THE DEVELOPMENT OF A QUICK DRY FABRIC FOR OUTDOORS GARMENTS

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Copyright statement

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Table of contents

List of Figures and Tables

Abstract

Engineered clothing systems are one of the major textile research areas. These systems have a huge potential in providing protection and comfort to the wearer. Basically, multi-layered fabric technique is used, in which each layer contributes a substantial moisture removal function. The process of moisture removal is greatly affected by the surrounding conditions, such as pressure, temperature and humidity. If these quantities are much higher than the inner microclimate, the moisture removal process is affected, due to reduced hydrostatic pressure. However, the technology of heating in textile systems is widely available but not used as a way of improving and controlling moisture removal.

The project main objective is to investigate the feasibility of using heating elements together with knitted spacer structures so as to maintain and transfer moisture by capillary effect in order to be used for moisture management textiles.

To achieve this a mathematical model to study the moisture transfer process was created and simulated results based on knitted spacer fabric with a construction of 2 tucks and 2 ends was found to be significant. It showed that application of 4W heating using a carefully designed Thermoknit knitted elements which was integrated on the inner side of the spacer fabric successfully improved the moisture transfer by 30% per 11.5 X 11.5 cm sample size. This was further studied on the novel, constructed test rig with two mini-chambers that created controlled climatic conditions as experienced when a textile is situated between the inner microclimate and the outside environment. The same conditions and properties were used for the spacer fabric sample and found to coincide with numerical results.

A prototype garment was created using the 2-tuck-2-end spacer fabric with integrated Thermoknit heater elements on the inner side of the garment.

Chapter 1

1.0 Introduction

Performance textiles is one of the leading developments in the textiles industry. It provides a platform to improve the functionalities of standard textiles. The key functions of textiles are to provide protection and warmth to the wearer. But these functions are continuously undergoing improvements and performance textiles have been at the centre of emerging technologies due to the unique relationship between technology and the end-users. Everyone uses or rather applies textiles in their lifetime and at the same time embraces improved technology. Textiles are the closest one can select to interact with the end-users which is important when one wishes to improve and protect the human body; textiles act as a vital bridge. One of the main areas which is endlessly being developed is moisture management. Here textiles are used to manage the way in which the human body perspires by controlling sweat transfer and evaporation, thus protecting the inner body.

The human body is self-regulating in the sense that it will automatically control its core body temperature. This is important as any increase or decrease in core body temperature could result in fatal body failure. For example during a high level of human body activity, the body's core temperature is increased, and it needs to be cooled down. This is achieved with sweat in the form of moisture, which is produced by sweat glands located in the body and the skin. This moisture should leave the skin immediately in order to allow more of it to be secreted in the glands; normally the sweat is evaporated at the skin thus resulting in the cooling of the skin and the body. However, the evaporation process of the sweat at the skin is influenced by several factors, one important factor being the textile structure of the garment, as it is at the boundary after the skin. As such the textile structure has the task of removing the sweat from the skin to the outside environment for evaporation. This would prevent saturation of sweat on the skin and hence efficient body cooling.

Thus moisture management in the garment is important to the wearer and it should be engineered to control and manage the way moisture is safely and comfortably transferred from the skin to the outer environment. Textiles are widely used for protection and comfort and in performance textiles moisture (sweat) management has become one of the key considerations, solely due to the next-to-skin positioning. As such during the last few decades major research effort has been steered into controlling and maintaining moisture in performance textiles.

1.1 Aims and Objectives of the research

1.1.1 Hypothesis

Textiles have undergone many evolutions since their first use by humans many thousands of years ago and much research has been conducted to produce efficient and more environmentally friendly products. Technical textiles dominate the current science and engineering research. Currently technical textiles are categorized into many different fields such as automotive, medical, sports, geotextiles, military and construction. The research demonstrated in this thesis falls into the category of the sports and recreation area of technical textiles; also called sportex. Currently the main market of sportex is in Europe, North America and Asia. These regions have relatively cold climates which makes sportex an ideal material for clothing when performing a sporting activity outdoors. Even indoors sportex materials are used as they enhance the wearer's performance in sporting activities. The current focus in sports technical textiles is to improve the moisture removal process, whilst still being lightweight and providing warmth (sometimes these are called breathable fabrics).

The basic concept used in the design and construction of current sportex materials is to maintain the skin in a dry condition by moving the sweat away as quickly as possible and then enabling it to evaporate in the outside environment. This is achieved today by creating a fabric structure with a hydrophobic surface on one side and a hydrophilic surface on the other side of the fabric, which is accomplished by using special chemical finishing processes and employing hydrophobic synthetic fibres and/or hydrophilic natural fibres; the different technologies that are currently employed by the sportswear industry are explained in detail in Chapter 2 of the thesis. The hypothesis of the thesis is a new novel concept of using heat to enhance the hydrostatic pressure difference between the two surfaces of a knitted spacer structure in order to encourage moisture transfer and fast evaporation of moisture to the outside environment. The use of a knitted spacer structure would also boost the moisture wicking action within the structure due to improved capillary effect; the mechanisms of moisture management is explained in detail in Chapter 3 of the thesis.

1.1.2 Aims of the project

The main aim of the project is to develop a smart fabric with embedded knitted heaters to generate heat as a way of improving the hydrostatic pressure difference between the two surfaces of knitted spacer structure.

1.1.3 Objectives of the project

The project has been divided into specific objectives given below, which will be used to focus and simplify the process:

- To formulate a theoretical model to explain the moisture transfer in fabrics;
- To validate the theoretical model with experimental results;
- To optimize the theoretical model;
- To select fibres and yarns to be used in fabric manufacture;
- To develop a knitted spacer fabric embedded with knitted heater elements;
- To design and develop a smart prototype garment for outdoor activities.

1.1.4 Significance of the project

The main important significance resulting from this research is the introduction of new and novel concept in moisture management in textiles by utilising a heating system for the sole purpose of maintaining an enhanced hydrostatic pressure difference across the textile fabric, and the knowledge created during the programme of research as carried out. The new structure will increase the levels of comfort to the wearer as the surfaces of the new fabric are maintained at higher dry levels due to increased moisture transfer across the fabric to the outer environment and encouragement of evaporation of moisture to the outside environment. This method will also improve the functionality of moisture management fabrics as it can be used in cold environments, thus improving the overall performance during outdoor activities. In terms of the performance, athletes have to be well prepared in terms warming up of muscles before sporting events and the technology created within this research could be applied to provide necessary warming up of the athletes prior to the event and improve their performance during the event.

Another significance outcome is the new knowledge created through mathematical modelling and experimentation of moisture transmission due to the temperature gradient in the fabric structure. A mathematical model capable of predicting moisture transmission across a knitted spacer structure when it is kept vertical, the author believes, will introduce a new understanding to the scientific community. A model was created by Delkumburawatte (G.B.Delkumburawatte, 2011), to study moisture transmission across a spacer fabric but assumed the spacer is placed horizontally and took into account the influence of gravity. In reality, the fabric is held in a vertical position by the wearer during sport and outdoor activities and the influence of gravity is minimal and this has been considered in this thesis resulting in new knowledge. In order to validate the new models with experimental data a new test rig was designed and developed. This test system comprises of two mini chambers: one with a hot environment and the other maintaining a cold environment. The hot mini chamber will be used to simulate conditions found in human skin and the cold mini chamber can be used to replicate environmental conditions in which the wearer could be located. The new test system will have the potential of changing these conditions and at the same time monitoring the moisture transmission and evaporation processes of fabric samples placed between the two mini chambers. It is envisaged that this test system will enhance the portfolio of test equipment currently available to evaluate moisture management in textiles. Therefore the combination of mathematical modelling and experimental testing of fabrics in a vertical position under simulated environmental conditions will contribute to the important field of moisture management in textiles.

Integration of heating into spacer fabrics, in order to create a technical fabric with excellent drying capabilities, will be in-line with newly emergent smart fabrics that we see today. Smart fabrics are types of fabrics with an additional functionality embedded into the textile during manufacturing to provide both aesthetic functions of the textile and functionality. This can be sensing, lighting, computing and heating. Market figures in this industry are souring; according to report by European Economic and social committee (Butaud-Stubbs, 2013), and it is evident that this industry is growing at a very fast rate and attracting more investment than before. The EU market alone is valued at over USD 62 billion, which is about 20% to 33% of the main sub-segments of the USD 230 billion world technical textile market including non-woven and composites (Butaud-Stubbs, 2013). Technical textiles consumed worldwide about 22 Billion tonnes of fibres in 2010 and that is just 27.5% of a total consumption of all textile and clothing applications (Butaud-Stubbs, 2013). These market figures makes the project more interesting and position it at an important potential stage in future technical textiles.

Heating textiles as moisture management textiles are also one of the growing sectors in textiles. Heating systems are used in various areas in the society for purposes of providing warmth and drying in colder climates (see Figure 1.1.4.1).

Figure 1.1.4.1: Sock drying by using a home radiator heating system

The importance of the project is that there is a double functionality in the heating system. This is because heating will be used in the project to provide a heating effect for fast drying (moisture evaporation) as well as improving moisture transfer. It could be argued that this could be achieved with currently-available, heating textiles. However, this is not the case as in the present research a new, novel, smart textile was designed to handle moisture and to drive it through the fabric quickly to the outer environment by using carefully-integrated heating elements in the core of the textile structure, which is a knitted spacer. As such the implementation of a low power heating system into the textile, and the technology behind the heating itself, are one of the useful impacts of the research.

Chapter 2

2.0 Literature Review

2.1 Introduction

The primary objective of this chapter is to map out the existing knowledge base on how moisture is managed in textiles, i.e. to demonstrate the current theories, science and technology on the subject. This will also enable the state-of-the-art on moisture management in textiles to be highlighted and to identify the knowledge gaps which need to be addressed in the thesis. The secondary objective of the chapter is to underpin the current test methods employed to measure moisture absorbency, transfer and evaporation in textiles.

2.2 Background

The management of moisture in textiles has been one of the leading textiles research areas since the development of synthetic fibres and major improvements in fabric coating systems. The textile industry is interested in understanding how to manage the sweat within a textile structure as textiles are an essential product that every human has to use in terms of personal protection, so there is a great market potential. Also in terms of performance in various sports activities clothing could enhance and improve the performance of the wearer. This together with improvements in technology mean that the timing is perfect for improvement of textiles (Associates).

Apart from sporting activities, climatic environments also affect how people move from one location to the next in fear of extensive climatic conditions. In the northern hemisphere in continental Europe, Asia and North America, in winter periods, it’s very challenging to spend extended periods of time outdoors due to extensive cold conditions these areas are subjected to. In medical terms, the human body functions are adversely affected when exposed to cold climates such as these without proper covering (Zhang, 2002, Wan and Fan, 2008), which can result in a phenomenon called hypothermia (Amico and Lekakou, 2000, Au, 2011, Kar et al., 2007). History shows that humans used wolf and sheep skin to cover themselves in cold climates, but these were not reliable and affordable. So the appetite for creating effective clothing for cold environments became one of the major development in textiles.

It is evident that weather protection and sporting activities provide a major driving force in the development of garments and textiles with superior moisture handling capabilities (Associates). However another factor driving this development forward is the increased attention paid to creating comfortable garments. Human beings feel comfortable when their senses are well satisfied (Schimmel, Sweeney, 1990). In this case, the skin senses that are satisfied by temperature and textiles play an important role in maintaining an optimum skin temperature. They have the ability to assist the control of the body core temperature of the wearer by providing necessary thermal protection against the outer environment. Textiles also provide air permeability between the skin and outer environment due to their type of construction which further improves the sensorial feeling and promotes this much-needed comfort (Zhang, 2002, Sweeney, 1990, Minor, 1960).

Moisture management textiles are well known for their ability to protect and provide necessary comfort to the wearer. When a human body is undergoing extensive activity, muscles and other tissue release large amount of heat due to metabolic actions. The human body has a self-regulating process, which tends to release generated heat to the outside environment. This heat is released as sweat across the skin as a way of maintaining the core body temperature of 37^{o}C. As garments are always worn over the skin the textiles worn next to the skin must assist in the required moisture removal process during sweating, and moisture management textiles should support this action by allowing moisture in terms of sweat from the skin to be removed and evaporated to the atmosphere.

2.3. Moisture management textiles

The mechanism by which moisture management textiles transfer moisture from the skin to the outer environment is mainly through capillary action which transfers the sweat to the outer surface of the textile structure where it is absorbed and evaporated to the outer environment (Kissa, 1996, Hsieh, 1995, Dullien, 1992, Crow, 1998). In typical moisture management textiles, the textile surface in contact with the skin absorbs moisture due to wicking and then transfers it to the outer fabric surface by wetting and capillary actions for evaporation. A pressure difference is created between the outside and inside (skin contact) fabric surfaces as moisture moves, which is responsible for the kinetics and dynamics of the moisture transmission. A patent granted to Osmolife in 2009 used a different technique to provide moisture movement between two conductive textile layers separated by a porous material (Volden et al., 2009). This process used a physical phenomenon called electrosmosis. Electrosmosis is the physical phenomenon into which fluids are moved across narrow microchannel by application of electrical pulse. An electrical pulse generator connected to the two conductive layers forming a series of unidirectional pulses which were interrupted by pulses of opposite polarity on the textile layers. These pulses resulted in a series of electroosmotic movements of fluid across the textile structures.

The main factors to be considered in moisture management textiles for effective comfort and moisture transmission will depend on the type of fibres used in the making of the textile. Moisture management textiles research involves interaction of textile fibres and moisture released from skin as sweat. The focus is to understand the interaction and provide ways to improve sweat removal process from the skin for evaporation. This study uses distilled water as the representation of sweat produced from the skin. Different research (Brojeswari Das, September 2007) has been conducted to investigate sweat properties and ingredients. Results showed that distilled water had effectively similar properties as liquid sweat which makes distilled water viable for use as the liquid during the investigations.

Fibres that have a tendency to attract water molecules are called hydrophilic fibres (R. Bagherzadeh1, 2012). These fibres have more hydroxide groups in their chemical structure that would attract water molecules. A scientific way of determining hydrophilic fibres is by contact angle. This is an angle formed when water droplets come into contact with solids. In this case a solid object is the fibre surface. Literature suggests that with contact angles less than 90^o, as shown on figure 2.3.1 below, wetting occurs on the solid surface, in our case the surface of the fibre gets wets and which translates to water attraction.

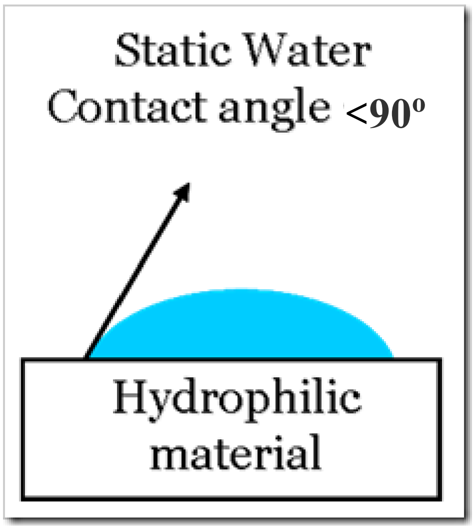


Figure 2.3.1: Hydrophilic material contact angle

These types of fibres are mostly found as natural fibres such as cotton and wool. Textiles made from these fibres are very effective at attracting sweat from the skin but do not necessarily dry quickly. This is due to the nature of moisture absorbency that tends to be into the fibre structure, so drying takes longer as moisture has to be removed from the inside of the fibre. Research (R. Bagherzadeh1, 2012, Ramachandran, 2004)has shown that most natural fibres tend to get saturated during high sweat rates, with the fibres reaching saturation. This prevents moisture movement. Another type of fibre used is hydrophobic. Apart from hydrophilic, these do not have significant hydroxide molecules that could attract water molecules and hence they have the tendency of attracting less water molecules. Contact angles in hydrophobic materials are greater than 90^{o} see figure 2.3.2 below;

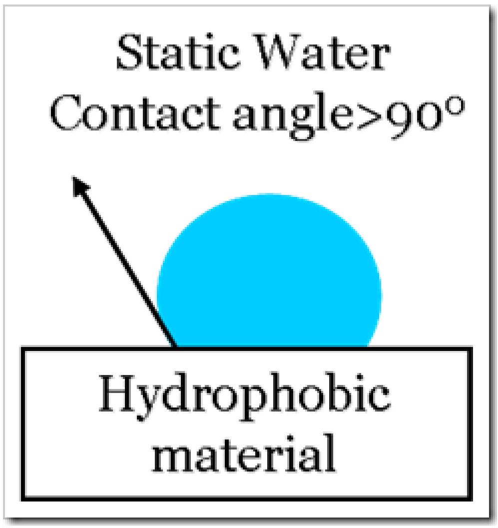


Figure 2.3.2: Hydrophobic material contact angle

Moisture management textiles use hydrophobic fibres because they have a higher drying rate than hydrophilic fibres. Most natural fibres, which are hydrophilic, tend to absorb moisture on the surface and inside the fibres compared to synthetic fibres which absorb moisture only on surface of the fibre (R. Bagherzadeh1, 2012). This makes it easier for moisture to be removed due to less force required and also since fibres are closely packed together it is easier to create air pockets, which enhance capillary action, and heat loss. Hydrophobic fibres are mainly made from synthetic fibres such as nylon, polyester and lyocell. Stretch synthetic fibre such as Lycra produced by Invista (*Invista*), have also been used in moisture management textiles. This type of fibre is used together with other hydrophobic or hydrophilic fibres together. The main advantages of using Lycra is to provide stretch, a soft feel and a recovery effect. Moisture management textiles have to be in contact with the skin to perform effectively. The more that they are in contact to the skin, the more the soft feeling of the fabric quick moisture absorption are provided.

