min. The difference between the two temperatures was calculated. From that result, the differences between each black and ERC-treated fabric pair were determined and the values are presented in Table 7.4. This helps to identify the effects of the ERC-treatment. A similar sequence was followed in the outdoor environment and the testing results are presented in Table 7.4. Data for individual fabrics were analysed with FLIR quickreport 1.2 software using two different methods (Figure 7.6 and Figure 7.7). First, the average temperature (Ar) for a selected area was used to summarise the surface temperature. Second, the point of interest, spot (Sp), was used to measure the surface temperature on the spot of the fabric. These methods were used to make sure all fabrics had an accurate temperature reading.

Table 7.4 Comparison between the infra-red imaging results obtained under two sets of conditions.

Test	Indoor				Outdoor			
	Greige (° C)	Black (° C) [x]	ERC treated (° C) [y]	<b>Difference between black and ERC treated (° C) [x-y]</b>	Greige (° C)	Black (° C) [x*]	ERC treated (° C) [y*]	<b>Difference between black and ERC treated (° C) [x*-y*]</b>
W100	35.3	35.8	35.5	<b>0.3</b>	39.8	52.2	51.9	<b>0.3</b>
P63W37	34.9	35.9	35.3	<b>0.6</b>	40.3	51.8	50.9	<b>0.9</b>
P50W50	36.7	37.3	36.4	<b>0.9</b>	38.7	51	50.3	<b>0.7</b>
P100	39.4	39.8	39.7	<b>0.1</b>	39.8	48.4	46.6	<b>1.8</b>

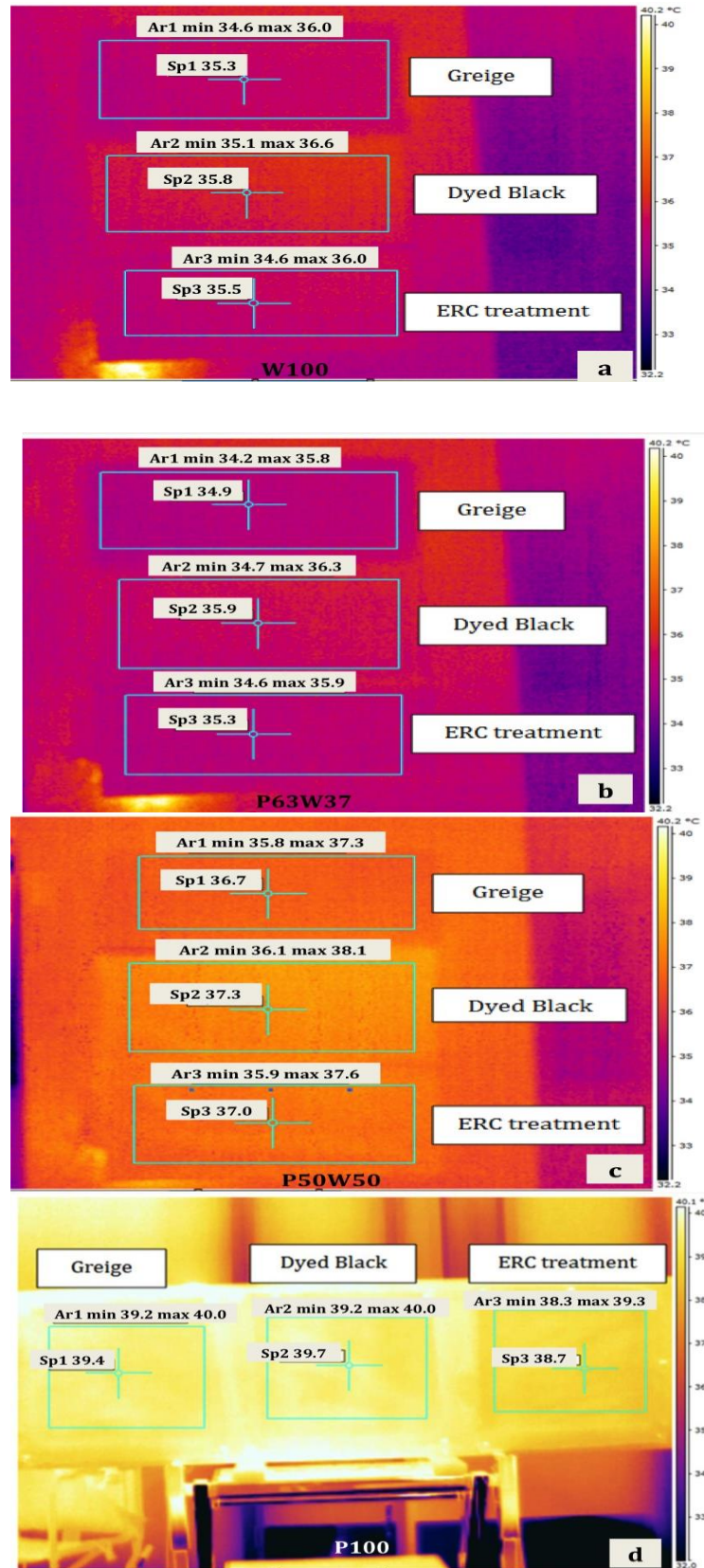


Figure 7.6 Infra-red images of the surface temperature distribution on the tested fabrics when greige, dyed black and treated with ERC at 35° C. a) W100, b) P63W37, c) P50W50 and d) P100