Increased technological know-how of synthetic fibres has resulted in the development of fibres with inherent and superior fibre properties. Literature shows that fibres with certain cross section provide effective moisture transfer (Drirelease, Rossi, 2000, Furtech, 2012, Ramachandran, 2004). Cross sections such as oval, bean, trilobal, and mickey-mouse shaped are the most used today. These shapes of fibre structures are essential in providing large surface areas and micro channels for moisture to pass through. Fibres having larger cross-sectional areas due to their fineness are also used (E. Onofrei, 2011). This is achievable by polymer extrusion processes which allow fine filament fibre diameters to be controlled and produced. These are very useful in providing large areas for moisture spreading, movement and hence effective evaporation. Fine synthetic fibres such as polyester and nylon are the main examples. They produce fabrics which are lightweight, breathable and strong. Leading industry examples include Coolmax fibre by Invista (*Invista*) illustrated in figure 2.3.3 below.

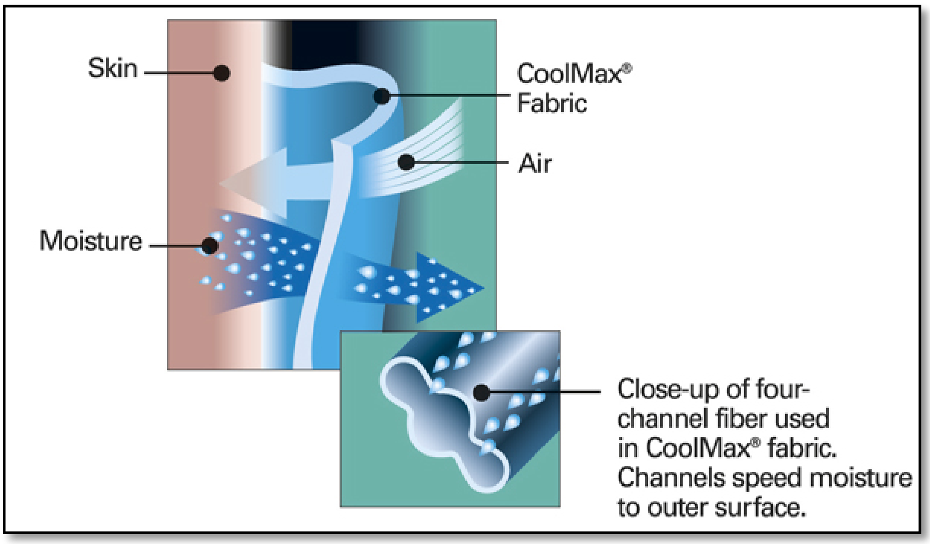


Figure 2.3.3:Coolmax fibre micro channels(*Invista*)

This has multichannel and a large surface area to provide effective moisture transfer and hence keep the skin surface dry. The main applications for this type of moisture management textiles are in sports and outdoor wear. These environments requires weather-proof textiles that can withstand strong wind and rain and still keep the wearer dry by effectively transferring moisture to the outer environment. A Coolmax comfort system is shown on figure 2.3.4 below.

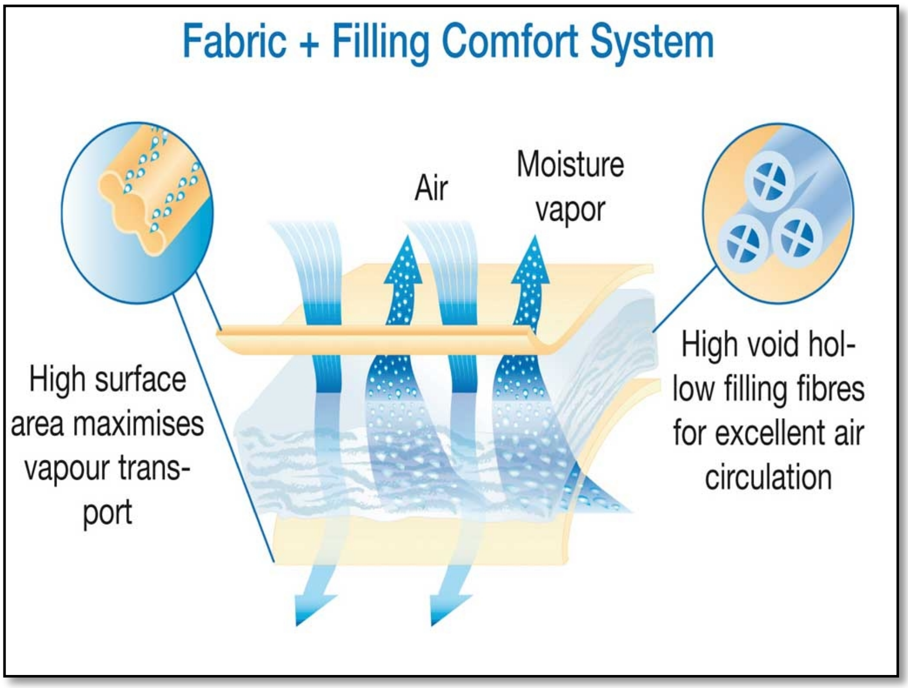


Figure 2.3.4: Coolmax comfort system(*Invista*)

Another important factor in moisture management textiles is the fabric construction. Knitted textiles tend to be more superior compared with woven and non-woven textiles(Saeed, 2006, G.B.Delkumburawatte, 2011, Sedigheh Borhani, Fangueiro et al., 2010). Knitting is the process of interlooping yarns in the sense that a fabric is created by a series of interconnected loops called stitches (Spencer, 2001). The resulting fabrics possess excellent draping and stretching properties which are important in making moisture management textiles. Furthermore, today finer-knitted fabrics can be produced with finer loops due to constant development in machinery, which leads to softer and smoother fabric. Generally, knitted fabrics possess huge advantages in terms of fabric porosity which is useful in allowing air to pass through for good air permeability. Knitted fabrics can be of two types either weft or warp knitted (Spencer, 2001, Karaguzel, 2004). The main difference is in the direction of yarn path in the structure: in a warp knitted fabric the yarn path is in the longitudinal direction where as it lies in the orthogonal, lateral direction in a weft knitted structure. This is due to the way in which the yarns are delivered to the needles of the knitting machine; in warp knitting each needle is supplied with one yarn end similar to the warp of a weaving machine, while in weft knitting all the needles are provided with the same yarn for fabric construction.

As stated earlier, moisture management textiles are required to remove the sweat produced from the skin as quickly as possible to the outside environment without causing the wearer to feel uncomfortable. The wearer will feel uncomfortable when sweat in the form of moisture is left to condense on the skin (on the inner part of the fabric) and this condensing effect causes a wet, cold feeling to the skin (Sweeney, 1990, Watt). So the fabrics have to be designed to effectively remove any moisture and provide a surface area for it to evaporate. To achieve this, substantial research (Moseley and Dhir, 1996, Delkumburawatte and Dias, 2011, Eschler, *Invista*) has been conducted to develop fabrics which provide excellent moisture transmission and high comfort levels. Literature also suggests that a system of layering is effective (Gore-tex, Au, 2011). Here a textile material is constructed in layers with each having a specific function. For example, a three-layer design will consist of a layer to provide a moisture absorption function which will be closest to the skin, followed by a middle layer which will receive and absorb moisture from the inner layer and transport it to the outer protective layer for evaporation. The layers consist of different type of fibres, the innermost layer, which is responsible for moisture absorption, generally consists of high-moisture-absorption and quick-dry fibres. This layer could be made from synthetic fibres and/or a blend of natural fibre. The middle layer must consist of hydrophobic fibre but should have sufficient space for moisture to be transported by capillary forces to the outer layer. The outer layer's main task is to provide the surface area so that moisture can be evaporated whilst protecting the middle, the inner layer and the skin from the outside environment. Also a two-layer design which involves two different types of fibres used in the manufacture of fabrics layers. This referred to in the literature as a pull-push system (E. Onofrei, 2011, Dibisport). This involves a hydrophilic layer on the inside to provide excellent moisture absorption and a hydrophobic layer on the outside to provide a surface area for evaporation of moisture. This means that inner layers pull moisture and present it to the outer layer that pushes it to the surroundings. This process would effectively provide necessary moisture removal and leave the skin dry and comfortable. Another similar way used in recent moisture management textiles involves using a synthetic membrane as the middle layer (Gore-tex). This membrane is carefully constructed to possess micro openings of predefined size. These micro-openings (micro-pores) are designed to allow moisture to pass through whilst preventing water molecules from going through. This means that moisture from the inside (layer next to the skin) is allowed to pass to the outer environment but at the same time water from the outside is prevented from entering to move towards the skin. This effect is sometimes referred to as a breathable effect and a textile fabric with this membrane is regarded as a breathable fabric. This mechanism of moisture transfer is due to the fact that theoretically moisture will flow from a region of high pressure to a lower-pressure region. When the human body is producing sweat, the air layer next to the skin, defined as the microclimate, possess a higher level of humidity and pressure than the outer surroundings. This imbalance creates a pressure difference and hence dictates moisture flow. This technology has been widely accepted and is now used in the development of textiles for sports and recreational activities as well as for outdoor textiles. This well-known, patented technology was invented by Gore-Tex Inc.(Gore-tex). See below figure 2.3.5 below for illustration;

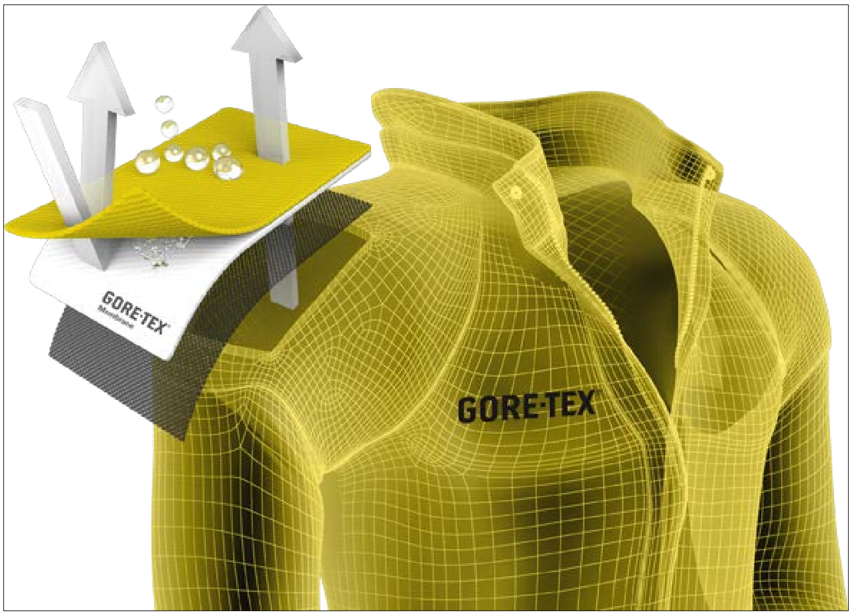


Figure 2.3.5: Gore-tex membrane technology(Gore-tex)

Gore-Tex was co-invented by Wilbert L. Gore and Gore's son, Robert W. Gore (chemheritage). Bob Gore stretched heated rods of PTFE and created expanded polytetrafluoroethylene (ePTFE). His discovery of the right conditions for stretching PTFE was a happy accident, born partly of frustration. Instead of slowly stretching the heated material, he applied a sudden, accelerating yank. The solid PTFE unexpectedly stretched about 800%, forming a microporous structure that was about 70% air. It was introduced to the public under the trademark Gore-Tex. Gore-Tex textiles are used widely today and their use is still expanding. The same technology of membranes with predefined micro pores has been adopted to provide water resistance in wide numbers of applications including shoes, hats, and gloves and in recent times its emergence in telecommunication industry has been seen, to make water-proof mobile phones and other electronics equipment.

Another type of fabric construction used in moisture management textiles using synthetic membranes is the process called the punching technique (E. Onofrei, 2011, R. Bagherzadeh1, 2012, R. Bagherzadeh, 2012). This involves coating a synthetic hydrophobic layer on the inside layer of the hydrophilic fabric. This system would provide moisture absorption through hydrophilic layer while the hydrophobic layer keeps the skin dry. Among the industry leading membranes include Symaptex (Sympatex) and Respire membranes. Figure 2.3.6 below illustrates the technology;

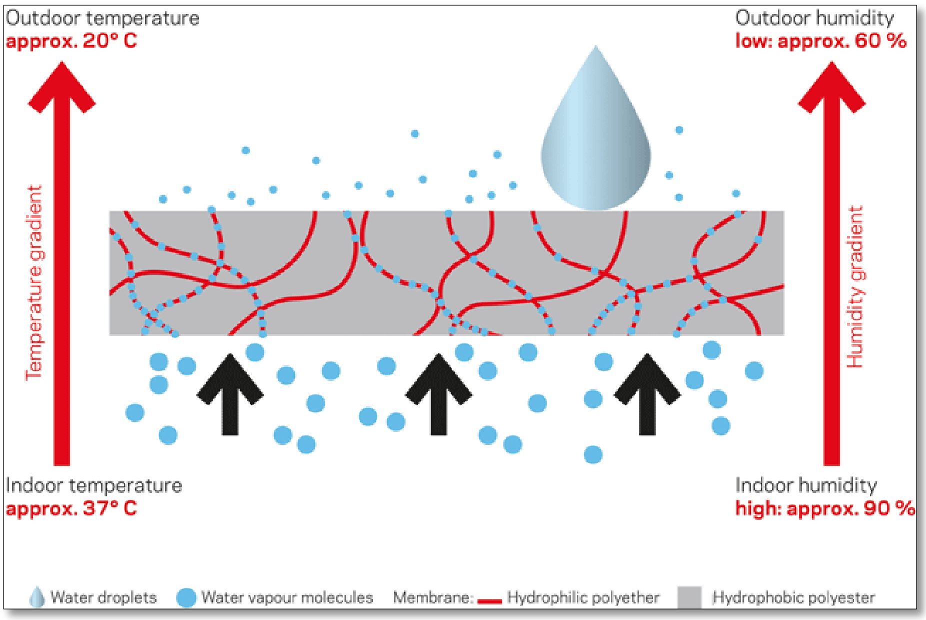


Figure 2.3.6: Sympatex membrane technology(Sympatex)

A similar technology used by Schoeller (figure 2.3.7 below) in their fabric called 3XDRY uses only a single layer of textile but one into which two membranes or finishes are added

(Schoeller). On the inside of the fabric, a hydrophilic finish is added to help with moisture absorption and distribution while the outer side uses a hydrophobic membrane. This provides a surface area for moisture evaporation and protection.

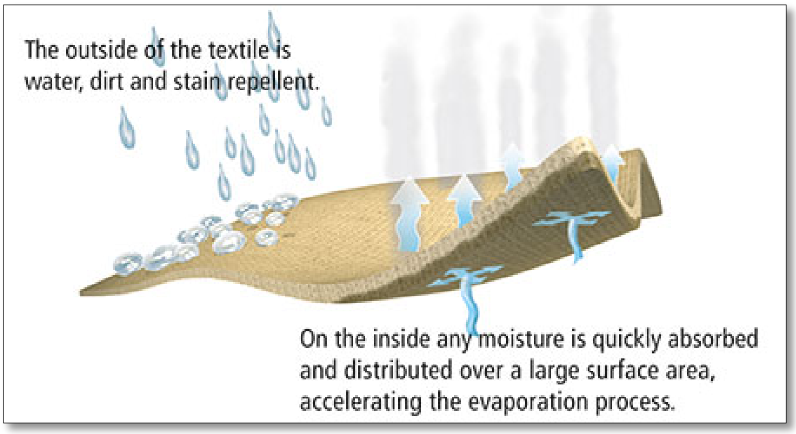


Figure 2.3.7: Schoeller fabric technology(Schoeller)

Another application of membranes in moisture transfer involves the use of an electroosmotic process to provide fluid motion (Heldal and LAUPER, 2013). This membrane consists of pores which allow electrolysed fluids to pass through. Basically, according to Heldal and Lauper, most surfaces possess a negative charge due to surface ionisation which would build along the surface to create an electric double layer. The porous layer membrane is placed between two porous conductive layers connected to the pulse generator which provides the necessary pulse for fluid movement due to attraction of ions on the electric double layer to the oppositely charged electrode. The pulse generator provides an intermittent voltage between the two conductive layers to produce the required pulse for fluid motion.

Spacer fabrics are a type of construction technique used in moisture management textiles. Spacer fabric is a type of knitted fabric that consist of two layers joined together by spacer yarn in between (R. Bagherzadeh, 2012, E. Onofrei, 2011),see figure 2.3.8 below. The spacer yarn that joins the two layers can be varied in terms of length and number of joining points between the two layers. This variation provides huge advantages as the middle layer consisting of spacer yarn can be used to provide variable air pockets to control moisture flow and also provide insulation. The main applications of spacer fabric include compression paddings, sports cushions, sound insulation, heat insulation and moisture management textiles. All these applications depends on the density of spacer yarn used between the two layers. For sports padding, sound insulation and compression padding; the spacer yarn density is high. For heat insulation applications, the spacer yarn layer has a medium density to provide air pockets for insulation which prevents heat loss by convection. In moisture management textiles, spacer yarns could be high or medium density to allow moisture flow between the two layers by capillary forces while the other two layers are used as absorption, protection and evaporation media.

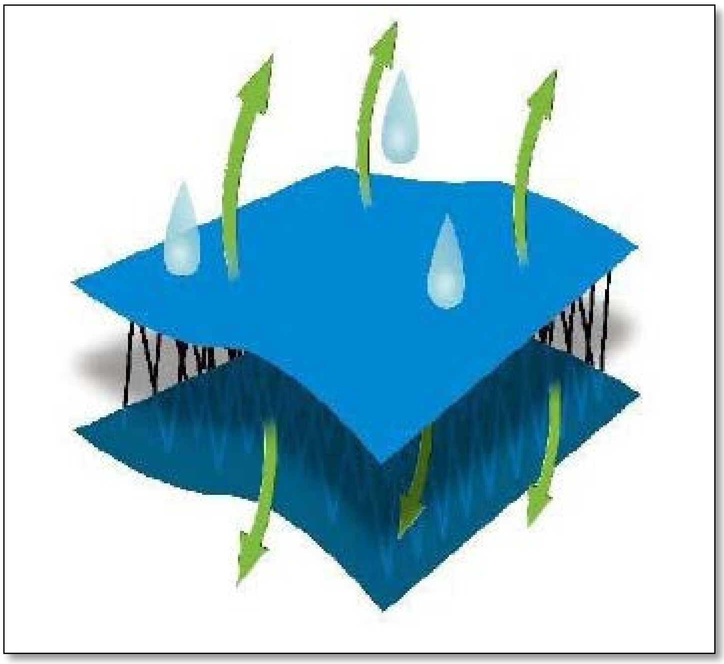


Figure 2.3.8: Spacer fabric for moisture management textiles

The types of fibres used in spacer fabrics can be both natural or synthetic depending on the type of applications.

Plating is also one of the techniques used in moisture management textiles fabric construction. This is the process of simultaneously forming loops from two yarns (E.

Onofrei, 2011). Two different types of yarns may be used, so that their combined properties provide effective moisture handling. Plating of both hydrophilic and hydrophobic yarns can be used to produce fabric with excellent moisture absorption and ability to keep the skin dry. DriRelease (Drirelease) is among the moisture management textiles which uses plating method and figure 2.3.9 below illustrates this.

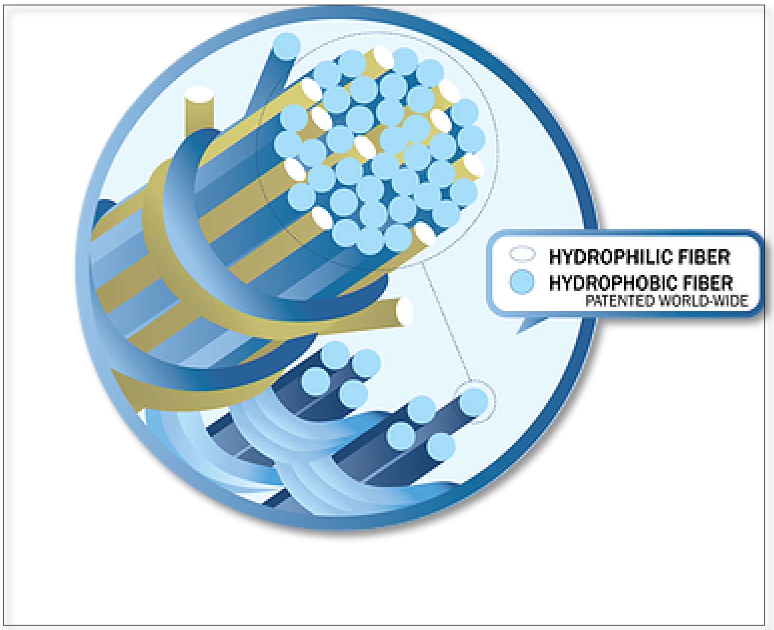


Figure 2.3.9: DriRelease fibre technology(Drirelease)

New, emerging technologies in moisture management textiles incorporate the application of microencapsulation technique. In this process, special materials called thermocules are encapsulated into the fibre structure to provide useful functions, as shown in figure 2.3.10 below. Among the most well-known is outlast technology which uses phase-changing materials originally developed for NASA (Outlast). Encapsulating these materials into the yarns that are mostly viscose fibre, introduces unique functions.

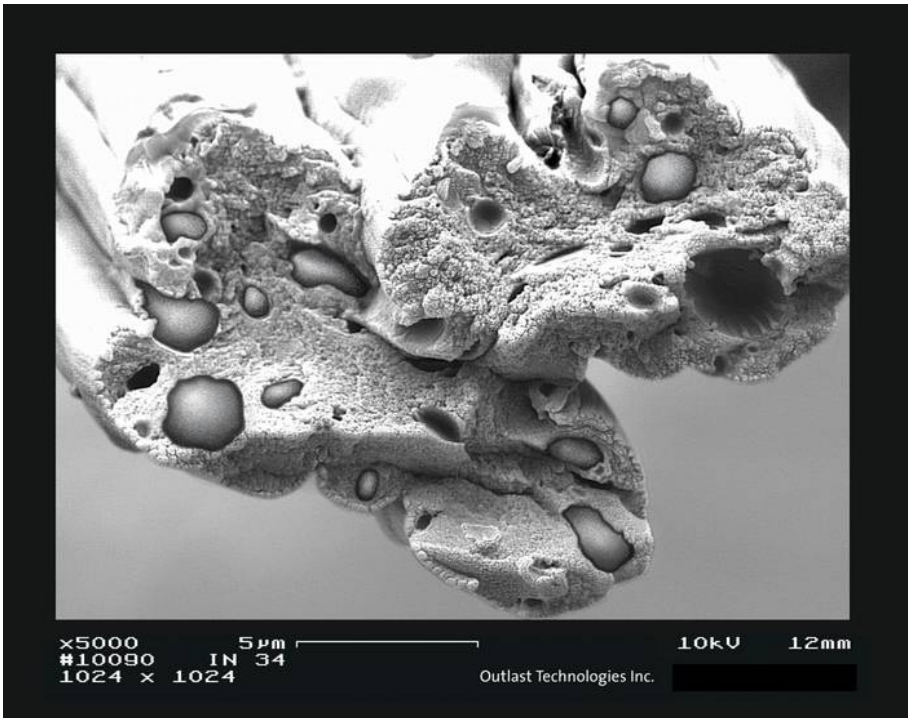


Figure 2.3.10: Magnified image showing Outlast fibre microencapsulation(Outlast)

Phase-change materials are a type of materials that changes shape due to changes in temperature. For instance, when exposed to an increase in temperature they expand as a result of heat absorption (keeping the area cooler), and release this heat when the temperature drops. The process can be illustrated by figure 2.3.11 below.

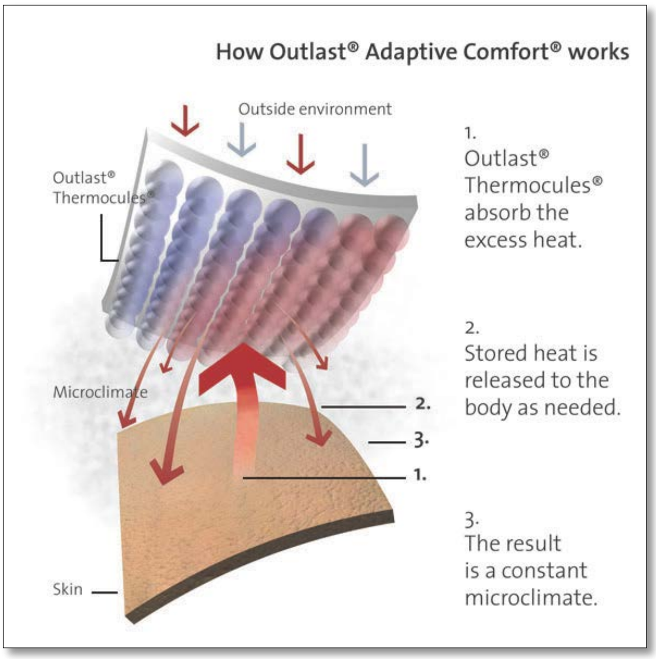


Figure 2.3.11: Outlast fabric technology(Outlast)

Outlast claims this technology reacts quicker than most moisture management textiles as it detects when a cooling effect is required by absorbing the excess heat before the body sweats. This helps the body to feel comfortable soon enough before actual sweating occurs.

The literature review shows that considerable research effort has been devoted to understanding the scientific principles of moisture transfer in textile structures which has resulted in the development of new fibres, yarns and manufacturing technologies to improve moisture management in textiles, but the successes to date still leave room for more improvement. As described in the methodology section later in chapter 3; the performance of most moisture management textiles is affected by the surroundings in which they operate. In surroundings involving extreme weather conditions, moisture movement across the textile fabrics from skin to the outer side can be affected by reduced hydrostatic pressure differences caused as a result of the outside weather conditions. In this case moisture which was supposed to be transferred to the outer environment remains within the fabric causing discomfort to the wearer as the sweat is contained within the fabric which would hinder further movement of sweat. This could cause condensation of sweat occurring inside the fabric. Also as sweat is being accumulated within the fabric, fabric porosity would be reduced preventing air movement and the fabric breathability would be effected. A major improvement which is the basis of this research is to prevent such a scenario by increasing the hydrostatic pressure difference between the outer surface and the inner surface of the fabric. The aim of the research is to investigate how the hydrostatic pressure difference could be increased by creating a temperature gradient between the two outer surfaces of a knitted spacer structure in order to improve the moisture transfer and evaporation in the structure. This can be achieved by increasing the temperature slightly on one surface which would increase the inner pressure (pressure generated due to inner temperature and humidity as explained in detail in chapter 3) and hence increase the overall hydrostatic pressure difference and improve moisture transfer. In order to achieve this a new type of textile have to be developed which will have the ability to accommodate a heating system as well as providing moisture management. Currently knitted spacer fabrics are been used in impact, noise insulation and moisture absorption applications. Due to the capability for producing complex structures on modern, computerised flat-bed knitting machines this technology was utilized to produce spacer structures for the research.

As the evaluation of moisture transfer in textiles is crucial to this research an intensive literature review on equipment and test methods which are currently used for testing moisture management textiles was carried out and its results are summarised in the following sections.

2.4 Liquid absorption and wicking test methods

Wicking is the process by which a liquid material travels into fabrics as they come into contact with each other (Saeed, 2006, Kissa, 1996, Yanılmaz and Kalaoğlu, 2012). This can happen when the fabric is completely or partially immersed in a liquid. After the liquid has made contact with the fabric, another process called wetting occurs, which is basically the spreading of liquid within the fabric. These two processes are very important in fabric absorption characteristics, as they determine the amount of fluid a fabric can absorb. The more wicking ability that a fabric possesses, the more liquid it can absorb and vice versa. In the wicking process, the amount of liquid coming into contact with a fabric is important. This can be divided into two major scenarios; wicking from finite and infinite reservoirs. Finite reservoir wicking is the type of wicking in which the amount of liquid coming into contact with a fabric is limited. The amount of liquid presented to the fabric is less and available for short period of time. This situation can be demonstrated by a drop of water falling onto a fabric sample. Infinite reservoir wicking, however, comprises a larger amount of liquid reaching the fabric layer for an extensive time during which more liquid is allowed to come into contact with the fabric than in finite reservoir wicking. In the majority of test methods the technique of wicking from an infinite reservoir is used to evaluate the performance of moisture management textiles by measuring the time an extensive amount of liquid is expected to reach the fabric surface. Furthermore, wicking from an infinite reservoir can be classified into longitudinal wicking, transverse wicking and immersion.

2.4.1 Longitudinal wicking test

The longitudinal wicking which is sometimes called vertical wicking is the test used to quantify the wicking in textile fabrics. It is one of the most commonly-used methods of testing wickability of fabrics. This type of test is carried out by hanging a piece of fabric with its lower end immersed in distilled water (see Figure 2.4.1.1). The test sample should measure 50 mm wide and 15 mm long according to the British Standard reference BS 3424-18 method 21A (1973). Part of the sample to be immersed in water is also described on the standard. Counterbalancing weights are attached to the bottom end of the sample to prevent bending and allowing the sample to be aligned straight. As in all textile testing conditioning of the samples prior to testing is crucial, and as such all the samples are pre-conditioned at standard 20^{o}C and 65% humidity for 24hrs. The main factor to observe in this test is how long the liquid will rise through the fabric and to what height. In order to keep track of liquid rise a special dye is mixed with water so that it will provide a visible effect when rising across the fabric. Since the mass of water absorbed depends upon the fabric structure and the thickness, and only the height to which the water has risen in the sample is measured, this test does not provide the mass of liquid absorbed by the sample in a given time. However the weight of liquid absorbed can be calculated at the end of the test from the initial and the final weights of test sample.

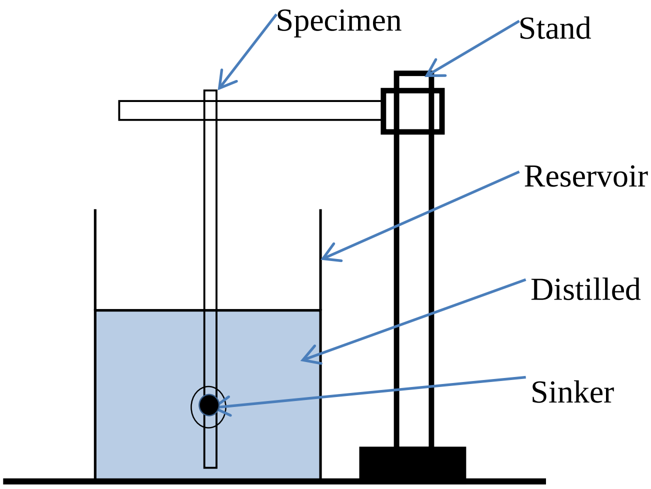


Figure 2.4.1.1: Apparatus for vertical wicking test

2.4.2 Downward wicking test

The downward wicking test is another type of test used to describe the wicking of fabric. It is similar to vertical test but this test is designed to overcome the effect of gravity. Gravity has a potential effect in liquid rise as it pulls the liquid back due to its weight and this affects the vertical rise. The downward wicking test is carried out in two stages. The first one is to determine the upward wicking rise where one end of the sample fabric strip is suspended between a rotating rollers on one side while the other end is immersed in water. In the second stage the fabric sample is suspended vertically from the roller with one end in water while counterbalancing weights are added at the other end (see Figure 2.4.2.1). The main objective of this setup is to pull water to the rollers through the siphoning effect and then allow wicking to occur from the roller downwards. Simulation theories on downward wicking tests suggest that no overtaking effect is observed as compared to the vertical wicking test in which gravity affects the vertical rise of liquid through samples.

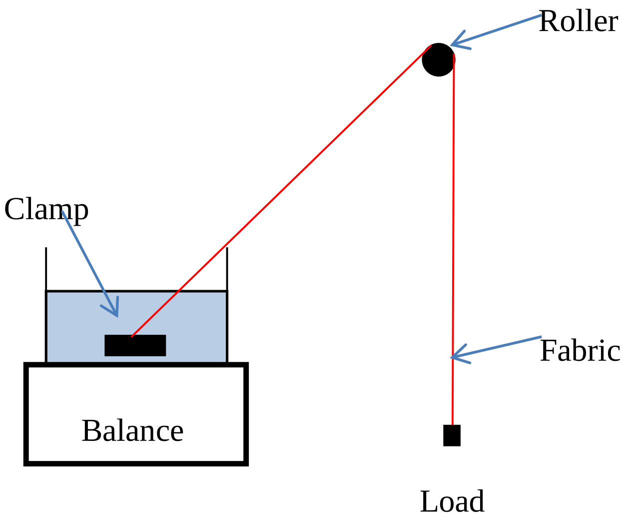


Figure 2.4.2.1: Arrangement of downward wicking test

2.4.3 Transverse wicking test

This type of test refers to the movement of liquid through the thickness of the fabric, and is considered as the most important test because it mimics the real life situation of fabrics. Most textiles are used to prevent the wearer from cold conditions while allowing moisture (sweat) to transfer across the fabric to the outer environment. The liquid transfer through the fabric is more difficult to measure compared to the vertical and the downward tests as the test distance, i.e. the fabric thickness, is relatively small and also the time taken for the liquid to travel across the fabric is very short. Wicking, by definition, is the ability of a fabric to take up liquid spontaneously in the absence of any external forces. This means movement of liquid in the fabric takes place against a zero pressure head.

2.4.3.1 Plate test method

This is one of the tests used for testing transverse wicking in fabrics. Literature shows no applicable test standard for this type of test. However, the plate test method, which could be used to evaluate transverse wicking in a fabric, consists of a use of a horizontal, sintered glass plate which is fed by water from the bottom by a horizontal capillary tube (Figure 2.4.3.1.1). The capillary level of liquid in the sintered glass can be adjusted to simulate the sweating of human skin. During the test a circular fabric sample is placed on top of the sintered glass and a weight is placed on top of the fabric sample to allow constant contact between the fabric and the surface of the sintered glass. The rate of moisture uptake by the fabric sample is determined by noting the movement of the meniscus on the capillary. The mass of liquid uptake by the fabric sample can be calculated by considering the cross sectional area of the tube. The weight applied on top of the fabric sample provides pressure to the fabric and this pressure application affects the liquid flow through the fabric sample. The higher the pressure, the more liquid would be drawn up by the fabric sample. A low pressure could prevent fabric moisture draw. As such, an optimum level of pressure is important for correct measurement. The literature points out some known problems with this test; one of which is the resistance of fluid flow. This is reduced as water is drawn in from the tube. An air bleed system of constant resistance is thought to be the solution to overcome this effect.