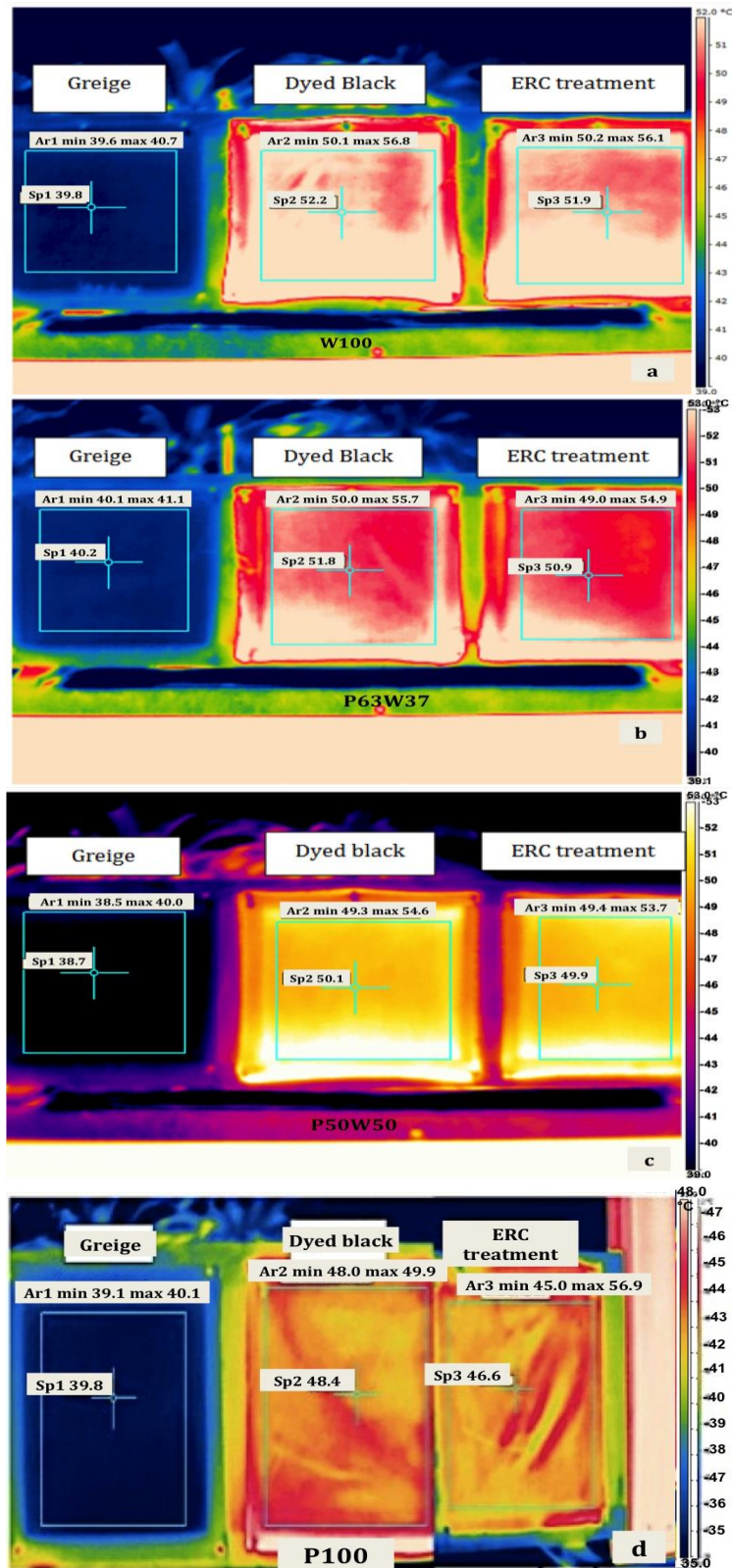


Figure 7.7 Infra-red images of the surface temperature distribution on the tested fabrics when greige, dyed black and treated with ERC at 40° C. a) W100, b) P63W37, c) P50W50 and d) P100

The thermal images and profiles (Figure 7.6 and Figure 7.7) obtained under two different sets of conditions as shown in Table 7.4 revealed that the heat distribution on the wool fabric treated with ERC reduced the temperature by around 0.3° C relative to the black-dyed fabric at 40° C, and in the indoor experiment, the ERC-treatment reduced the temperature by around 0.3° C compared to the black fabrics (Table 7.4). In comparison, the surface temperature of ERC-treated fabric P63W37 radiated less heat (around 0.9° C) than its untreated black fabric in the natural outside at 40° C, but in the controlled indoor experiment the surface temperature reduced radiated heat to 0.6° C in the ERC-treated fabric (Table 7.4). Fabric P50W50 after the ERC treatment had less radiant heat (around 0.7° C) at 40° C compared to its untreated black fabric. On the other hand, when the ERC-treated fabric was tested in the controlled indoor experiment at 35° C, the fabric absorbed less heat (around 0.9° C) compared to outside. The ERC-treated P100 reduced the radiated heat by around 1.8° C compared to its untreated dyed black fabric in the natural outside temperature at 40° C. However, when the fabric was tested in the controlled indoor experiment at 35° C, the ERC-treated fabric had lower radiated heat (around 0.1° C) compared with the dyed black fabric, as shown in Table 7.4.

Most of the greige fabrics had lower temperatures compared with the dyed black and ERC-treated fabrics. This result agrees with that of Nielsen [140], who found that the heat absorption due to sunlight in black garments is greater than in white garments. The composition of fabrics can also be identified as a contributory factor. This is seen by the higher temperature of P100 fabric in indoor conditions wherein the pure polyester fabric could not dissipate the heat like the fabrics with a wool component. In the outdoor conditions the trend was reversed when the higher lustre of the synthetic material probably reflected some of the incident radiation. Overall, when applying the ERC-treatment on abaya fabrics, it significantly reduced the surface temperature of the ERC-treated fabrics ( $p < 0.001$ ) more than fabrics only dyed black.

## 7.5 Summary

The main objective of this section was to investigate the effect of applying an energy-reflecting chemical treatment on abaya fabrics dyed a black colour. The experimental results showed that the energy-reflecting treatment slightly improved the thermal comfort properties under the current experimental conditions. In the case of air permeability and water vapour resistance, there were no statistically significant differences at a 95% confidence interval between dyed fabrics with and without the treatment. However, the blended fabrics (50/50 polyester/wool fabric, and 63/37 polyester/wool fabric) showed improved water vapour resistance and moisture management performance. Thermal imaging results show that the application of an energy-reflecting chemical treatment on black-dyed fabric reduced the radiant heat by around 1.8–0.7° C when the fabrics were tested in the natural outside at 40 ° C. When the same fabrics were tested in the controlled indoor environment, it was found the radiant heat reduced by around 1.1–0.6° C. The results also lead to the conclusion that the black 100% polyester and polyester/wool blend fabrics appear to be thermally more comfortable than the 100% wool fabrics, especially after an energy-reflecting chemical treatment.

# **Chapter 8 Conclusion and suggestions for future work**

## **8.1 Introduction**

The objective of this research was to investigate the abaya, a mandatory outer garment for women as stipulated in the Qur'an, in Saudi Arabia. The focus was to obtain an overview of the abaya, its use, features and desirable characteristics. Objective evaluations relating to the comfort of the abaya are reported for the first time. Further, in a pioneering attempt to improve thermal comfort, the use of energy-reflecting chemicals to reduce radiant heat absorption by black fabrics was investigated.

The research began with a survey of women studying or working at King Abdul Aziz University in Saudi Arabia. The aim was to understand the factors affecting the abaya's thermo-physiological comfort properties. The survey identified the textile materials that are widely used for the abayas worn by the participants. The survey findings provided the basis for experiments that investigated: a) the properties of fabrics commonly employed in fashioning the abaya; b) the thermal comfort of the abaya in combination with daily-wear clothing ensembles using a thermal manikin; and c) improving the thermal comfort properties of the traditional abaya by chemical treatments. In the course of the research, critical properties related to thermal comfort are fabric drape, stretch and recovery, air permeability, 3D body scans and temperature logging were studied. Sophisticated equipment such as an IR thermal-imaging camera, sweating guarded hot plate, moisture management tester and thermal manikin were employed. This thesis work has resulted in seven refereed publications so far.

## **8.2 Conclusion**

### **8.2.1 Survey outcomes**

This is the first survey about understanding the abaya for its comfort. It presents the opinion of a small population of women in Saudi Arabia regarding the comfort of the abayas they were using. The survey provided an insight into the problems and causes of discomfort by wearing an abaya in hot environments. It revealed that the degree of comfort depends on the type of abaya fabric and the design as well as the clothing worn underneath.