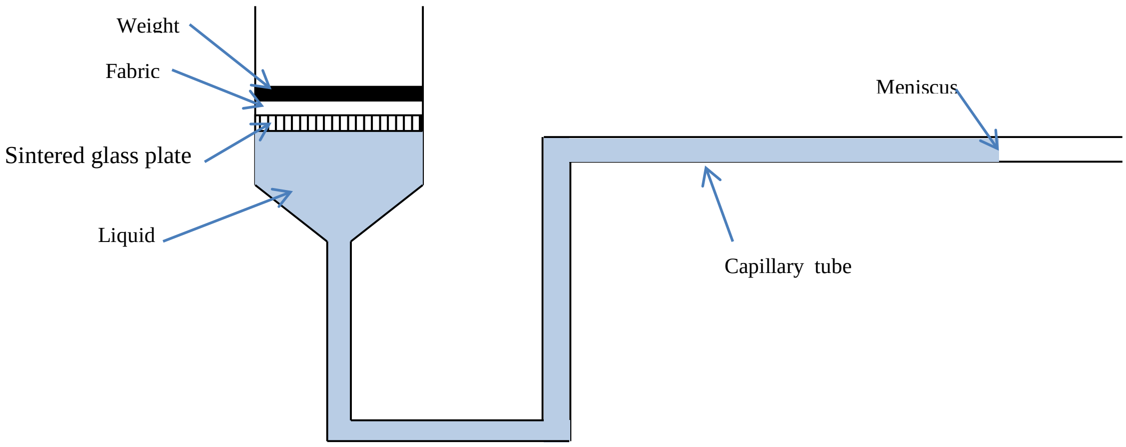


Figure 2.4.3.1.1: Arrangement showing plate test

2.4.3.2 Gravimetric Absorbency testing system (GATS)

This is another type of testing used to measure a fabric’s ability to absorb moisture. It is a much improved and an accurate way of measuring fabric moisture absorbency. The system was introduced by McDowell in 1982 utilising an automatic gravimetric technique to monitor real time movement of liquid in a fabric as a function of time (Saeed, 2006, standard, 2002).

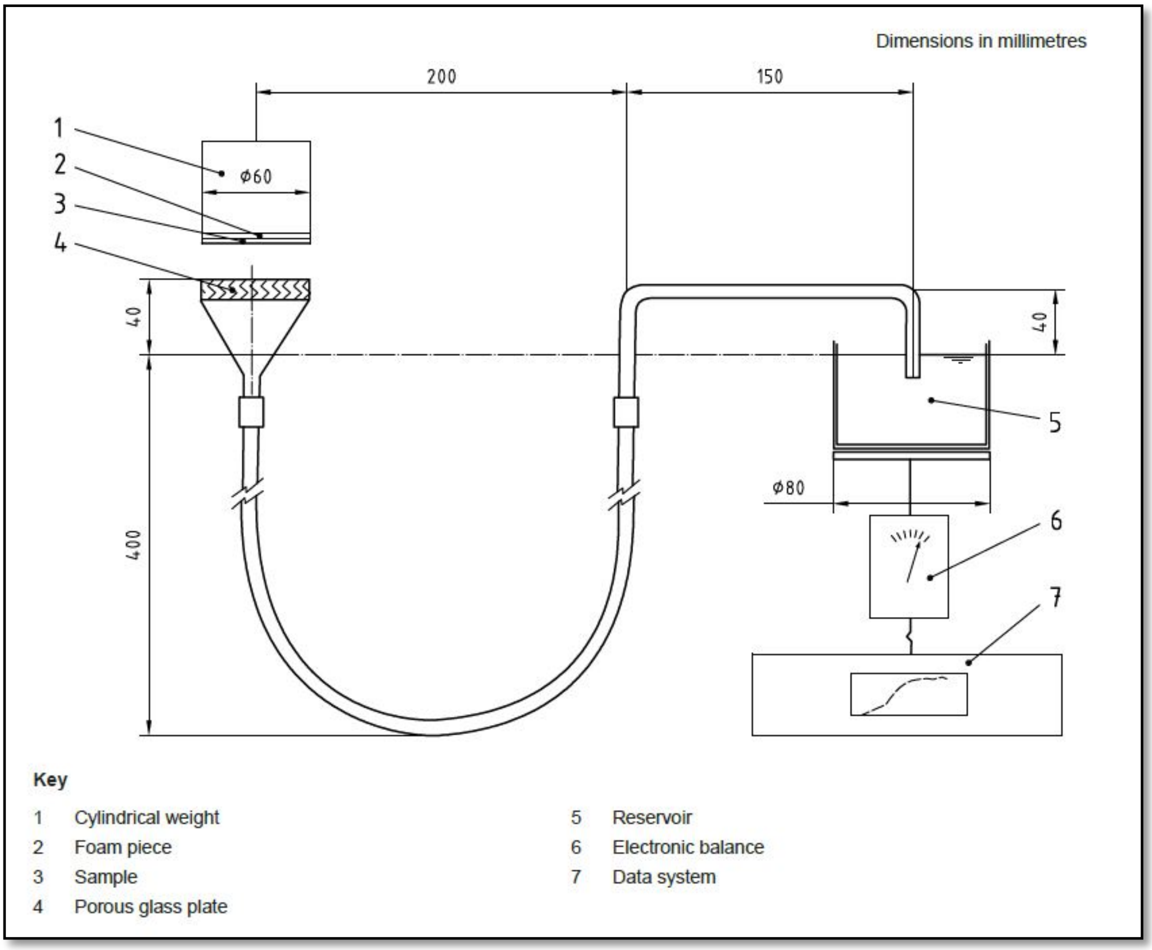


Figure 2.4.3.2.1: GATS principle(standard, 2002)

The arrangement of GATS consists of three main parts; the fabric test plate, water reservoir and the Data acquisition system. The fabric test plate consist of a porous plate having a 2mm hole in the middle. This hole allows water to be presented to the circular test sample of 3.5 inch diameter placed on top of the test plate. Water comes to the test plate from the reservoir and is connected by a rubber tube at the bottom of the test plate. The vertical level of the test plate can be adjusted to provide zero pressure head so that the liquid is only supplied as per demand of the fabric sample. The reservoir is filled with distilled water and it is positioned on top of a precision digital weighing balance which is connected to a computerised data acquisition system. The data acquisition system records the water flow information and the weight change in the reservoir as the fluid is moved to the test plate due to the absorption of the test sample. Real-time information is displayed on the computer screen as the experiment runs.

The GATS system, manufactured by MK Systems is used widely by academia and industry. The M/K GATS has been designed to comply with ISO 9073-12:2002 Apparatus for Demand Absorbency, Apparatus for USA Patent 6,048,123, Tappi T-561, ASTM D5802, which also has the new M/K System's USA Patented liquid interface(MKSystems). It should be noted that moisture absorbency testing of all fabric samples reported in the thesis was carried out with a GATS manufactured by M/K Systems shown below.

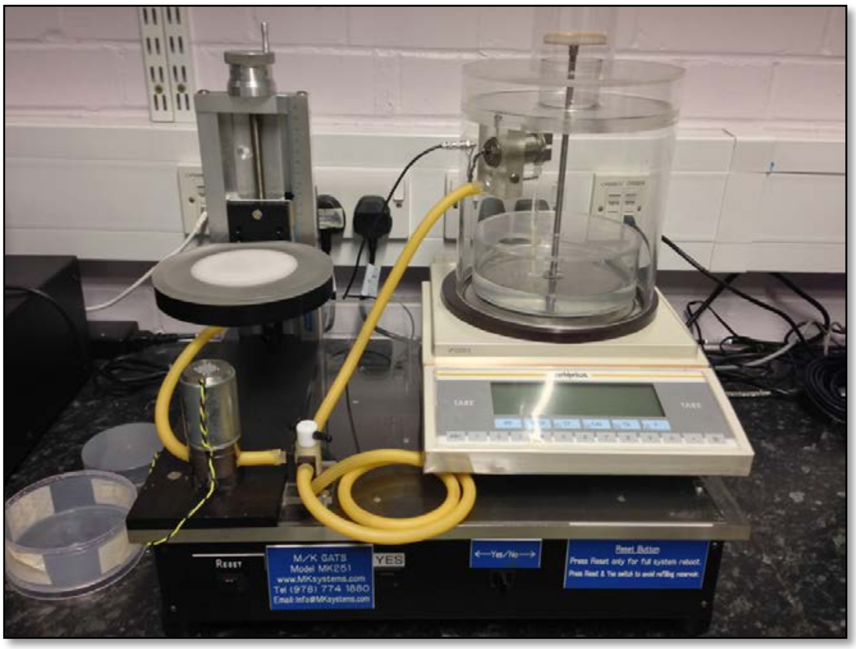


Figure 2.4.3.2.2: MK GATS equipment(MKSystems)

The GATS system measures two important parameters when measuring fabric absorption. These are rate of absorption and total absorbency capacity of the fabric. The maximum absorbent capacity (V) is defined as the total amount of liquid absorbed in grams for the entire sample.

The maximum absorbent capacity (V) is expressed as:

$$Maximum\ absorbent\ capacity = V = \frac{grams\ of\ liquid}{grams\ of\ fabric}\left(\frac{g}{g}\right) \ldots\ldots\ldots\ldots\ldots\ldots (2.4.3.2.1)$$

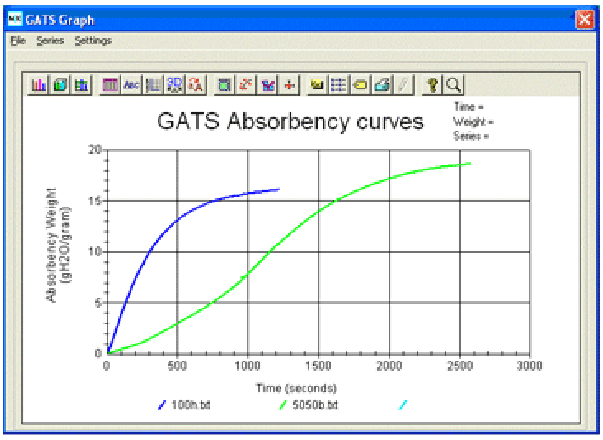


Figure 2.4.3.2.3: GATS absorption curves(MKSystems)

The specific absorbent capacity (C), can be expressed in terms of absorbent capacity as:

$$\text{Specific absorbent capacity} = C = \frac{V}{W} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.4.3.2.2)$$

Where: W = weight of dry specimen in grams

The system can also be used to calculate the liquid flow rate (Q). This is defined as the total amount of liquid in grams absorbed by the material per unit time (T) in minutes. This is expressed as grams of liquid per min:

$$Flowrate = Q = \frac{V}{T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.4.3.2.3)$$

The specific flow (q) rate can be simply obtained by having the ratio of flow rate to the weight of the fabric in grams of liquid per grams of fabric per unit time, (g/g.min);

$$specific\ flow\ rate = q = \frac{Q}{W} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.4.3.2.4)$$

2.5 Moisture transmission

The above section briefly explained moisture absorption in a textile fabric and different measurement techniques. The important definition of textile comfortability is to keep the wearer with a moisture-free, dry environment and also to ensure that moisture in terms of sweat is moved away from the skin to the outer-most layer of a garment for evaporation (Watt, Sampath et al., 2012). The human body is a self-regulatory system in which the core body temperatures has to be maintained at an optimum level for the proper function of vital organs and systems. This is achieved easily during normal activities. However, an imbalance is caused when performing activities such as sports in which the body core temperature is increased due to muscle movements. In order to remove this excess heat, sweat is produced via the skin which comes into contact with the inner layers of the clothing; often called the second skin. As such this layer must possess high absorption capabilities and also the ability to transfer the absorbed moisture to the outer garment layers for evaporation.

Literature (Yi Li and Qingyong Zhu, 2003, Srikiatden and Roberts, 2007, Gibson and Charmchi, 1997) shows that during sweating, moisture vapour can be created on the human skin during exercise, and this moisture vapour has to be transmitted to outer layers of the garment in order to avoid moisture condensation on the skin, i.e. within the microclimate. The microclimate is the mini space formed between the human skin and the textile, comprising its own temperature, pressure and humidity. As a result the relative humidity in the microclimate region could increase due to the accumulation of moisture which may cause condensation and bring about a clammy feeling for the wearer.

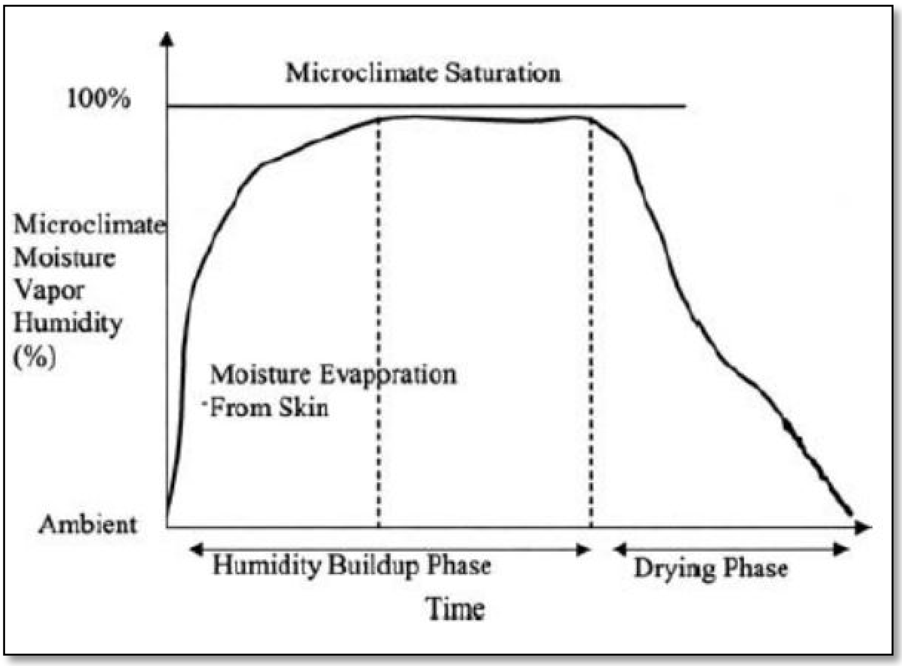
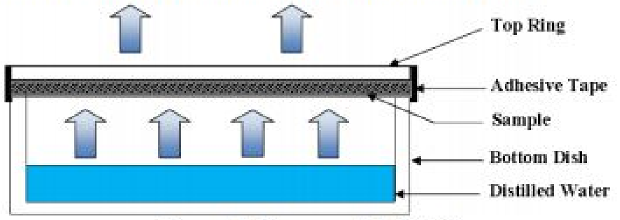


Figure 2.5.1: Humidity variation in microclimate(Nahla Abd El - Mohsen Hassan Ahmed, 2012)

Therefore, textile fabrics should be designed to facilitate efficient moisture vapour removal. As the mechanism of vapour transmission is by diffusion, absorption and desorption, different techniques for measuring moisture vapour transmission have been developed by several researchers (Nahla Abd El - Mohsen Hassan Ahmed, 2012). These have been summarised in Table 2.5.1 below.

Table 2.5.1: Test methods to quantify moisture vapour transmission

	Method	Standard	Principle
1	**Sweating guarded hot plate method**	**ISO 11092**	In this method, the water vapour transmission is measured in terms of evapourative heat resistance (Ret) of the material, i.e. amount of power required to maintain the heated plate at skin temperature (35°C) when moisture vapour evapourates from the plate and diffuse through test sample place kept on top of it. A sample measuring 5 inch X 5 inch is placed on the hot plate (or membrane) that is saturated with water to simulate sweating. The heat resistance **(Ret)** is given by the equation: **Ret (m2 Pa W-1) = A (Ps – Pa)/H** **Where, A = test area in m2, Ps = vapour pressure at plate surface, Pa = vapour pressure in air, and H = input power**
2	**Evapourative dish method**	**(BS 7209)**	According to the British standard BS 7209:1990, the test specimen is sealed over the open mouth of a test dish which contains 46 ml of distilled water and the assembly is placed on a rotating turntable and allowed to rotate in a controlled atmosphere of 20°C and 65% relative humidity. Following a period of one hour to establish equilibrium of water vapour pressure gradient across the sample, successive weighing of the assembled dish at first and fifth hour gives the amount of water permeated (M) through the specimen. The MVTR is then calculated using the equation: **MVTR (g/m2/24hr) = 24M/At Where, M = mass of water vapour in grams lost in t hours** **A = area of the sample exposed to vapour (0.0054113 m²)**  **Figure 4. Evapourated Dish(9)**
3	**Upright cup method**	**(ASTM E 96-80)**	In this method, sample being tested is placed on top of a 155ml aluminum cup that is filled with 100ml of distilled water and covered with gasket and clamps. This assembly is kept inside a controlled chamber where temperature, relative humidity and air velocity are maintained at 21 ± 0.6°C, 50 ± 2% and 2.8 ± 0.25 ms-1 respectively. The weight of the cup assembly is measured after 3, 6, 9, 13 etc. respectively. The water vapour transmission is then measured using the following equation:**WVT (g/h/m2) = (G/t) / A (2.9) Where, G = weight change in grams, t = time during which G occurred in hours, G/t = slope the straight line (wt. loss/unit time) in g/h/m², A = sample area in m²**
	Desiccant (inverted cup) method	**(ASTM E 96-80)**	The test specimen is sealed on top of the open mouth cup that contains the desiccant (anhydrous calcium chloride, dried at 400°F before use). The assembly is then kept inside the controlled chamber as in the upright cup method. Periodical weighing of sample assembly will determine the water vapour transport through the specimen.
5	**Dynamic moisture permeation cell**	**(ASTM F 2298)**	It measures the moisture vapour diffusion resistance of the sample by passing mixture of dry and wet-saturated nitrogen streams above and below the sample. By carefully measuring the relative humidity of input and output streams the vapour diffusion resistance is determined. A humidity gradient of 90%, air temperature of 20 ± 1°C and gas flow rate of 200 cm3/sec is maintained throughout the experiment. The water vapour diffusion resistance is calculated using the equation:

Literature (Kissa, 1996, Watt) also reports that the main mechanism for transmitting moisture in a textile fabric is the capillary effect. This effect causes water to be transmitted through narrow tubes. The main factors which influence the capillary system of a textile structure are the types of fibres used, the length of capillary and the hydrostatic pressure difference between the two sides of the capillary. Generally the type of yarns used to manufacture textile fabric with good moisture-transfer characteristics should possess high capillary effect which is created due to the formation of micro channels between the fibres of the yarn; this would allow micro tubes to be formed in the textile structure to allow moisture to transfer in the textile fabric. Fibres with different cross-sections have been developed by synthetic fibre manufacturers for the sportswear industry who have designed fabrics with enhanced moisture management (Drirelease, Gore-tex, DuPont). The length of the capillary in the textile structure also plays an important role as it influences the amount of moisture that can be transmitted to the outer environment.

Lucas Washburn kinetics can be used to explain the dynamics of the capillary effect. This shows that the longer the capillaries are, the less time is required to move moisture within the fabric. Another factor affecting moisture transmission is the hydrostatic pressure difference between the two ends of the capillary. The capillary ends next to the skin, in the region that is sometimes known as the microclimate, possess conditions which create an inside pressure (Buck, 1981). Similarly the other end, which will be on the surface of the fabric, and exposed to outside environmental conditions, will be at atmospheric pressure. This difference in pressure plays a major role in the transmission of moisture across the fabric. As such, in order to achieve effective moisture flow within fabric, the pressure on one side of the fabric has to be higher than the pressure on the other side of the fabric. A higher pressure difference, known as hydrostatic pressure difference, will enhance moisture transmission at a high rate.

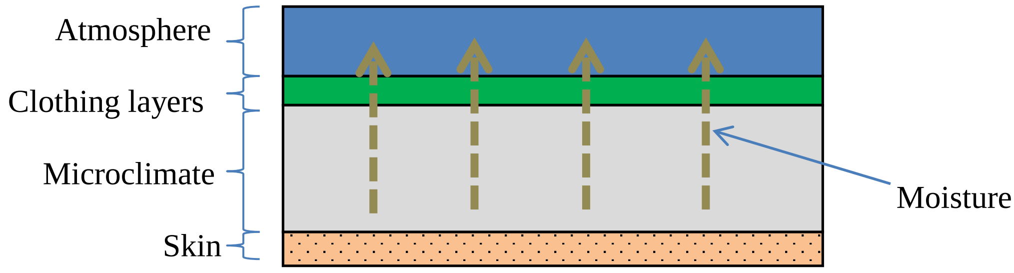


Figure 2.5.2: Cloth-body system

The moisture transmission across a textile structure can be studied by subjecting the textile structure to real environmental conditions and then by monitoring its performance. This means that two different environmental chambers have to be created, i.e. hot and cold chambers to mimic actual environments, in which the fabric can be tested. To continuation in ensuring realistic test conditions, actual fabrics made into garments are used on a human manikin. Currently, fabrics are tested on a manikin that is created to mimic a human, in order to create repeatable data. Among the pioneers of this technology are the Hohenstein Institute in Germany (Hohenstein). Three different manikins named ‘Charlie’, ‘Charlene’ and ‘Sherlock’ have been designed to test fabrics at different environment conditions. Sensors, sophisticated sweating mechanisms and weighing systems are integrated within the manikins to facilitate moisture transmission and to determine moisture transmission characteristics precisely. This technology is used by researchers and manufacturers to study the performance of garments under different conditions.

Figure 2.5.3: Hohenstein Testing manikin(Hohenstein)

Recently, a new technology was developed (GHANMI H.) which utilise electrical capacitance measurement to monitor moisture transmission across fabrics (Figure 2.3.4). This involves placing electrode plates on both sides of the textiles fabric to measure the capacitance. The research has shown that the measurements can be influenced by the moisture passing through the fabric. Experimental results have demonstrated similar moisture transmission behaviour of fabrics tested with Hohenstein and capacitance measurement technologies.

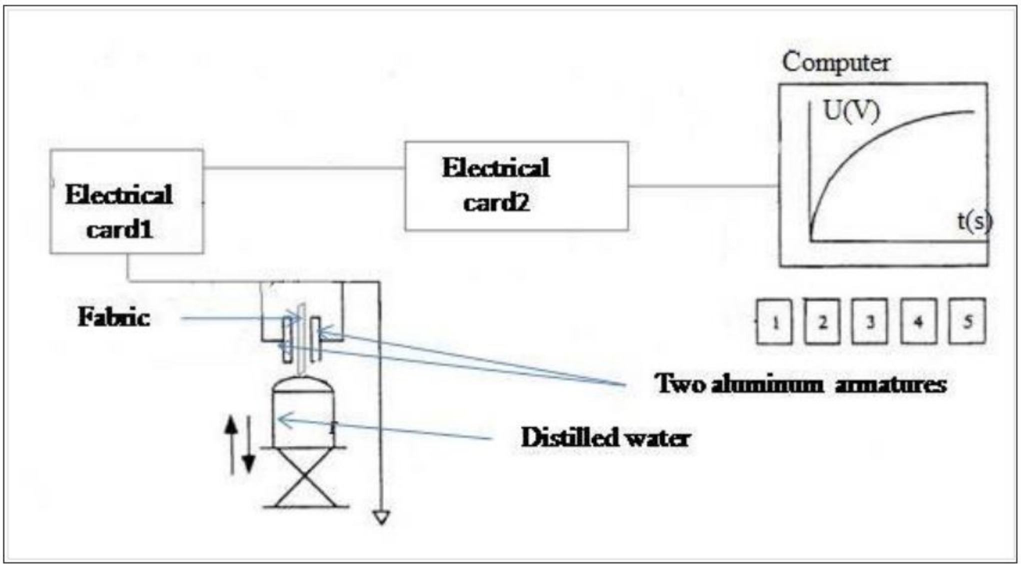


Figure 2.5.4: Capacitance method schematic diagram(GHANMI H.)

2.6 Knitted Spacer fabrics

2.6.1 Introduction

Today, knitted spacer fabrics (KSS) are used for moisture management. Spacer structures are produced on knitting machines with two needle beds. Two independent fabric layers are formed on the two needle beds using separate yarns, and the two fabric layers are then interconnected using a third yarn, called the spacer yarn during the knitting process (Ray, 2012, Spencer, 2001). The thickness of the knitted spacer structure can be adjusted by varying the length of the spacer yarn between the two fabric layers, and the spacer yarns lying between the two fabric layers forms the third layer of the structure.

Spacer fabrics produced on double needle bar warp knitting machines have been used for making of automotive and upholstery textiles for quite a while in a process in which the warp knitted spacer fabric is sliced in the middle, in order to produce two sets of fabrics with pile effects. This technique is still utilized for making seats and upholstery for buses and trains. Initially spacer fabrics were produced by weaving, however, the advancements made in two needle bar warp knitting technology resulted in these used in sportswear during the 1980s. Later the technology was developed by circular weft knitting machine builders to produce weft knitting spacer structures in order to widen the product range for their customer base.

Today woven spacer fabrics are solely used to produce textiles for the automotive sector. However, the end product is not a spacer fabric as it is sliced in the middle to produce two parts with pile effects as mentioned earlier. As such knitting can be considered as the main production system used to produce spacer fabrics, which are predominantly used in designing sportswear and outdoor garments. Due to the way in which yarns are interlooped the technology of knitting is classified into two main groups: warp and weft knitting. The technology of weft knitting is, today, further subdivided into two groups, flat-bed knitting and circular knitting, and all knitting technologies are exploited in producing spacer structures.

2.6.2 Design of spacer fabrics

Spacer structures are designed based on the functionality and performance that is desired from an end product. The key factors to be considered are the type of fibres to be used, the method of fabric construction and the required porosity and thickness of the spacer fabric. Generally, the amount of fibres in the spacer yarn would influence the moisture transmission kinetics. Modern, computerised flat-bed knitting machines are built with two needle beds and individual needle selections to knit, tuck and miss positions. These machines also support the changing of the relative positions of the needles in the two needle beds via needle bed racking techniques. The proprietary CAD/CAM systems, which have been evolved into an advanced state by the machine manufacturers provide an excellent platform to programme modern flat-bed knitting machines to produce a variety of different spacer structures.

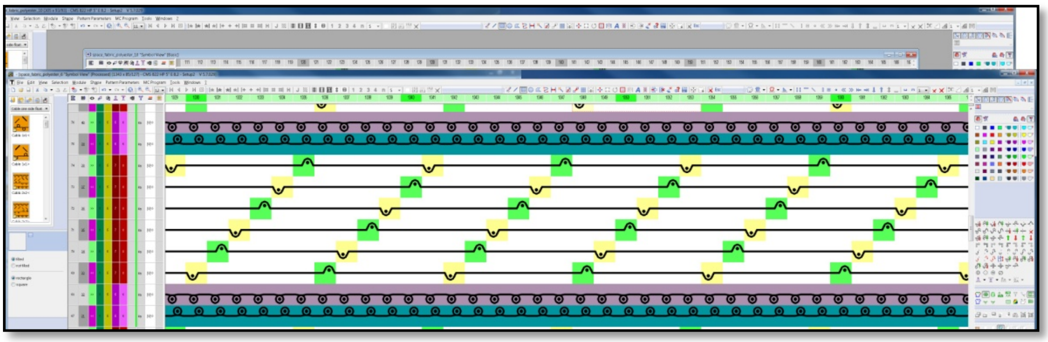


Figure 2.6.2.1: Spacer fabric CAD program on Stoll M1 plus(Stoll)

2.6.2.1 Yarn selection

In designing the spacer fabric for an outdoor garment, which is the main focus of this PhD thesis, polyester, micro-fibre yarns were used to knit all three layers of the spacer structure due to the very low moisture absorption characteristics of polyester. This allowed for the creation of a spacer structure consisting of hydrophobic outer surfaces that would dry fast. Natural fibres such as wool and cotton are best known for their absorption properties but with higher drying times (Saville, 1999). When designing a spacer fabric for moisture-management applications one has to create a structure with a quick absorption and drying capabilities so as to prevent moisture build up close to the skin. In such a structure, the main function of the middle layer will be to transport the moisture between the two outer layers enabling the moisture to be evaporated on the surface of the outer layer. Ideally, the fibres used for the inner layer should not absorb moisture and should facilitate moisture propagation along the outer fibre surface. As spacer yarns are arranged in straight configurations between the two outer fabric layers in the inner layer, capillaries are formed promoting moisture transmission. Generally, spacer structures are produced by using monofilament yarn for the spacer. However, the moisture transmission within the inner layer could be boosted by using multifilament yarns as such a configuration would increase the number of capillaries in the inner layer. One could also achieve a higher moisture transmission efficiency by the selection of the diameter and the geometry of the filaments of the multifilament spacer yarn. As such

167/48dTex polyester yarns were used by the author to produce the spacer structures of the research. All the three layers of spacer structures were knitted from the same multifilament polyester yarn on a gauge 16 Stoll CMS flat-bed knitting machine in order to produce a soft fabric.

2.6.2.1 Manufacturing process

Knitted spacer fabrics can be produced by using circular rib, flat-bed and warp knitting machines. Double needle bar warp knitting machines are the first machines used in the production of knitted spacer fabrics. However, the main disadvantage of the technology is the need of warp beams and the complexity of their preparation compared to weft knitting machines. Rib circular knitting machines can produce spacer fabrics but requires the use of large number of yarn packages, generally around 96 - 144, which could not be justified within this research. By using a computerised flat-bed knitting machine one can produce a spacer structure using three yarn packages, and, therefore, gauge 16 Stoll 822 HP CMS knitting machine to produce all samples used in the research.

The key factors to be considered when designing knitted spacer structures are the yarn count (thickness) and the amount of spacer yarns (the number and the length of spacer yarns) used to form the middle layer. The spacer fabrics for wearable applications should be thin and light to ensure comfort. Thinner fabrics will have less resistance to moisture transfer as moisture has to travel a lesser distance when compared with thicker designs. The spacer structure should also be able to protect the wearer from heat loss and sensations of cold. A possible solution could be to entrap pockets of air within the fibre to prevent heat loss in the spacer structure. Another important consideration is the type and amount of spacer yarns to be used in the inner layer. The inner layer will be used to transfer moisture from one outer layer to the outer layer for evaporation. Generally, this is achieved by engineering the capillary effect from the inner layer, that takes place due to the zigzag configuration of spacer yarn between the two outer layers. Current understanding (Au, 2011) is that the higher the number of spacer yarns in the inner layer, the more capillaries are formed, leading to higher transfer of moisture within the inner layer. This could be achieved by modifying the manner in which the two outer layers are interconnected by spacer yarn. However, this has to be realised carefully as when more spacer yarns are packed into the inner layer their angle of inclination would be altered, affecting the resultant moisture travel through the length of the capillaries. Another way to enhance the moisture transmission is to increase the number of filaments in the spacer yarn (Dias and Delkumburawatte, 2007). A higher the number of filaments leads to more channels being available for transmission of moisture, allowing moisture transmission at a faster rate.

2.6.2.2 Type of knitted structures

Due to the immense number of different structures which could be produced on a modern computerised flat-bed knitting machine the selection of the structure(s) for the outer layers are important. However, as two independent fabric layers have to be formed to create a spacer structure, only plain knitted structures and their derivatives can be used. The spacer yarn has to be anchored into the outer layers during the knitting process, which could be achieved either with tuck loops or stitches. The way in which these could influence the moisture management has been studied in this PhD research.

2.6.2.3 Selection of test samples of spacer fabrics

As a broad portfolio of different spacer structures could be produced on a computerised flat-bed knitting machine, six different spacer fabrics were produced and tested for moisture absorption. These were given the codes KSS6, KSS4 and KSS2. The number represents the length of spacer yarns laid in between the two needle beds during knitting, for example KSS6 means that the spacer yarn was laid between the needle x in the front needle bed and the needle (x + 6) in the back needle bed during knitting. KSS6 was the thickest and the heaviest sample while KSS2 was the thinnest and lightest sample with KSS4 having properties in between KSS6 and KSS2. These were chosen to provide a broad understanding of moisture-handling capabilities.

2.6.2.4 Spacer fabric moisture absorption experimentation

Preliminary tests were carried out to understand the factors that would influence the moisture absorption and transmission characteristics of knitted spacer structures, in order to analyse their properties precisely. This also enabled the selection of spacer structures suitable for the research.

The first set of experiments focused on the absorption properties of the spacer fabrics using a GATS system. As explained in section 2.3, the GATS system utilizes a zero pressure head to test the moisture absorption and the wettability of fabrics. It is easy to use and provides real-time data with a high degree of accuracy. The GATS system used in the research was from MK Systems Inc. and the set-up is given in figure 2.6.2.4.1 below.

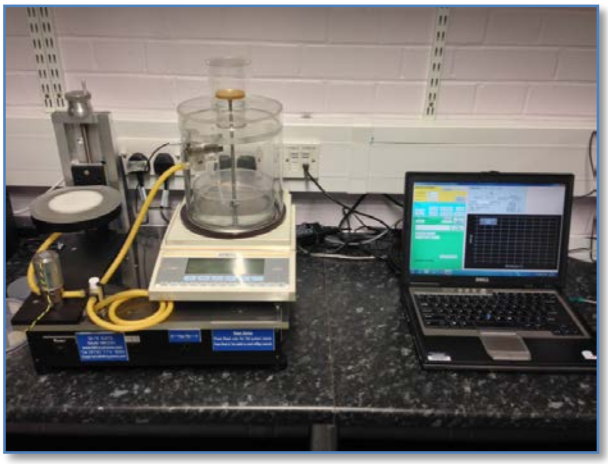


Figure 2.6.2.4.1: MK GATS system set up

The important physical properties of spacer fabric samples used in the preliminary testing of moisture absorption are summarised in table 2.6.2.4.1 below;

Table 2.6.2.4.1: Spacer fabric properties

Sample	Weight/ 5X5cm^2 [grams]	Thickness [mm]		Number of spacer yarns	Distance between needles	Number of courses per cm	Number of wales per cm
		Average	STDev				
KSS6T3E	2.18	3.73	0.013	3	6	11	8
KSS6T2E	1.82	3.51	0.011	2	6	10	8
KSS6T1E	1.42	3.15	0.019	1	6	11.1	8.2
KSS4T3E	1.73	2.71	0.009	3	4	13	9.2
KSS4T2E	1.39	2.62	0.009	2	4	12.2	9
KSS4T1E	1.22	2.47	0.017	1	4	11	8
KSS2T3E	1.29	1.95	0.007	3	2	12	10
KSS2T2E	1.26	1.90	0.009	2	2	11	9
KSS2T1E	1.06	1.85	0.015	1	2	13	9

The weight of moisture absorbed by the fabric during the test is measured by M/K245 in real time and a typical screen shot of the control and analysis software is shown in figure 2.6.2.4.2.