The survey identified that most abayas were made from woven synthetic (polyester) fabrics. The areas of the body that experienced maximum heat stress were the neck, front of the body and back of the body (which represent the torso area). The torso area typically has multilayers of clothing including bra, shirt, abaya and some part of a headscarf. Wearing jeans or slacks with short sleeves or sleeveless dresses underneath the abaya increased the comfort and the freedom of movement as compared to a skirt or *jalabiah* (a traditional dress falling straight from the shoulder to the ankle with a loose fitting shape). The fabrics investigated in this research were selected for further investigation based on the survey results.

### **8.2.2 Fabric properties**

Traditionally, woven fabrics were used for abayas because their stiffness in comparison to knits made them conducive to hide the body contours of women. The increasing use of knitted fabrics globally is making them a fashion choice as well. Therefore, this study selected some woven and knitted fabrics that are used commercially for abayas. Studies on the woven and knitted fabrics confirmed that fabric structure, fibre composition and other fabric properties significantly affected the comfort performance of abaya fabric. Among the woven fabrics, 100% polyester (3/1×1/3 mixed twill weave), 65/35 polyester/cotton (plain weave), 80/20 viscose/polyester (crepe weave) and 100%

polyester (satin weave) fabrics, the last fabric, polyester produced using a fine yarn count, had the best air permeability, drapeability and moisture management properties. It also had the lowest thermal resistance and lowest water vapour resistance. However, the fine yarn count in this fabric was observed to make it slightly translucent.

Knitted fabrics selected for abayas were mainly evaluated for thermal comfort properties. The polyester/elastane (96/4) single jersey knit fabric showed better air permeability, stretch and recovery properties, lower thermal and water vapour resistance compared with the nylon filament fabric, polyester/cotton (65/35) single jersey fabric, wool single jersey fabric, and 50/50 wool/nylon fabric. The polyester/elastane fabric did not appear to be able to effectively evaporate water into the environment and would keep the sweat between the skin and the next surface of the fabric. Since knitted fabrics are normally not dimensionally stable, knitted abayas could take on body contours. This may be avoided by using thicker fabrics with a greater mass per unit area or a modified abaya design.

### **8.2.3 Thermal manikin testing**

Three designs of abaya (worn from the shoulder with either tight sleeves or loose sleeves and worn from top of the head with tight sleeves), in combination with daily-wear clothing ensembles (underwear, long-sleeved shirts as well as skirt/slacks) and shoes were investigated. Each design of abaya was made from a knitted and a woven fabric. This research is the first to utilise a sweating thermal manikin (female form) to assess the thermal comfort of the abaya in combination with common daily-wear clothing ensembles. Both stationary and walking modes were evaluated. Analysis of data was carried out on the basis of key locations of the body such as head, torso, lower torso and the abaya.

Temperature logging and an infra-red (IR) camera measured the surface temperature between daily wear clothing and an abaya. Infra-red thermography results were consistent with established findings that surface temperatures decrease when the layers

of clothing increase. Air gaps between the body (manikin) and multiple layers of clothing and an abaya affect the heat loss as still air serves as an excellent insulator.

The skirt ensemble had higher thermal and evaporative resistance than the slacks ensemble in the stationary standing mode. However, this trend was reversed in the walking mode, because the air movement increased, which helped to release the warm and wet air close to the body. Irrespective of type of clothing, the thermal resistance and evaporative resistance in the abaya combinations were higher than for the clothing ensemble by itself.

Among the types of abaya design evaluated, those worn on the head offered slightly higher thermal and evaporative resistance than those worn from the shoulder with tight or loose sleeves. In addition, abaya combinations in the studied woven fabric could be slightly more comfortable than chosen knitted abaya combinations, although the abaya itself contributes heavily to thermal stress in hot weather. These results highlight the importance of the air trapped in the microclimate between the body and garments on thermal comfort properties.

#### **8.2.4 Improvement of comfort performance for abaya fabrics**

The use of an energy-reflecting chemical to improve the thermal comfort of the traditional black abaya was investigated. The experimental results showed that such treatment slightly improved the thermal comfort properties without significantly affecting air permeability and water vapour resistance at a 95% confidence interval. However, among the fabrics evaluated the blended fabrics (50/50 polyester/wool fabric and 63/37 polyester/wool fabric) showed improved water vapour resistance and moisture management performance. Thermal imaging results showed that the treatment with an energy-reflecting chemical of a black abaya type fabric reduced the radiant heat by around 1.8–0.7° C when the fabrics were tested in a natural outdoor environment at 40 °C and

40% RH. When the same fabrics were tested under controlled indoor conditions of 35 °C and 40% R.H, it was found the radiant heat reduced by around 0.9–0.1° C. The results also lead to the conclusion that the black 100% polyester and polyester/wool blend fabrics studied appeared to be thermally more comfortable than the 100% wool fabric, especially after the energy-reflecting chemical treatment.

### **8.3 Suggestions for future work**

After conducting the work presented here and reviewing the literature available in the public domain, the following areas have been identified for future work:

- The current survey was conducted only in Jeddah, Saudi Arabia; it will gather broader information if the survey includes other parts of Saudi Arabia as well as the Arabian Gulf and other Islamic countries in the Middle East. Information from Islamic populations in India and African countries would provide a global perspective.
- This pioneering study was conducted under standard conditions. Therefore, a further study in simulated or natural environments in high temperatures is recommended. This would assist in understanding the mechanism for maintaining thermal comfort under extremely high environmental temperatures (i.e above 40° C).
- Woven and knitted fabrics produced from different fibres (such as silk, bamboo blends, coolmax® polyester, polyester microfibre or super-absorbent yarns etc.) can be explored for abayas. Such fabrics should have parameters similar to the existing abaya fabrics in terms of colour, weight, thickness, structure and yarn count. Thermal comfort would be the comparison factor.
- Abayas can also be designed to permit ventilation by adding minute holes on both sides of the abaya while maintaining modesty and adhering to the guidelines of the Qur'an.
- The composition and design of the garments worn underneath the abaya may be varied and the thermal comfort evaluated in combination with the abaya.



- New or alternate energy-reflecting chemicals may be evaluated that can help to improve the performance of abaya fabrics.

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## Appendix A



Design and Social Context College Human Ethics Advisory Network (CHEAN)  
Sub-committee of the RMIT Human Research Ethics Committee (HREC)

### Notice of Approval

Date: 24 November 2012  
Project number: CHEAN A-2000778-09/12  
Project title: Understanding thermal comfort performance of Abaya  
Risk classification: Low Risk  
Investigator/s: Salwa Tashkandi  
Approved: From: 24 November 2012 To: 24 November 2015

I am pleased to advise that your application has been granted ethics approval by the Design and Social Context College Human Ethics Advisory Network as a sub-committee of the RMIT Human Research Ethics Committee (HREC).

Terms of approval:

**1. Responsibilities of investigator**

It is the responsibility of the above investigator/s to ensure that all other investigators and staff on a project are aware of the terms of approval and to ensure that the project is conducted as approved by the CHEAN. Approval is only valid whilst the investigator/s holds a position at RMIT University.

**2. Amendments**

Approval must be sought from the CHEAN to amend any aspect of a project including approved documents. To apply for an amendment please use the 'Request for Amendment Form' that is available on the RMIT website. Amendments must not be implemented without first gaining approval from CHEAN.

**3. Adverse events**

You should notify HREC immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.

**4. Participant Information and Consent Form (PICF)**

The PICF and any other material used to recruit and inform participants of the project must include the RMIT university logo. The PICF must contain a complaints clause including the project number.

**5. Annual reports**

Continued approval of this project is dependent on the submission of an annual report. This form can be located online on the human research ethics web page on the RMIT website.

**6. Final report**

A final report must be provided at the conclusion of the project. CHEAN must be notified if the project is discontinued before the expected date of completion.

**7. Monitoring**

Projects may be subject to an audit or any other form of monitoring by HREC at any time.

**8. Retention and storage of data**

The investigator is responsible for the storage and retention of original data pertaining to a project for a minimum period of five years.

**9. Special conditions (if applicable)**

In any future correspondence please quote the project number and project title.

On behalf of the DSC College Human Ethics Advisory Network I wish you well in your research.

Daniel Martini  
Ethics Coordinator  
College of Design & Social Context  
RMIT University  
Ph: (03) 9925 2974  
daniel.martini@rmit.edu.au

## Appendix B

KINGDOM OF SAUDI ARABIA  
MINISTRY OF HIGHER EDUCATION  
KING ABDULAZIZ UNIVERSITY  
HOME ECONOMICS



المملكة العربية السعودية  
وزارة التعليم العالي  
جامعة الملك عبد العزيز  
الاقتصاد المنزلي

Department of Clothing and textiles

### إفـادة

تقوم الطالبة / سلوى محمد أمين طاشكندي المبتعثة من قبل جامعة الملك عبد العزيز ، قسم الملابس والنسيج بعمل رسالة لنيل درجة الدكتوراه في جامعة RMIT بقسم الملابس والنسيج في إستراليا.

بعنوان ( An investigation of thermal comfort properties of abaya fabrics )

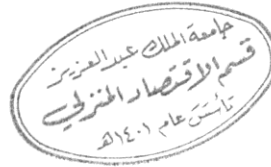
وتحتاج إلى جمع معلومات ميدانية من جامعة الملك عبد العزيز وحيث أن الطالبة إحدى عضوات قسم الملابس والنسيج بجامعة الملك عبد العزيز .

فإنه لا مانع لدينا من توزيع الاستبيان داخل الحرم الجامعي متمنين لها التوفيق والسداد لكل ما يحبه الله ويرضاه.

والله الموفق ...

مشرفة قسم الملابس والنسيج

د. مها بنت عبدالله الدباغ



HOMIECON.KAU.EDU.SA

هاتف: ٠٢٠٢٦٩٥٢٠٠٠ فاكس: ٠٢٠٢٦٩٥٢٠٠٦ Tel: (02)6952000 Fax: (02)6952006

ص. ب. ٤٢٨٠٧ جدة ٢١٥٥١ P.O.Box 42807 JEDDAH 21551

رقم التودج: HOM.060.F001 الإصدار: الأول

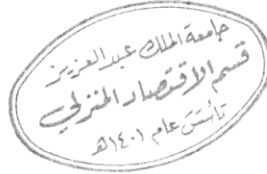
ع. الغامدي

### To whom it may concern

We would like to inform you that our graduate student Salwa Mohammed Amin Tashkandy who is studying In RMIT university is conducting an investigation as a part of the completion of the PHD under the name of( An investigation of thermal comfort properties of abaya fabrics) and it is our pleasure to have her to distribute her survey in King Abdul-Aziz university campus  
Thank you for your cooperation

**Head of textile and clothing department**

**Dr Maha Aldabbagh**



HOMEECON.KAU.EDU.SA

هاتف: ٢٦٩٥٢٠٠٠ فاكس: ٢٦٩٥٢٠٠٦ (٠٢) Tel: (02)6952000 Fax: (02)6952006

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رقم الترخيص: HOM.060.F001

ع.الغامدي



## Appendix C



### INVITATION TO PARTICIPATE IN A RESEARCH PROJECT



#### PARTICIPANT INFORMATION

**Project Title:** Understanding thermal comfort performance of Abaya Fabrics.

**Investigators:**

**Researcher's name:** Salwa Tashkandi. PhD candidate.

Email Ph. + (613) 99259439.

**Senior Supervisor:** A/Prof. Lijing Wang.

Email: [lijing.wang@rmit.edu.au](mailto:lijing.wang@rmit.edu.au) Ph. +(61 3) 9925 9414.

**Supervisor name:** Dr. S. Kanesalingam.

Email: [sinnappoo.kanesalingam@rmit.edu.au](mailto:sinnappoo.kanesalingam@rmit.edu.au) Ph. +(613) 99259162.

As a student and staff of King Abdul Aziz University you are kindly invited to participate in a research project *Understanding thermal comfort performance of Abaya Fabrics* being conducted by RMIT University and King Abdul Aziz University in Saudi Arabia. Please read this information sheet carefully and be confident that you understand its contents before deciding whether to participate. If you have any questions about the project, please ask one of the investigators.

**Who is involved in this research project? Why is it being conducted?**

The primary investigator is Salwa Tahskandi. She is a PhD candidate in School of Fashion & Textiles at RMIT University, Melbourne, Australia. This project is part of her PhD thesis work. A/Prof. Lijing Wang, who is Senior Supervisor, and Dr Kanesalingam, who is second supervisor, supervises this research. The King Abdul Aziz University sponsors this survey. The project has been approved by the RMIT Human Research Ethics as well as Kingdom of Saudi Arabian, King Abdul Aziz University.

**What is the project about? What are the questions being addressed?**

This survey aims to study textile substrates for traditional Muslim women's garment, Abaya, to enhance moisture management capabilities and garment thermal comfort properties, as well as to investigate ways to improve the microclimate condition between these substrates and the skin. The survey questions have been designed for women who wear the Abaya. We plan to approach between 50-100 participants. The age range between 18- 60 years old. The result of this research will help to understand the level of comfort in Abaya.

You will be asked to provide feedback in general information about Abaya, and Abaya fabrics. You will also be asked to provide feedback on the feeling when you wear Abaya in summer, durability and washing frequency and maintainability.

**If I agree to participate, what will I be required to do?**

If you agree to be a participant, you will be asked to complete a survey by answering the questions which relate directly to your experience with wearing Abaya. It is anticipated that this survey will take approximately 10 to 15 minutes of your time. Most of the questions are answered by selecting from the choices, or providing a brief response, but long answers are not required.

**What are the possible risks or disadvantages?**

There are **no** specific risks associated with this project. Many of the questions in the survey are not personal and it's just focusing on participant's experience with wearing Abaya. Also, participants are welcome to examine the survey documents before making a decision as to whether complete the

survey form or not. The decision to participate is voluntary and you have the right to withdraw your participation at any time.

Your responses are anonymous, and the results from this study will be analysed and may be presented in thesis and/or publications.

**What are the benefits associated with participation?**

There is no direct benefit to the participant as a result of their participation. However, the result might help future development of Abaya that can have improved thermal comfort performance in hot environment.