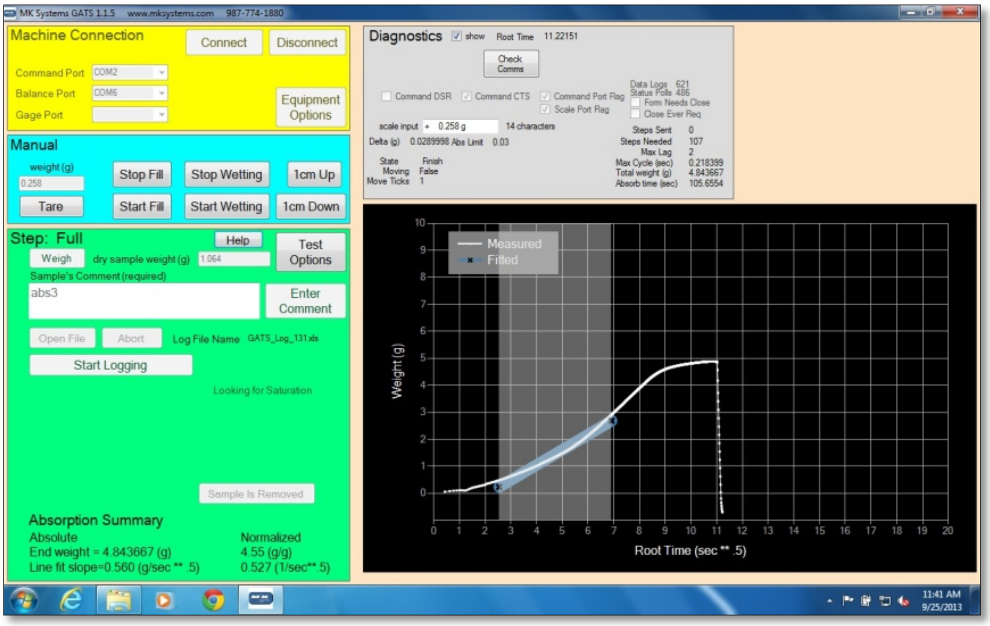


Figure 2.6.2.4.2: MK GATS system software control

The control software also defines the steps to be carried during the test. The major steps involved during measurements are:

- Equipment setup: the control software will take one through various steps to ensure the lower reservoir is filled with the correct amount of water, which is 580g.
- Sample weighing; the weight of the sample is measured and recorded for later use;
- Data storage; the software creates an Excel file with the measured data;
- Experiment run; after creating a location for data storage the control software will prompt the user to place the sample on the fabric plate holder and start the data acquisition process. Real time information is displayed on the computer screen as water is absorbed by the sample;
- When sample saturation is reached, the data acquisition will be stopped, and the reservoir will be refilled with water for the next test.

The results of the preliminary testing are given in the figures below;

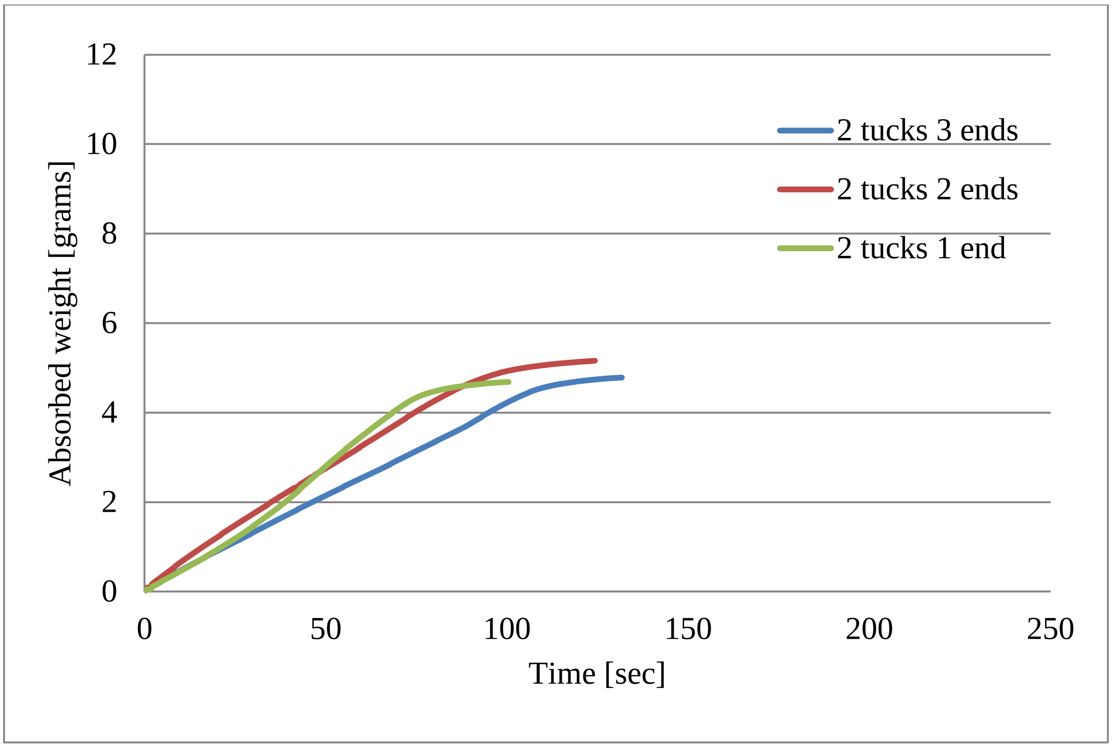


Figure 2.6.2.4 3: KSS2 absorption results

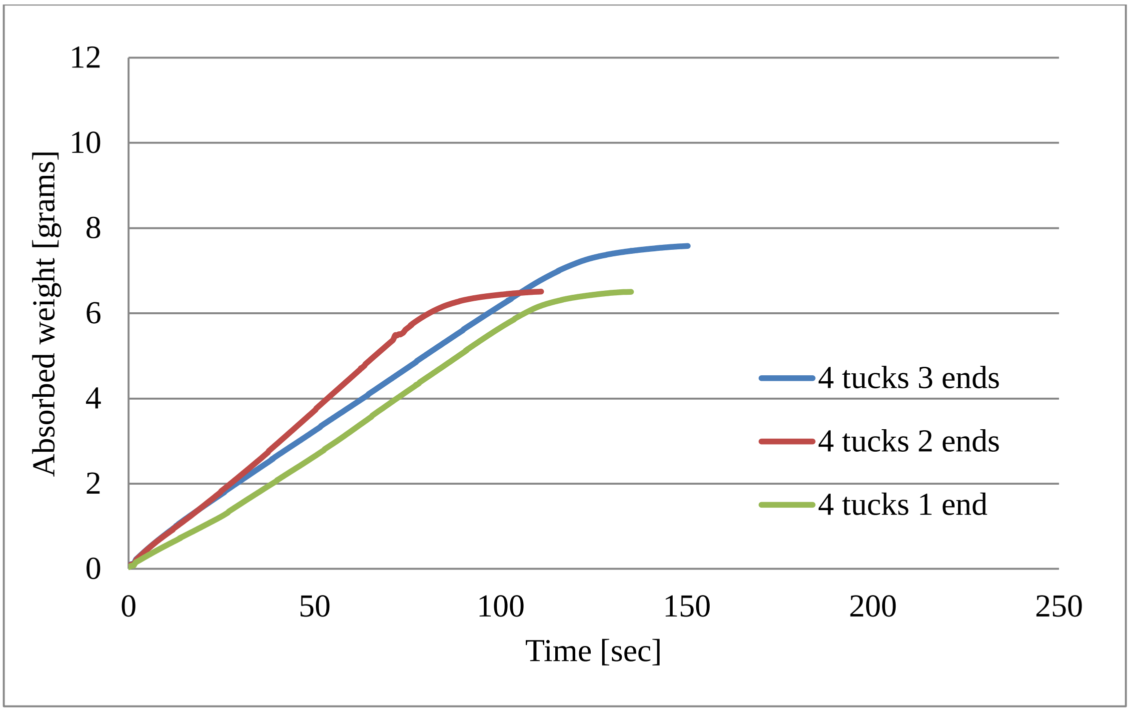


Figure 2.6.2.4.4: KSS4 absorption results

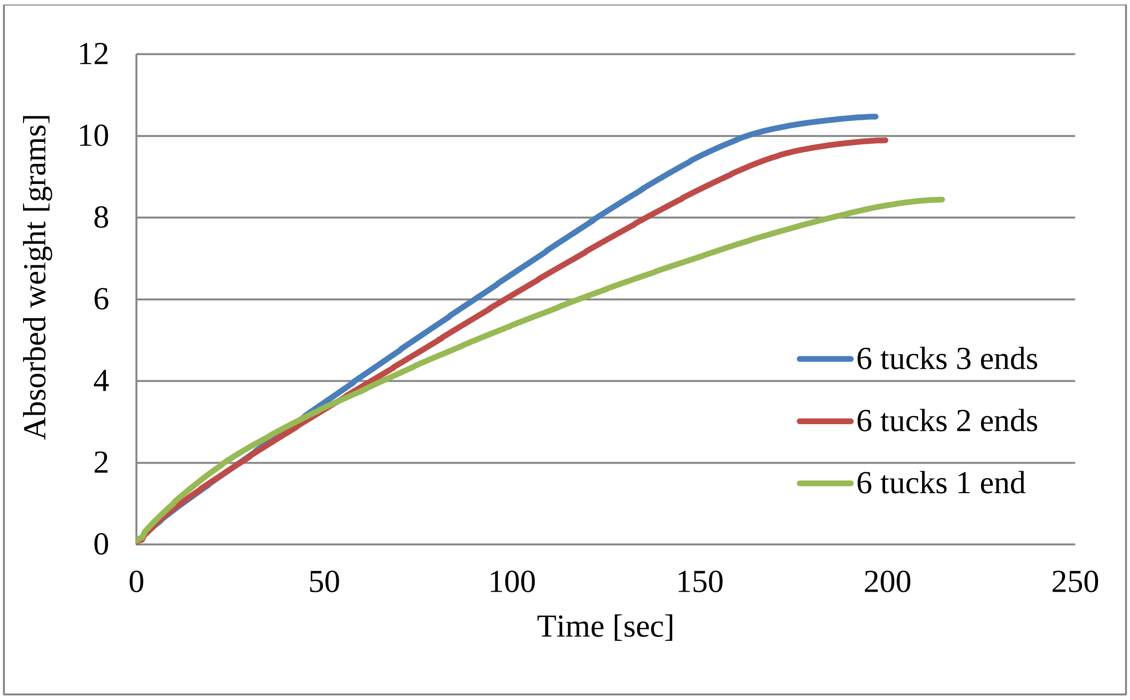


Figure 2.6.2.4.5: KSS6 absorption results

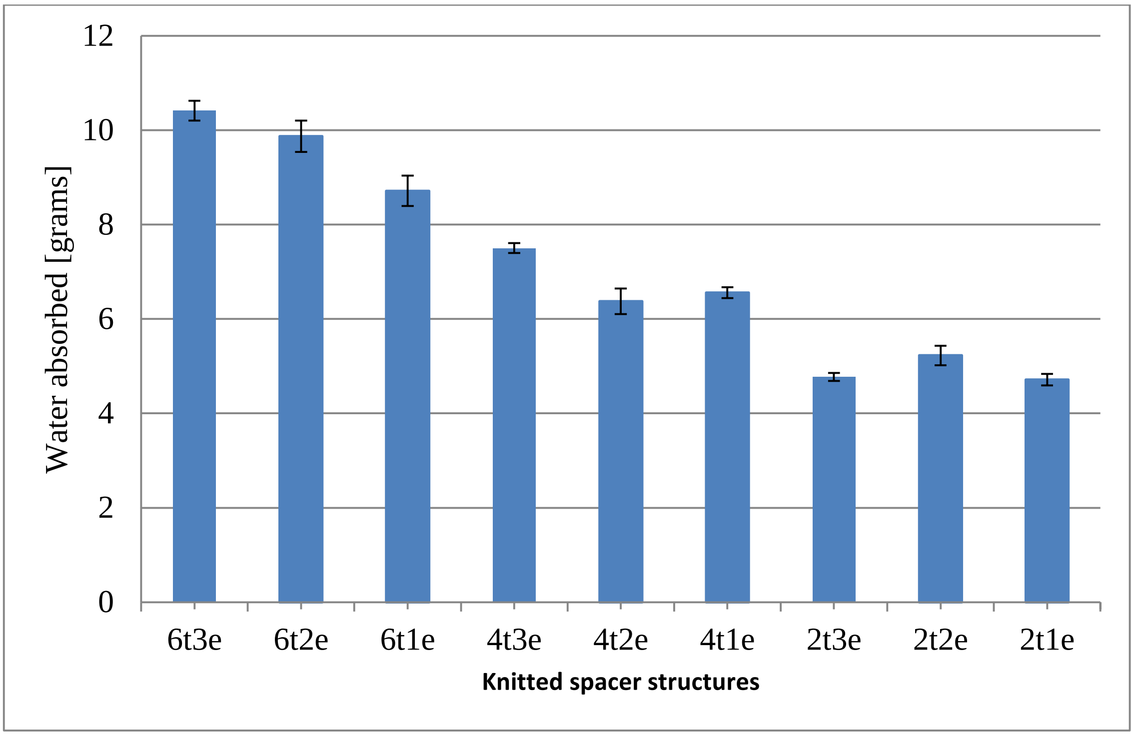


Figure 2.6.2.4.6: Average water absorbed for knitted spacer fabrics

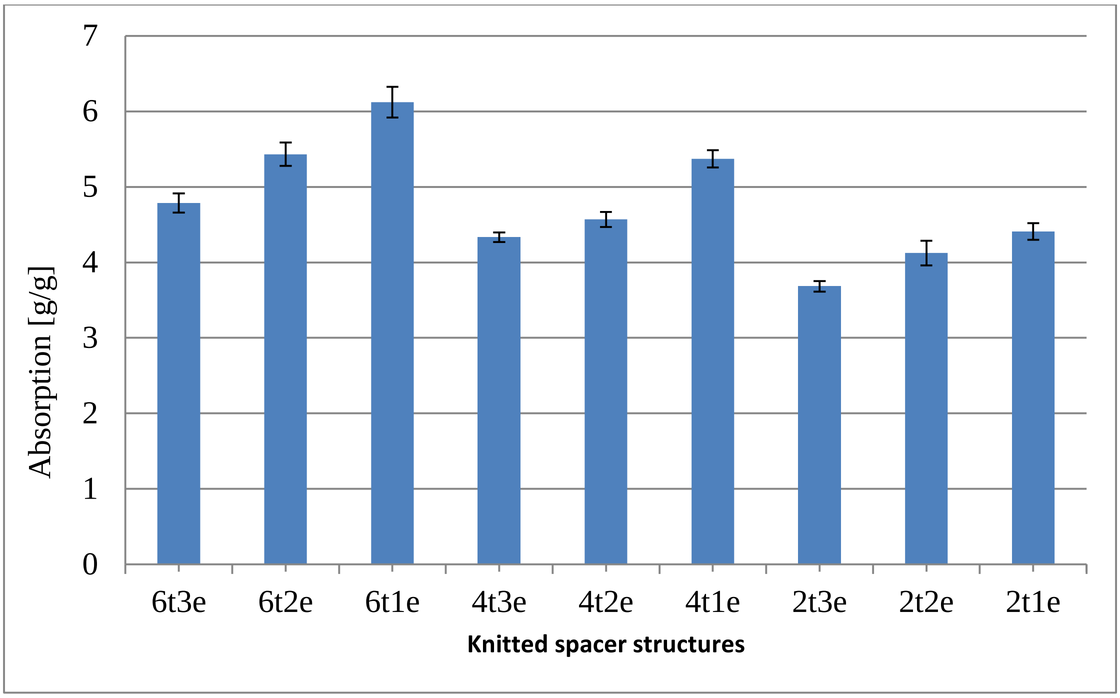


Figure 2.6.2.4.7: Average water absorbed per gram of dry fabric weight

The above experiments were conducted to analyse moisture absorption characteristics for various, knitted spacer fabrics. It is clearly shown in figures 2.6.2.4.6 and 2.6.2.4.7 that KSS6 had a higher moisture holding capacity than KSS4 and KSS2. This could be due to KSS6 having more spacer yarns between the two, single jersey layers, which in turn could create more capillary channels, and hence more water could pass through. However KSS6 is the heaviest and thickest compared to KSS4 and KSS2. This could be an issue as to make an outdoor garment one of the important factors is the fabric weight and thickness. So although KSS6 holds more water than KSS4 and KSS2; it could be not be essential to be used in the project. KSS2 shows more potential to be used here, due to its lightweight and thickness.

KSS2 with 2 tucks also proves to be imminent as shown on figures 2.6.2.4.6 and 2.6.2.4.7; that it has more water holding capacity than ones on 1 tuck and 3 tucks. The main reason here could be due to the orientation of spacer yarns within the structure. Spacer yarns are knitted into the structure by tucking in both front and back needle beds.

So the number of tucks running within these faces could have an effect on how the spacer yarns are arranged in terms of angle of inclination, and hence affect the capillary length formed. This is important, as the longer the capillary formed, the longer it would take moisture to pass through and vice versa.

The rate of moisture uptake results (figures 2.6.2.4.3, 2.6.2.4.4 and 2.6.2.4.5) also reveals that all the spacer samples possess almost similar rates at 0 to 100 seconds. After 100 seconds; the difference started to appear with KSS4 and 2 slowing down due to less water holding capacity than KSS6. This is important, as the quicker the moisture is absorbed the better it will be transmitted to the outer side for evaporation.