**What will happen to the information I provide?**

To preserve participant anonymity, PLEASE DO NOT place your name or any identifying information anywhere on the survey. Thus, none of the information you provide can in any way be linked back to you. Upon submission, the final report will not include any identity reference. The report will just provide numbers and will not refer to any personal information.

The project results may be published as a report article or conference paper; it may also be included in the PhD thesis. The project outcome will be written with simple language for non-specialists readers. Participants will not receive a copy of the final report or published paper due to anonymous survey and the need for copyright protection of the research. However, after publication, the Kingdom of Saudi Arabia, King Abdul Aziz University will receive a copy of the reported outcome of the research because the organization has been involved in the research. Interested participants are welcome to have a look at the results through their organization or publisher. Because of the nature of data collection, we will not obtain any written consent from you. Instead, we assume that you have given consent by your completion and return of the questionnaires.

According to Human Research Ethics Committee guidelines the research data will be kept securely at RMIT for five years after publication, before being destroyed. The hard copy collected data will be archived in the RMIT School of Fashion and Textiles. Data may also be stored in electronic format by scanning the hard copy into a PDF file. In addition, for participant's privacy no one can access this data excluding the candidate and supervisors of this research. If you accidentally identify yourself on the survey form, we will destroy the form and keep no record of the form.

**What are my rights as a participant?**

You have the right to withdraw your participation at any time, without prejudice, and the right to have any questions answered at any time. If you choose to discontinue the survey, simply stop filling in your answers.

**Whom should I contact if I have any questions?**

If you have questions about the survey at any time during your participation you should contact the investigators listed above. If you have an ethical issue or complaint about the survey, you can contact the Secretary, RMIT Human Research Ethics Committee, University Secretariat, RMIT, GPO Box 2476V, Melbourne, 3001. The telephone number is (03) 9925 1745. Details of the complaints procedure are available from the above address.

***Thank you for devoting some time to reading this statement and considering its contents.***

Yours sincerely

Salwa Tashkandi

A/Prof. Lijing Wang

Dr. S. Kanesalingam

## Appendix D



### Understanding thermal comfort performance of abaya

#### فهم الأداء الراحة الحرارية للعباية

You are kindly invited to participate in a research project *Understanding thermal comfort performance of Abaya* being conducted by RMIT University and King Abdul Aziz University in Saudi Arabia. Please read this information sheet carefully and be confident that you understand its contents before deciding whether to participate or not. If you have any questions about the project, please ask one of the investigators

[lijing.wang@rmit.edu.au](mailto:lijing.wang@rmit.edu.au); [sinnappoo.kanesalingam@rmit.edu.au](mailto:sinnappoo.kanesalingam@rmit.edu.au)).

This survey aims to study textile substrates for traditional Muslim women's garment, Abaya, to understand moisture management capabilities and garment thermal comfort properties, as well as to investigate ways to improve the microclimate condition between these substrates and the skin.

This survey will take approximately 10 to 15 minutes of your time. Most of the questions are answered by selecting from the choices. Some may ask you to provide a brief response, but long answers are not required. Note that the results of the questionnaire will be used only for scientific research. The results of this study will contribute to improving the design and comfort aspects of the fabric and Abaya. Your opinion and additional comments are welcome.

يرجى منك أن تشاركي في مشروعني فهم الأداء البحثي الراحة الحرارية للعباءة التي تجربها جامعة RMIT وجامعة الملك عبد العزيز في المملكة العربية السعودية. يرجى قراءة ورقة المعلومات بعناية والتأكد من فهم محتوياته قبل أن تقرري ما إذا كنت تريد المشاركة أو لا. إذا كان لديك أي أسئلة حول هذا المشروع، من فضلك اسألني الباحثة.

يهدف هذا الاستبيان الى دراسة ركائز النسيج للباس المرأة التقليدي الاسلامي وهو العباية، لتعزيز قدرات إدارة الرطوبة والملابس خصائص الراحة الحرارية وكذلك للتحقيق في سبل تحسين المناخ المحلي بين هذه الركائز والجلد.

وهذا الاستبيان يستغرق حوالي 10 إلى 15 دقيقة من وقتك. يتم الاجابة على معظم الأسئلة من خلال اختيار من الاختيارات، أو تقديم رد مختصر، ولكن لا يطلب منك الإجابات الطويلة. فإن نتائج هذه الدراسة تساهم في تحسين جوانب التصميم والراحة للنسيج والعباءة. ملاحظة أنه سيتم استخدام نتائج الاستبيان للبحث العلمي فقط. وأمل الإجابة بدقة ورأيك هو أكثر من موضع ترحيب.

❖ الرجاء اختيار اجابة واحدة

A- Personal general information		أ - معلومات شخصية
1. Age group	الفئة العمرية:	<input type="checkbox"/> 18-20 <input type="checkbox"/> 21 -30 <input type="checkbox"/> 31 - 40 <input type="checkbox"/> More than 40.
2. Profession:	المهنة	<input type="checkbox"/> University student طالبة <input type="checkbox"/> Employee/employer صاحبة عمل/ موظفة <input type="checkbox"/> Unemployed/housewife ربة منزل/ غير موظفة
3. Academic Qualifications:	المؤهلات العلمية	<input type="checkbox"/> Up to high school ثانوية عامة <input type="checkbox"/> Diploma دبلوما <input type="checkbox"/> Bachelor degree ب كال وركوب <input type="checkbox"/> Postgraduate دراسات عليا

B- Information on the current type abaya used	معلومات عامة عن العباية	
<p>4. Why should you wear the abaya? Because its ..... لماذا ترتدي العباية؟ لأنه .....</p>	<input type="checkbox"/> Religion <input type="checkbox"/> Tradition <input type="checkbox"/> Other (Specify) ..... .....	معتقد ديني معتقد تقليدي اخرى تذكر ..... .....
<p>5. What type of abaya design do you usually wear? ماهو تصميم العباية التي تلبسيتها؟</p>	<input type="checkbox"/> The normal one which is worn from the shoulder and has tight sleeves <input type="checkbox"/> The loose sleeves <input type="checkbox"/> The top of the head <input type="checkbox"/> The butterfly design <input type="checkbox"/> Other design	التصميم العادي يلبس على الكتف وكم ضيق العباية ذات الكم الواسع عباية الرأس عباية الفراشة تصميم اخر
<p>6. How many abayas do you buy in a year? خلال السنة الواحدة كم عدد العبايات التي تقومين بشرائها</p>	<input type="checkbox"/> 1 ~ 2 <input type="checkbox"/> 3 ~ 4 <input type="checkbox"/> More than 4	ما بين 1- 2 ما بين 3 - 4 أكثر من 4
<p>7. What are the reasons that make you change the current abaya/ abayas? ماهي السبب التي تجعلك تغييرين عبايتك الحالية</p>	<input type="checkbox"/> New style <input type="checkbox"/> New fabric <input type="checkbox"/> More comfortable <input type="checkbox"/> Gift <input type="checkbox"/> Other (specify) ..... ..... .....	موضة جديدة قماش جديد البحث عن عباية مريحة هدية اخرى تذكر ..... ..... .....
<p>8. Where do you buy your abaya من أين تشتريين عبايتك؟</p>	<input type="checkbox"/> Abaya shop <input type="checkbox"/> Market stalls <input type="checkbox"/> Overseas <input type="checkbox"/> Homemade <input type="checkbox"/> Specify. ..... ..... .....	من محلات العبايات من البازارات خارج البلاد صناعة منزلية اخرى تذكر ..... ..... .....
<p>9. What type of textile design used for current abaya? هل تفضلين العباية</p>	<input type="checkbox"/> Knitted Fabrics <input type="checkbox"/> Woven fabrics	اقمشة محبوكة ( الجرسى) اقمشة منسوجة
C- Comfort while wearing abaya		الراحة العامة عند ارتداء العباية
<p>10. When wearing abaya in hot weather, do you feel: عندما ترتدين العباية في الجو الحار, كيف تشعرين؟</p>	<input type="checkbox"/> Hot. <input type="checkbox"/> Normal <input type="checkbox"/> Discomfort <input type="checkbox"/> Specify..	حار عادي غير مريح اخرى تذكر..

<p><b>11. At what environmental temperature do you feel discomfort when you wear abaya?</b></p> <p>في اي درجة حرارة تقريبا تحسبن بأنك غير مرتاحة عند لبس العباية؟</p>	<p><input type="checkbox"/> From (20 to 25° C)</p> <p><input type="checkbox"/> From (26 to 30° C)</p> <p><input type="checkbox"/> From (30 to 35° C)</p> <p><input type="checkbox"/> More than 36° C</p>
<p><b>12. How long do you stay outside when you go from home wearing the abaya (The longest period you stay outside in a hot summer day)?</b></p> <p>ماهي المدة التي تقضينها بالعباية وانتى خارج المنزل؟</p>	<p><input type="checkbox"/> More than 4 hours      تقريبا 8 ساعات</p> <p><input type="checkbox"/> 2-4 hours      تقريبا 4 ساعات</p> <p><input type="checkbox"/> 1-2 hours      تقريبا ساعتين</p> <p><input type="checkbox"/> 0-1 hours      تقريبا ساعة واحدة</p>
<p><b>13. How well do you describe abaya fabric breathability:</b></p> <p>كيف يمكن اعتبار نفاذية القماش للهواء؟</p>	<p><input type="checkbox"/> Very poorly      سيئ جدا</p> <p><input type="checkbox"/> Poor      سيئ</p> <p><input type="checkbox"/> Unacceptable      غير مقبول</p> <p><input type="checkbox"/> Acceptable      مقبول</p> <p><input type="checkbox"/> Very good      جيد جدا</p>
<p><b>14. Do you think that the multiyear clothing underneath the abaya can affect the level of comfort?</b></p> <p>هل تعتقدي أن طبقات الملابس تحت العباية يمكن أن تؤثر على مستوى الراحة؟</p>	<p><input type="checkbox"/> Yes      نعم</p> <p><input type="checkbox"/> No      لا</p> <p><input type="checkbox"/> May be      ربما</p> <p><input type="checkbox"/> I do not know.      لا أعلم</p>
<p><b>15. Describe the comfort level of abaya with multilayer of clothing?</b></p> <p>صفي مستوى الراحة في العباية مع الطبقات المتعددة من الملابس؟</p>	<p><input type="checkbox"/> Very uncomfortable.      غير مريحة إطلاقا</p> <p><input type="checkbox"/> Uncomfortable.      غير مريحة.</p> <p><input type="checkbox"/> I do not know.      لا أعلم</p> <p><input type="checkbox"/> Comfortable.      مريحة.</p> <p><input type="checkbox"/> Very comfortable.      مريحة للغاية</p>
<p><b>16. What do you usually wear underneath the abaya?</b></p> <p>ماذا ترتدي عادة تحت العباية؟</p>	<p><input type="checkbox"/> Blouse (long sleeves) with skirt      قميص طويل مع تنورة</p> <p><input type="checkbox"/> Blouse (short sleeves) with skirt      قميص قصير مع تنورة</p> <p><input type="checkbox"/> Blouse (long sleeves) with slacks or jeans      قميص طويل مع بنطلون او جينز</p> <p><input type="checkbox"/> Blouse (short sleeves) with slacks or jeans      قميص قصير مع بنطلون او جينز</p> <p><input type="checkbox"/> T-shirt with skirt      تي شيرت مع تنورة</p> <p><input type="checkbox"/> T-shirt with slacks or jeans      تي شيرت مع بنطلون او جينز</p> <p><input type="checkbox"/> Jalabiah      جلابية</p>

	Specify اخرى تذكر						
	..... .....						
<b>17. What kind of sleeves do you prefer to wear with abaya? Why?</b> أي نوع من الأكمام تفضلين لبسه مع العباية؟ ولماذا؟	<input type="checkbox"/> Long sleeve <input type="checkbox"/> Short sleeve <input type="checkbox"/> Sleeveless <input type="checkbox"/> Specify.	كم طويل كم قصير بدون أكمام اخرى تذكر					
<b>18. What areas in the body do you feel heat stress, while wearing the abaya:</b> في أي منطقة من الجسم تشعرين بحرارة شديدة عندما ترتدين العباية:	<input type="checkbox"/> Top of the head <input type="checkbox"/> Back of the head <input type="checkbox"/> Neck <input type="checkbox"/> Back of the body <input type="checkbox"/> Front of the body <input type="checkbox"/> Legs	أعلى الرأس خلف الرأس العنق خلف الجسم (الظهر) امام الجسم (الصدر) المنطقة السفلية (الفخذ)					
<b>19. In which part of the clothes do you feel more heat stress with the abaya?</b> في اي جزء من الملابس تشعرين بحرارة شديدة مع العباية؟	<input type="checkbox"/> Blouse <input type="checkbox"/> Skirt <input type="checkbox"/> T-shirt <input type="checkbox"/> slacks or jeans <input type="checkbox"/> Jalabiah <input type="checkbox"/> Specify.	قميص تنورة تي شيرت بنطلون او جينز جلابية اخرى تذكر					
<b>20. How well does the abaya absorb sweat:</b> ما مدى امتصاص الملابس للعرق؟	<input type="checkbox"/> Very poorly <input type="checkbox"/> Poor <input type="checkbox"/> Unacceptable <input type="checkbox"/> Acceptable <input type="checkbox"/> Very well	سيئ جدا سيئ غير مقبول مقبول جدا رائع					
<b>21. How comfortable (rate: 1: Discomfortable; 2: tolerable, 3: Neutral; 4: comfortable; 5 very comfortable) is the abaya when you are:</b>	اعطي درجة : 1 : غير مريح , 2: مقبول , 3: عادي , 4: مريح , 5: مريح جدا						
			1	2	3	4	5
<input type="checkbox"/> Walking outside in the sun. عندما تمشي تحت أشعة الشمس							
<input type="checkbox"/> Inside the car في داخل السيارة							
<input type="checkbox"/> In public place في الأماكن العامة							
<input type="checkbox"/> Market في الأسواق							