2.7 Chapter summary

In this chapter, an intensive literature search of moisture management of fabrics and testing techniques was conducted. This brought a broad understanding of technologies available and how they can be used in the project for the creation of smart fabric. Spacer fabrics were found to be the way forward due their flexibility, lightweight, absorption capabilities and versatility. These spacer fabrics are produced by knitting on a computerised, flat-bed knitting machine. Samples of different structure types were produced and an investigation of moisture absorption was conducted using the moisture absorption tester. This was carried out specifically to investigate moisture take-up rate and other physical properties such as weight, number of spacer yarns and thickness.

The next step was to continue with the mathematical modelling basing on the spacer fabric so as to investigate the moisture transfer across the fabric and to demonstrate how the introduction of heat could enhance the process. The results analysis assisted in selecting an appropriate type of spacer fabric for further use.

Chapter 3

3.0 Research Methodology

3.1 Introduction

In this section systematic analysis of all the theoretical methods and techniques applied in this project will be explained. In depth step-by-step paradigms involved in the execution of the project will be categorized to bring the most important meaning. The research is based on quantitative methods. In this sense, scientific methods and theories will be applied in line with the aims and objectives. After that; scientific experiments using the same theories and principle will be performed and the results analysed to validate the proposed theories. The key important steps applied throughout the research are summarized below.

3.2 Background

An in-depth literature study was carried out in order to understand and underpin the existing knowledge base. This did help to identify gap(s) in the existing knowledge base, which enabled the formulation of the hypothesis of the thesis and provided the basis of the programme of research.

The literature search demonstrated that the use of heating to enhance the moisture transfer characteristics of a fabric has not been investigated. However, the literature review showed a wide knowledge of engineering of fabrics with enhanced moisture transfer capabilities (Lukas, 2003, Patnaik, 2006, Schwartz, Watt, Hsieh, 1995, Ramachandran, 2004, Simile, 2004, Matila, 2006) all the research has focused on how to increase the hydrostatic pressure difference between the inner microclimate and outer environments, in order to boost moisture transfer. The review also revealed the effect of moisture movement when the outer environment pressure exceeds that of the inner (Lukas, 2003, Pan. N, Au, 2011).

Literature also reports on the technology of designing and manufacturing of heating fabrics (Au, 2011, Matila, 2006, Watt, Pan. N, EXO2theheatinside), but no references could be found on the use of heating in order to improve the moisture transfer characteristics of fabrics

Therefore the research into combining heating with the existing knowledge of engineering fabrics to increase the hydrostatic pressure between fabric layers was identified as a potential area of investigation. It was also recognised that it is necessary to understand the application of localized heating to enhance moisture management in textiles.

3.3 Research method

This section will discuss the proposed methods and outcome of the research. The main research question is how to integrate heated elements on one layer of knitted spacer fabric for the solely purpose of enhancing moisture transfer by improving hydrostatic pressure difference between the two sides of the knitted spacer structure. A knowledge gap identified on the literature review in chapter 2, demonstrates that, heat has not been used as the way to improve hydrostatic pressure difference between the two sides of the textile structure and hence integration of heat on the knitted spacer fabric would promote quick drying on knitted textile structure.

To do this, a quantitative methodology will be utilised into which scientific theories and formulas will be used to define the process of moisture transfer across the knitted spacer fabric with integrated heaters. This will help to identify the main factors to be considered and experimented in the research. Literature review has identified the main physical phenomena governing the interaction of moisture with textile (i.e. knitted spacer fabric) and how moisture is transferred within the textile structure. Lucas Washburn and Hagen-

Poiseulle formulas are identified as the main physical relations into which interaction and transfer of moisture through textile structure could be studied.

After identification of main physical phenomenon, a numerical investigation followed by experimentation of moisture interaction and transfer through a knitted spacer fabric will be performed. Numerically by mathematical modelling and experimentally by using test equipment. This process will formulate necessary relations and formulas explaining the moisture transfer across the knitted spacer fabric with influence of added heaters and all could be compared between the two methods. All the main factors and variables in the numerical calculations and experimentation will be considered here. This will include the inner and outer environmental conditions, fabric properties, and heater element characteristics. Integration of heater elements onto the knitted spacer fabric will be designed and manufactured and necessary numerical and experimental investigations performed so that an active outdoor fabric and can be designed and manufactured into a quick dry garment.

The proposed research methodology is illustrated on figure 3.3.1 below;

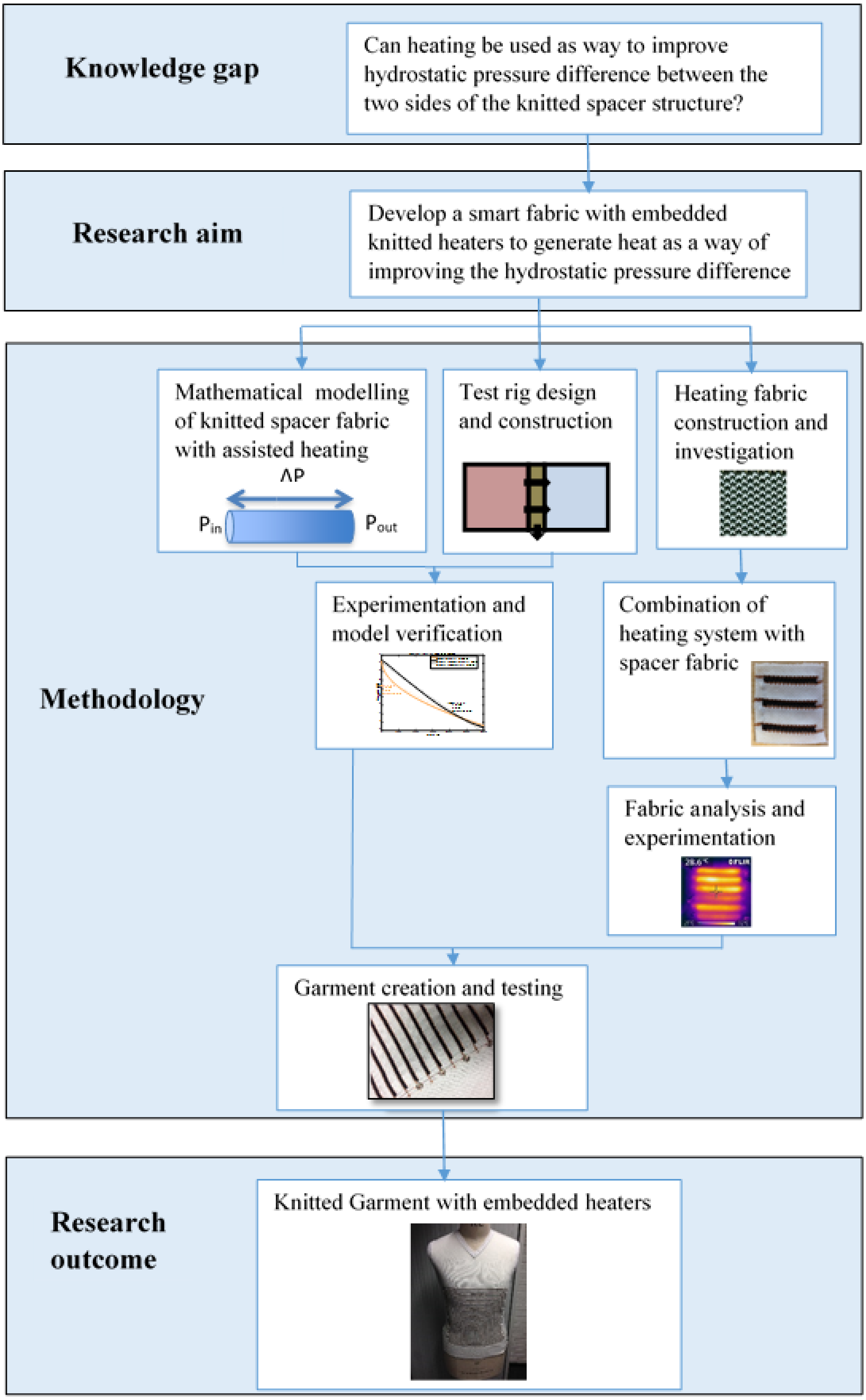


Figure 3.3.1: Research methodology

3.4 Scope of the project

The project main objective is to understand the effluence of heating on hydrostatic pressure difference created between the two sides of the knitted spacer structure. Application of heating would increase the inner microclimate pressure which in turn would drive absorbed moisture towards the other side (outside) of the knitted spacer fabric for improved moisture transmission. Since the application of heating will be during high level of sweating actions, literature(E. Onofrei, 2011, Sweeney, 1990) shows that human body temperature is high at this point and any application of further heating would be unnecessary and uncomfortable to the human skin. Also human body itself at high level of activities, would create some heat which could be captured and used to improve the moisture process. The PhD project will be concentrated on the effect of applied heat to the moisture transfer process between the two sides of the fabric and any heat produced by the human body and effect of heat to the human body would be out of focus of the project. The study of effect of heating used on the fabric to the human body could be used as the next point of study in the future.

3.5 Structure of the thesis

The thesis comprises of 8 chapters; a brief description of chapter contents are described below:

Chapter 1: Introduction

A brief introduction on technical textiles is introduced together with a brief explanation of its importance in maintaining human body climate in various outdoor conditions.

Chapter 2: Literature Review

A broad overview of existing knowledge and technologies on moisture management textiles are discussed in this chapter. Moisture testing techniques and processes that are currently employed in the discipline are studied too. An understanding of the existing knowledge base and identification of gap(s) in the knowledge is developed, which was important in formulating the project objectives.

An overview of knitted spacer fabrics is also provided in the chapter.

Chapter 3: Research methodology

This chapter will involve the methods and steps into which the project will utilize to full fill the objective and research questions outlined in chapter 1. Also a visualization of the project roadmap will be provided here.

Chapter 4: Development of a mathematical model and optimization

This chapter will involve the development of a mathematical model to explain the moisture transmission process across the fabric. Different scientific theories and principles will be analysed and effective ones will be applied to formulate the model. To further proceed, the model will be solved and an appropriate solution method obtained using available mathematical and computing solutions. Once all mathematical solutions were satisfied; an experimental process mimicking the numerical assumptions, design and characteristics was performed to further prove the model. Different fabric samples having same properties as the one portrayed in the model were produced and used. Also all testing conditions of the fabric were emulated by designing an experimental testing rig where the experimental process was performed.

An optimization of the mathematical model that had been created was performed at this stage in order to fine-tune the formulated mathematical relationships.

Chapter 5: Fabric design and manufacture

Selection of suitable fibres, yarns and manufacturing process of the knitted fabric structure are discussed in this chapter. All the necessary fibre properties that were used in the development of the mathematical model were accessed so that they could be applied during the manufacturing process. The type of yarns and their properties will also be discussed and analysed. In the model design and simulation, yarn properties with outstanding results will be effectively considered. Fabric construction will also be applied to use the best results of moisture transmission from the model simulations.

This chapter contains an investigation of textile heating technology using the yarns that were chosen for study. . The different designs and major requirements are also discussed in this section. The work described in this chapter has been published in a book chapter (E. Mbise, 2015).

Chapter 6: Integration of heating elements

Development of a knitted fabric with localized heaters will be analysed relying on important information gathered. Heating element integration and fabric performance are the main areas of interest in the resulting fabric. The best combination showing that demonstrates outstanding simulation results from the model will be highly considered. The type and design of heating elements to be integrated with the fabric will be discussed and analysed. These properties can also be modelled and analysed by using the formulated model in chapter 4.

Analysis of the developed fabric will then be performed. Fabric moisture absorption properties will be found through experimentation by using an MK Gats moisture absorbency tester and moisture transmission process, using the in-house-designed environmental testing rig.

Chapter 7: Design and manufacture of smart fabric

The design of a new outdoor garment and its evaluation are reported in this section.

Chapter 8: Discussion and Conclusions.

A summary of project findings including any problems encountered and future trends for the technology.

Chapter 4

4.0 Mathematical modelling

4.1 Introduction

Outdoors clothing is one of the important necessities for outdoors activities. They provide protection to the wearer, especially from wind and rain. Another importance is to keep the wearer warm from a cold outside environment. The human body regulates itself from changes in temperature between the body surface, the skin and the outside. When the outside conditions are warmer than the body (higher than the normal body temperature of 37^{o}C), it tends to cool itself by using the perspiration process, in which the body heat is released in the form of sweat through the skin.

In the cooler outdoors environments, the surrounding conditions are generally lower than the microclimate inside the clothing. Outdoor clothing which are situated between the two environments (outside and microclimate), provides warmth to the inner body and prevents cold air from getting in. During activities, due to the increase of metabolic rate the core temperature of the human body would increase, and it is important to cool the body, i.e. a reduction of the overall temperature in the inner microclimate. As stated earlier this is achieved by the body dissipating heat in the form of sweat.

One of the importance of outdoors clothing is that, they are engineered to protect the inner body from the cold outside as well as facilitating the cooling of the inner body, which necessitates outdoor clothing to act as heaters and coolers. As the inner body produces sweat as a way of cooling itself, at some point, this sweat has to be removed from the micro-climate inner climate, in order to prevent a sense of uncomfortability to the wearer (Hong and Kim, 2007, Sweeney, 1990, Furtech, 2012, Gore-tex). Thus, outdoor clothing has to fulfil the task of removing sweat from inner side of the garment to the outside. Currently this is achieved with the construction of the garment and the structure of the fabrics used in the design (Drirelease, Watt, Pan. N). Outdoor garments are constructed with multiple fabric layers, with each layer performing a specific task. In a three layer construction, which is very typical today, the inner layer is made up of a knitted fabric made from hydrophobic yarns that is capable of wicking moisture (sweat) away from the skin and presenting it to the middle layer due to capillary action. In the middle layer the moisture would spread out and transfers it to the outer layer, which is made of a hydrophilic knitted fabric that could absorb and allow the moisture to be evaporated to the atmosphere. The middle layer is constructed from a material which would allow the moisture to pass through in one direction that is from the inside to the outside and prevent any water molecules to travel from the outside to towards the human body. These are known as unidirectional breathable materials (Gore-tex, Kissa, 1996).

According to Watt and Kissa moisture is removed from the inner microclimate to the outer by absorption, wicking and evaporation processes (Watt, Kissa, 1996). The effectiveness of the above physical processes would depend on the fabric's yarn properties, construction method and the hydrostatic pressure gradient between the inner microclimate and the outside fabric layer. Yarn properties have been explored (Miller, 2000, Hsieh, 1995, Schwartz, Minor, 1960) to obtain optimum wicking arrangement so that maximum wicking can be achieved to remove most of the moisture away from the skin. Similarly, the fabric construction systems have been studied (Dias and Delkumburawatte, 2007, Saeed, 2006) to understand the best arrangement of fibres in knitted spacer structures to provide the maximum comfort to the wearer. Hydrostatic pressure gradient between the inner fabric microclimate and outer fabric layer, have significant effect to moisture transfer from the inside of an outdoor garment to outside. This effect occurs when the outside environment is of high humidity and low temperature (most outdoor conditions). This raises the total outside pressure, which would hinder moisture migration from the inner low pressure microclimate.

The moisture removal process becomes affected due to change in outer temperature and humidity and an effective way to improve the moisture transfer process is required.

4.2 Background

Conventional textile structures, such as woven and knitted fabrics, are made from yarns, which are produced from fibres. A yarn is an assembly of fibres which are held together due to mechanical forces and its structure lends to the formation of fine capillaries between fibre surfaces (very fine tubes). As such textile structures are capable of transferring moisture through the structure and within the structure (i.e. within the fabric surface) due to absorbency and capillary effect (G.B.Delkumburawatte, 2011, Fan et al., 2000, C. Ye, 2008, Kissa, 1996). In textile structures, water is absorbed due to two phenomena, namely wetting and diffusion. Wetting is the process whereby a liquid comes into contact with a textile surface while diffusion is the process of liquid molecules movement inside a textiles structure from a region of high liquid concentration to a region of low liquid concentration. There are some important factors, which affect liquid absorption into textiles structures:

1. Fibre surface wetting characteristics i.e. hydrophobic or hydrophilic nature.
2. Geometric parameters of the fibre assembly. This includes thickness, porosity and capillary radii.
3. Properties of the liquid, i.e. the viscosity, the surface tension and the density;

In a textile structure when a drop of water comes into contact with its surface, three important events occur. Firstly, the wetting (Simile, 2004, Schwartz); this results in capillary forces being generated across the textile structure. As wetting increases the capillary action would increase resulting in wicking. It is this combination that forces liquid to move across the fabric.

Capillarity is the process of liquid penetration across a tube due to the surface tension of the liquid. It is this surface tension that would cause a hydrostatic pressure difference within the tube forcing the liquid to flow.