D- Details of abaya	تفاصيل العباية
<p><b>22. What kind of materials are used for your current abaya</b> ماهي الخامات المستخدمة في العباية الحالية</p>	<p><input type="checkbox"/> Natural fibre such as cotton, wool, silk and flax الأقمشة الطبيعية كالقطن, الصوف, الحرير, و الكتان</p> <p><input type="checkbox"/> Synthetic fibre for abaya such as polyester and nylon الأقمشة الصناعية كالبوليستر والنايلون</p> <p><input type="checkbox"/> fibre blends (طبيعي مع صناعي) أقمشة مخلوطة (طبيعي مع صناعي)</p>
<p><b>23. What type of fabric is used to make your favorite abaya:</b> <b>a) In terms of fabric thickness;</b> ما نوع القماش المستخدم في عبايتك المفضلة من حيث سماكة القماش</p>	<p><input type="checkbox"/> Thin (&lt;0.20mm) سمك خفيف</p> <p><input type="checkbox"/> Medium (0.23–0.46 mm) متوسط السمك</p> <p><input type="checkbox"/> Thick (&gt;0.74) سميك</p> <p><input type="checkbox"/> Specify. اخرى تذكر</p> <p>.....</p> <p>.....</p> <p>.....</p>
<p><b>b) In terms of fabric weight:</b> من ناحية وزن القماش</p>	<p><input type="checkbox"/> Lightweight (70–100 g/m<sup>2</sup>) وزن خفيف</p> <p><input type="checkbox"/> Medium weight (170–249 g/m<sup>2</sup>) متوسط الوزن</p> <p><input type="checkbox"/> Heavy (300–375 g/m<sup>2</sup>) ثقيل الوزن</p> <p><input type="checkbox"/> Specify. اخرى تذكر</p> <p>.....</p> <p>.....</p> <p>.....</p>
<p><b>c) In terms of transparency:</b> من ناحية شفافية القماش</p>	<p><input type="checkbox"/> Opaque غير شفاف</p> <p><input type="checkbox"/> Medium transparency متوسط الشفافية</p> <p><input type="checkbox"/> Low transparent أقل شفافية</p> <p><input type="checkbox"/> Specify. اخرى تذكر</p> <p>.....</p> <p>.....</p> <p>.....</p>
<p><b>d) In terms of the structure</b> من ناحية هيكل القماش</p>	<p><input type="checkbox"/> Looseness نسيج ذو فتحات واسعة</p> <p><input type="checkbox"/> Moderate structure نسيج ذو فتحات متوسطة</p> <p><input type="checkbox"/> Tightness نسيج ذو فتحات ضيقة</p> <p><input type="checkbox"/> Specify. اخرى تذكر</p> <p>.....</p> <p>.....</p> <p>.....</p>
<p><b>24. Is it acceptable for abayas to be in a different colour rather than pure black?</b> هل تقبلين بأن يكون لون العباية غير الأسود؟</p>	<p><input type="checkbox"/> No. لا</p> <p><input type="checkbox"/> Yes, Specify the colour نعم , حددى اللون</p> <p>.....</p> <p>.....</p> <p>.....</p>



<p><b>25. How do you prefer the abaya to be in terms of:</b></p> <p><b>a) Width of abaya body:</b></p> <p>كيف تفضلين العباية ان تكون من ناحية وسع العباية على الجسم</p>	<p><input type="checkbox"/> Acceptable مقبول</p> <p><input type="checkbox"/> Too wide واسع جدا</p> <p><input type="checkbox"/> Comfortable مريح</p> <p><input type="checkbox"/> Tight ضيق</p>
<p><b>a) Width of sleeve cuffs:</b> أسورة الكم</p>	<p><input type="checkbox"/> Acceptable مقبول</p> <p><input type="checkbox"/> Too wide واسع جدا</p> <p><input type="checkbox"/> Comfortable مريح</p> <p><input type="checkbox"/> Tight ضيق</p>
<p><b>b) Width of sleeves:</b> عرض الكم</p>	<p><input type="checkbox"/> Acceptable مقبول</p> <p><input type="checkbox"/> Too wide واسع جدا</p> <p><input type="checkbox"/> Comfortable مريح</p> <p><input type="checkbox"/> Tight ضيق</p>
<p><b>c) Length of sleeves:</b> طول الكم</p>	<p><input type="checkbox"/> Up to the wrist لغاية الرسغ</p> <p><input type="checkbox"/> Cover the wrist يغطي الرسغ</p> <p><input type="checkbox"/> Under تحت الرسغ</p>
<p><b>d) Width across shoulders:</b> العرض عبر الكتفين</p>	<p><input type="checkbox"/> Acceptable مقبول</p> <p><input type="checkbox"/> Too wide واسع جدا</p> <p><input type="checkbox"/> Comfortable مريح</p> <p><input type="checkbox"/> Tight ضيق</p>
<p><b>e) Length of abaya:</b> طول العباية</p>	<p><input type="checkbox"/> To the ankle الى الكعب</p> <p><input type="checkbox"/> To the ground الى الأرض</p> <p><input type="checkbox"/> Below the knee أسفل الكعب</p>
<p><b>26. Describe the best style of abaya you prefer to wear it?</b></p> <p>كيف يمكن ان وصف العباية المناسبة لك</p>	<p>.....</p> <p>.....</p> <p>.....</p> <p>.....</p> <p>.....</p> <p>.....</p> <p>.....</p> <p>.....</p>

**Thank you for answering the question**

## Appendix E

Table E 1  $R_{ct}$  and  $R_{et}$  for DWC when the manikin in stationary and motion mode in the conditioned surroundings

DWC	Design	Stationary		Motion	
		$R_{ct}$	$R_{et}$	$R_{ct}$	$R_{et}$
Head	U	0.12±0.000	22.05±0.71	0.11±0.002	15.89±0.00
	U+S	0.12±0.002	21.07±0.19	0.12±0.001	17.35±0.34
	U+P	0.12±0.001	21.71±0.33	0.12±0.002	21.36±0.11
Torso	U	0.14±0.001	22.77±0.49	0.12±0.003	18.37±0.00
	U+SH+SK	0.21±0.001	28.85±0.82	0.18±0.004	23.94±0.51
	U+SH+SL	0.21±0.003	30.20±0.51	0.17±0.001	24.66±0.58
Lower torso	U	0.12±0.001	18.54±0.58	0.09±0.001	12.29±0.00
	U+SH+SK	0.25±0.003	45.12±0.76	0.14±0.005	17.96±0.33
	U+SH+SL	0.19±0.002	31.54±0.94	0.14±0.004	22.18±0.54
Abaya	U	0.13±0.001	19.55±0.85	0.10±0.002	14.04±0.00
	U+SH+SK	0.21±0.001	28.77±1.26	0.15±0.003	19.98±0.10
	U+SH+SL	0.18±0.003	26.86±0.87	0.14±0.002	22.37±0.08

Table E 2  $R_{ct}$  and  $R_{et}$  for DWC and different abaya combinations, when stationary and in motion in the conditioned surroundings

	Abaya Design		Stationary				Motion			
			$R_{ct}$ (m <sup>2</sup> . ° C/W)		$R_{et}$ (m <sup>2</sup> . Pa/W)		$R_{ct}$ (m <sup>2</sup> . ° C/W)		$R_{et}$ (m <sup>2</sup> . Pa/W)	
			Fabrics		Fabrics		Fabrics		Fabrics	
			WA	KA	WA	KA	WA	KA	WA	KA
Head group	AO	TS	0.20±0.001	0.21±0.001	30.48±0.62	31.62±0.56	0.161±0.001	0.165±0.001	27.78±0.04	27.58±0.40
		OH	0.25±0.001	0.25±0.002	39.68±0.49	40.55±0.32	0.172±0.001	0.193±0.001	28.75±0.57	33.76±0.71
		LS	0.20±0.001	0.21±0.002	31.82±0.40	32.16±0.25	0.162±0.002	0.165±0.001	24.15±0.59	27.07±0.17
	U+SH+SK+A	TS	0.21±0.001	0.22±0.002	28.44±0.44	30.56±0.47	0.214±0.002	0.223±0.002	29.02±0.05	29.62±0.55
		OH	0.26±0.003	0.28±0.001	31.52±0.68	35.64±0.51	0.226±0.001	0.253±0.003	30.24±0.48	31.12±0.36
		LS	0.21±0.002	0.23±0.003	28.89±0.68	31.34±0.37	0.216±0.004	0.214±0.003	29.86±0.18	29.02±0.24
	U+SH+SL+A	TS	0.21±0.002	0.22±0.004	29.01±0.44	29.91±0.46	0.199±0.004	0.203±0.001	29.59±0.19	30.12±0.27
		OH	0.26±0.004	0.27±0.002	30.06±0.68	32.06±0.49	0.239±0.001	0.244±0.001	32.21±0.27	34.91±0.32
		LS	0.21±0.002	0.23±0.004	29.31±0.68	30.44±0.13	0.199±0.002	0.199±0.003	29.09±0.22	30.23±0.46
Torso group	AO	TS	0.23±0.002	0.25±0.001	43.40±0.56	45.02±0.10	0.178±0.001	0.213±0.000	22.94±0.59	23.81±0.92
		OH	0.25±0.004	0.26±0.002	45.49±0.46	45.83±0.21	0.191±0.001	0.214±0.001	24.89±0.28	25.07±0.62
		LS	0.24±0.004	0.25±0.003	42.26±0.49	43.98±0.50	0.189±0.001	0.210±0.001	21.64±0.35	23.35±0.06
	U+SH+SK+A	TS	0.38±0.002	0.39±0.004	52.08±0.75	51.75±0.85	0.270±0.003	0.276±0.003	29.02±0.52	29.62±0.55
		OH	0.39±0.001	0.40±0.00	54.71±0.89	55.45±0.49	0.276±0.002	0.279±0.00	30.24±0.48	31.12±0.36
		LS	0.37±0.004	0.38±0.006	52.51±0.85	55.80±0.67	0.272±0.003	0.277±0.002	29.86±0.18	29.02±0.24

U+SH+SL+A	TS	0.37±0.002	0.38±0.001	52.47±0.89	57.03±0.28	0.273±0.001	0.277±0.001	30.39±0.38	30.90±0.05
	OH	0.40±0.004	0.42±0.002	56.82±0.99	57.62±0.70	0.273±0.001	0.276±0.003	29.58±0.05	32.59±0.22
	LS	0.40±0.004	0.41±0.001	54.84±0.41	57.49±0.94	0.278±0.001	0.278±0.002	31.36±0.26	31.99±0.08

Table E 3  $R_{ct}$  and  $R_{et}$  for DWC and different abaya combinations, when stationary and in motion in the conditioned surroundings

	Abaya Design		Stationary				Motion			
			$R_{ct}$ (m <sup>2</sup> . ° C/W)		$R_{et}$ (m <sup>2</sup> . Pa/W)		$R_{ct}$ (m <sup>2</sup> . ° C/W)		$R_{et}$ (m <sup>2</sup> . Pa/W)	
			Fabrics		Fabrics		Fabrics		Fabrics	
			WA	KA	WA	KA	WA	KA	WA	KA
Lower torso group	AO	TS	0.18±0.002	0.20±0.001	36.71±0.50	37.54±0.48	0.116±0.001	0.128±0.000	13.56±0.23	14.12±0.06
		OH	0.18±0.002	0.20±0.001	41.51±0.45	44.33±0.35	0.117±0.001	0.141±0.001	14.23±0.81	14.98±0.52
		LS	0.18±0.001	0.20±0.001	37.89±0.50	43.75±0.35	0.113±0.001	0.128±0.001	12.71±0.08	14.33±0.44
	U+SH+SK+A	TS	0.31±0.003	0.33±0.003	66.26±0.97	67.61±0.65	0.184±0.004	0.187±0.002	20.64±0.31	21.40±0.32
		OH	0.32±0.003	0.34±0.001	67.56±0.96	68.80±0.78	0.187±0.001	0.189±0.003	21.52±0.30	22.48±0.06
		LS	0.30±0.004	0.32±0.001	62.75±0.67	62.53±0.69	0.185±0.003	0.188±0.001	22.09±0.35	22.61±0.55
	U+SH+SL+A	TS	0.26±0.003	0.29±0.004	56.78±0.40	56.13±0.95	0.174±0.001	0.177±0.003	23.17±0.05	24.02±0.43
		OH	0.27±0.002	0.30±0.004	54.83±0.27	58.86±0.99	0.177±0.001	0.178±0.005	23.49±0.51	25.01±0.12
		LS	0.25±0.004	0.28±0.013	52.06±0.67	53.80±0.08	0.175±0.001	0.178±0.002	22.46±0.04	24.22±0.44
Abaya group	AO	TS	0.20±0.002	0.22±0.001	38.08±0.11	39.76±0.21	0.141±0.001	0.155±0.00	17.28±0.05	17.80±0.30
		OH	0.21±0.002	0.22±0.001	37.26±0.35	38.29±0.21	0.145±0.001	0.163±0.001	18.35±0.96	19.43±0.69
		LS	0.20±0.001	0.23±0.001	37.64±0.46	41.67±0.52	0.140±0.001	0.155±0.001	16.33±0.25	17.67±0.18
	U+SH+SK+A	TS	0.31±0.004	0.31±0.002	46.97±0.46	47.53±0.42	0.204±0.004	0.210±0.004	24.15±0.19	23.80±0.14
		OH	0.31±0.002	0.32±0.001	51.81±0.92	53.48±0.69	0.213±0.002	0.215±0.002	24.56±0.06	25.08±0.48
		LS	0.30±0.005	0.31±0.00	45.47±0.40	46.76±0.80	0.205±0.003	0.209±0.002	23.67±0.46	24.61±0.35
	U+SH+SL+A	TS	0.29±0.003	0.29±0.002	47.41±0.65	47.71±0.65	0.210±0.003	0.213±0.002	24.45±0.10	25.95±0.35
		OH	0.30±0.005	0.31±0.004	48.62±0.08	49.17±0.80	0.201±0.002	0.210±0.002	25.04±0.14	25.97±0.85
		LS	0.29±0.003	0.30±0.004	47.81±0.88	47.95±0.75	0.195±0.004	0.208±0.001	24.46±0.49	24.95±0.12