The fluid force was first derived by Laplace given in the following equation;

$$\Delta \boldsymbol{P} = \frac{\boldsymbol{2\gamma cos\theta}}{\boldsymbol{r}} \qquad (4.2.1)$$

Where;

$\gamma = surface\ tension\ of\ liquid$;$\theta = contact\ angle$; $r = radius\ of\ capillary$

The tube is considered to be vertical and this would cause an opposing force to be generated due to the weight of the liquid in the tube. The opposing pressure head can be given as;

$$\Delta \boldsymbol{P_h} = \boldsymbol{Lg\delta} \qquad (4.2.2)$$

Where;

$L = Liquid\ rise; g = acceleration\ due\ to\ gravity; \delta = density\ of\ liquid$

From equation 3.2.2 above, the actual change in the pressure gradient can be calculated as;

$$\Delta \boldsymbol{P} = \frac{\boldsymbol{2\gamma cos\theta}}{\boldsymbol{r}} - \boldsymbol{Lg\delta} \qquad (4.2.3)$$

When the tubular structure is horizontal, the weight of the liquid can be neglected and the hydrostatic pressure gradient would be caused due to surface tension alone. i.e. $Lg\delta = 0$

Hagen-Poiseulle's formula can be used to explain the phenomenon of volumetric flow of liquid through a textile structure. Literature (Watt, Kissa, 1996, Hsieh, 1995) points out that, liquid flow into a porous structure is affected by contact angle, capillary radius, density of textile fibres and viscosity of the liquid. Hagen-Poiseulle law for laminar flow can be expressed as;

$$\frac{dV}{dt} = \frac{\pi r^4}{8\mu L}\Delta P \quad (4.2.4)$$

Where;

$\Delta P = net\ pressure\ gradient; \mu = viscocity\ of\ liquid$

It is clear from the equations 4.2.3 and 4.2.4 that a hydrostatic pressure gradient would be generated across the textile structure. So combining this,

$$\frac{dV}{dt} = \left(\frac{2\gamma cos\theta}{r} - Lg\delta\right)\frac{\pi r^4}{8\mu L} \quad (4.2.5)$$

Considering that, $dV = dL.\pi.r^2$ Lucas and Washburn developed an equation based on Hagen-Poiseulle equation to calculate the linear flow rate when in equilibrium as;

$$\frac{dL}{dt} = \frac{r\gamma cos\theta}{4\mu L} \quad (4.2.6)$$

This equation as can be enhanced by considering the influence of gravity on the column of risen liquid and then the flow rate becomes;

$$\frac{dL}{dt} = \frac{r\gamma cos\theta}{4\mu L} - \frac{r^2 g\delta}{8\mu} \quad (4.2.7)$$

From equation 3.2.7, after integration of Lucas-Washburn equation, it can be simplified as;

$$L = \sqrt{\frac{r\gamma cos\theta}{2\mu}}.\sqrt{t} \quad (4.2.8)$$

Where;

$t = time$

4.3 Theoretical modelling

The concept of creating an active textile structure for managing moisture transfer is based on knitted spacer structure, which is considered to be of three layers. Knitted spacer structures have been studied recently and their potential as moisture management fabrics is reported in recent publications (G.B.Delkumburawatte, 2011, Delkumburawatte and Dias, 2011). The reasons for considering knitted spacer structures in this research are the ability to produce them on computerised flat-bed knitting machines easily with different types of fibres in order to achieve varieties of resulting fabric properties.

Delkumburawatte (G.B.Delkumburawatte, 2011), derived a mathematical model to define the capillary radius in a spacer structure. The parameters considered in his model included, the fabric thickness, the fabric structure, the course and wale spacing, the yarn crimp, the number of fibres in the yarn and yarn counts. This model was enhanced by the author with liquid transmission rate across knitted spacer structures by using Lucas-Washburn kinetics with the addition of heating elements and variation of different environmental conditions.

4.3.1 Capillary radius

In the development of capillary radius model, the following important assumptions were made;

- Spacer yarn in the spacer fabric lies in the zigzag path between front and back needle beds;
- Fibres are equally distributed and parallel to the yarn direction;
- Spacer yarn in the spacer structure is not twisted;
- Empty spaces formed by fibres in a cross section are assumed to be circular and are equivalent to average area of spaces in the bundle.

The above assumptions were used to formulate a model to calculate the radius of a knitted spacer structure (KSS) consisting of two plain knitted fabric layers forming the two outer surfaces of the KSS, which are interconnected by the spacer yarn forming a zigzag layout (G.B.Delkumburawatte, 2011).

The model created by Delkumburawatte (G.B.Delkumburawatte, 2011) for calculation of capillary radius is as follows;

$$\boldsymbol{r} = \sqrt{\frac{b.\frac{1}{w}.S - \frac{\left[rows.c.\sqrt{\left(b^2+\frac{S^2}{w^2}\right)}.\frac{1}{(1-crimp)}\right]}{10^5}.Tex/\delta_f}{NF.rows.\pi.c.\sqrt{\left(b^2+\frac{S^2}{w^2}\right)}}} \quad \ldots\ldots(4.3.1.1)$$

Where;

$\delta_f = density\ of\ fibre, w = wales\ per\ cm, c = courses\ per\ cm,$

$b = fabric\ thickness, \quad NF = number\ of\ filaments,$

$Tex = yarn\ count, S = number\ of\ needle\ spaces\ ,$

$rows = number\ of\ spacer\ courses\ between\ two\ single\ jearsy\ courses$

4.3.2 Liquid Transmission Rate

The transmission of liquid across a textile material is of great importance in moisture management fabrics(Wu and Fan, 2008, Fan and Wen, 2002, Fan et al., 2000, Saeed, 2006, G.B.Delkumburawatte, 2011). The ability of a KSS to transfer moisture has been modelled by the author. The capillary radius model developed by Delkumburawatte above was enhanced together with the following assumptions:

1. KSS has certain amount of moisture initially;
2. Convection heat transfer is considered between the surrounding air and the outer surfaces of the KSS;

The important part of the model is the consideration of the hydrostatic pressure gradient across the fabric due to the surrounding environment. A vapour pressure is generated depending on the micro climates and outside environmental temperatures and this would create variations in the hydrostatic pressure gradient affecting the moisture transfer. The diagram below (figure 4.3.2.1) briefly explains the schematics of a capillary and the pressure difference.

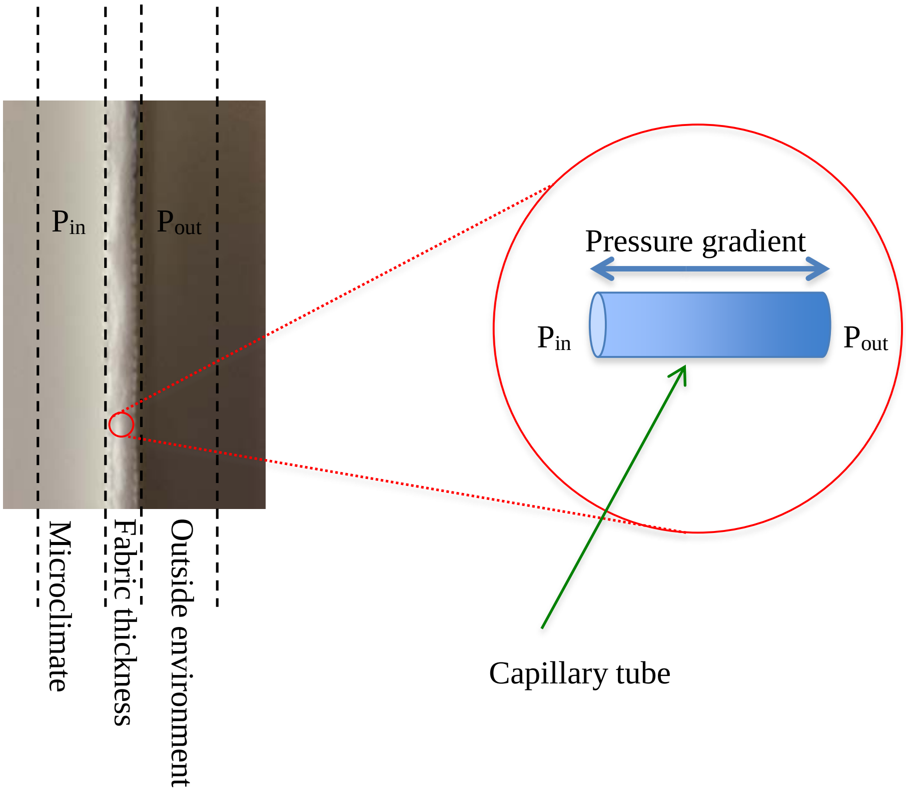


Figure 4.3.2.1: Development of hydrostatic pressure gradient across KSS

Integration of heating elements with one surface of a KSS can be used to increase the temperature of corresponding surface, and this would result in an increase in vapour pressure on that surface. This would also increase the hydrostatic pressure gradient across the assumed arrangement of capillaries.

Recalling Lucas Washburn formula from equation 3.2.8 above;

$$\boldsymbol{L = \sqrt{\frac{r\gamma cos\theta}{2\mu}}.\sqrt{t} = \sqrt{\frac{\Delta P.r^2}{2.\mu}}.\sqrt{t}} \quad \text{..(4.3.2.1)}$$

The net pressure difference across the KSS can be modified according to the above assumptions. This difference is affected by the difference in vapour pressure due to the rise in temperature of the surroundings and the KSS surface due to heating. This shows that, the hydrostatic pressure difference would be a significant driving force for managing of moisture in KSS.

Considering this difference, the process can be divided into two parts; one representing the inner microclimate (between the skin and KSS surface) and the second exposed to the outer environment. The inner microclimate is influenced by the temperature of the air surrounding the skin of the wearer and by the surface temperature of KSS nearer to the skin. To calculate the vapour pressures on the surface integrated with heater elements the Arden-Burk (Buck, 1981) function to determine saturation vapour pressures at different temperatures is used. The relationship is expressed below;

$$\boldsymbol{P_{sat} = A.exp\left[\left[B - \frac{temp}{C}\right]\left[\frac{temp}{D+temp}\right]\right]} \qquad (4.3.2.2)$$

Where;

$P_{sat} = Saturation\ pressure, temp = Temperature\ in\ degrees\ Celcius,$

$A = 6.1121, B = 18.678, C = 234.5, D = 257.14$

In order to obtain the vapour pressure at different temperatures, the relationship which uses relative humidity and saturation pressures, given below was utilised;

$$\boldsymbol{P_v = RH\ .\ P_{sat}} \qquad (4.3.2.3)$$

Under the assumptions that only convection heat transfer takes place and the thermal energy is supplied by the heating elements in the surface of KSS, the rise in temperature in the corresponding can be calculated using the equation (3.3.2.4) given below.

$$\boldsymbol{T_{surf} = \frac{Q}{h.A} + T_{surr}} \qquad (4.3.2.4)$$

Where;

$T_{surf} = Surface\ temperature, Q = heat\ rate, A = fabric\ cross\ section\ area,$
$T_{surr} = Surrounding\ temperature,$

$h = convective\ heat\ transfer\ coeficient\ of\ air$

The total pressure created by the microclimate is the sum of the pressures created by air and fabric surface temperatures.

$$\boldsymbol{P_{in} = P_{air} + P_{surf}} \quad \text{(4.3.2.5)}$$

However; the capillary pressure would also influence the inner microclimate, and taking this into account the total pressure created in the inner microclimate can be calculated as;

$$\boldsymbol{P_{v,in} = P_{air,in} + P_{surf,in} + P_{Cap}} \quad \text{(4.3.2.6)}$$

After determining the vapour pressures; the same procedure can be used to determine the pressure in the outer environment. This is the outer layer of KSS exposed to the atmosphere (no capillary effect is created from the outside) as shown below;

$$\boldsymbol{P_{v,out} = P_{air,out} + P_{surf,out}} \quad \text{(4.3.2.7)}$$

The overall pressure difference across the fabric structure can be obtained from difference in pressure between the total of inner microclimate and the outer KSS surface layer facing the atmosphere. The net pressure difference is the one responsible for forcing moisture to travel in the capillaries. Higher the difference more force would be generated increasing the transfer rate.

$$\boldsymbol{\Delta P_{net} = P_{v,in} - P_{v,out}} \quad \text{(4.3.2.8)}$$

Substituting the net pressure difference on equation 4.3.2.8 into equation 4.3.2.1; the rise of liquid into the capillaries can be obtained;

$$\boldsymbol{L(t) = \sqrt{\frac{\Delta P_{net}.r^2}{2.\mu}}.\sqrt{t}} \quad \text{(4.3.2.9)}$$

The zigzag (G.B.Delkumburawatte, 2011) arrangement of spacer yarns in the structure (see figure 4.3.2.2 below), would influence capillary layout to be at an angle other than 90^o to the two fabric surfaces.

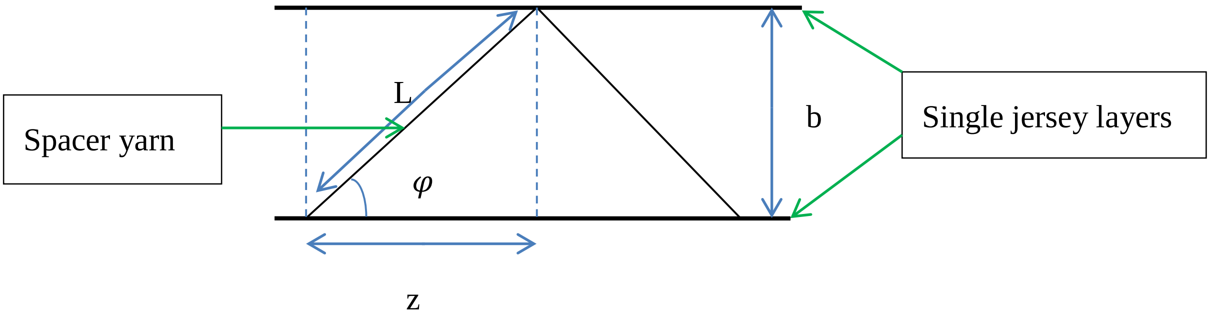


Figure 4.3.2.2: Cross section of a spacer fabric

$\varphi = capillary\ angle\ to\ the\ horizontal; L = liquid\ rise\ height;$

$b = fabric\ thickness, z = length\ between\ succesive\ needle\ tucks$

This will create a length which is much higher than where the capillaries are formed at right angle to the two plain knitted fabric courses. As such an angle factor has to be included into equation 4.3.2.9 to address this effect.

$$\boldsymbol{L(t)} = \sqrt{\frac{\Delta \boldsymbol{P_{net}.r^2.sin\varphi}}{\boldsymbol{2.\mu}}}.\sqrt{\boldsymbol{t}} \ldots\ldots(4.3.2.10)$$

In order to obtain the overall mass of the liquid transmitted across the KSS, we need to consider the number of fibres used in the KSS. The relationship to obtain the amount of liquid transferred across a textile fabric is documented in the literature (G.B.Delkumburawatte, 2011) as;

$$\boldsymbol{m_w = NF.\pi.r^2.Dw.Lh.L(t)} \ldots\ldots(4.3.2.11)$$

Where;

$NF = total\ number\ of\ filaments, L(t) = liquid\ rise\ height,$

$Lh = fabric\ length, Dw = Density\ of\ water$

The total amount of water transmitted can, therefore be calculated by subtracting the initial amount;

Thus;

$$\boldsymbol{m_{net} = m_{ini} - m_{w}} \qquad \text{………………………………….…………..(4.3.2.12)}$$

4.4 Numerical simulation

A mathematical model was developed to simulate and analyse moisture transmission process in textile structures. Pre-determined environmental conditions were defined and different fabric samples of different properties were used. The environmental conditions used in the simulations involved the inner microclimate condition and the outside conditions. Inner microclimate conditions were assumed to mimic the state of high human activities in outdoor environments. As such the inner side; temperature and humidity were assumed to be 37^{o}C and 25% respectively. Similarly, outside environmental conditions were selected to mimic outside conditions having temperature and humidity of 7^{o}C and 75% respectively.

Fabric sample of different knitted spacer fabrics in which between the two single jersey layers with different number of spacer courses were used. This variation created different fabrics behaviour in terms of size, thickness and porosity (capillary size). The specifications of some of the fabric samples are given in the table 4.4.1 below;

Table 4.4.1: Fabric properties

Sample	Spaces	Thickness [cm]		Weight /11.5cm X 11.5cm [grams]	Wales/ cm	Courses/cm	Capillary radii [μm]
		Average	Stdev				
KSS6T2E	6	0.420	0.007	7.54	8	11	39.97
KSS8T2E	8	0.488	0.007	8.71	9	11	36.57
KSS10T2E	10	0.550	0.005	9.74	9	10	39.25

Where; spaces is the number of needle tucks within one repeat

The properties of yarns used to produce KSS are tabulated below.

Table 4.4.2: KSS yarn properties

Application	Fibre type	Count /yarn end [dtex]	Total count [dtex]	Number of yarn ends per course	Number of filaments / yarn end	Total number of filaments in the structure
Yarn for plain knitted layers	Polyester	167	3.34	2	48	96
Spacer yarn	Polyester	167	3.34	2	48	96

Furthermore, the simulation required a liquid media to be used to travel across KSS in order to calculate its transmission rates. Literature (G.B.Delkumburawatte, 2011, Delkumburawatte and Dias, 2011, Hsieh, 1995) points out that; distilled water can be used as a liquid media for simulation because they have properties similar to sweat when used in ideal environmental conditions.

The properties of water used in the simulation are tabulated below;

Table 4.4.3: Constant values for the properties of water

Property	Value
Density	1.0 g/cm^3
Viscosity	0.00089 Pa.s
Surface tension	0.072Nm
Contact angle on fabric	75degrees

In order to calculate the required moisture transmission rates; Matlab R2012a computer package from Mathworks was used by using the m-file editor of the software package. Generally this would enable the demonstration of mathematical relationship between a set of input variables. The mathematical equations of capillary radius and moisture transmission rates were converted into Matlab code for simulations, which is given in Appendix 1.

The heat input across the inner and outer climates was 2.8W and the corresponding results of the predicted moisture transfer rate was obtained and plotted against time;

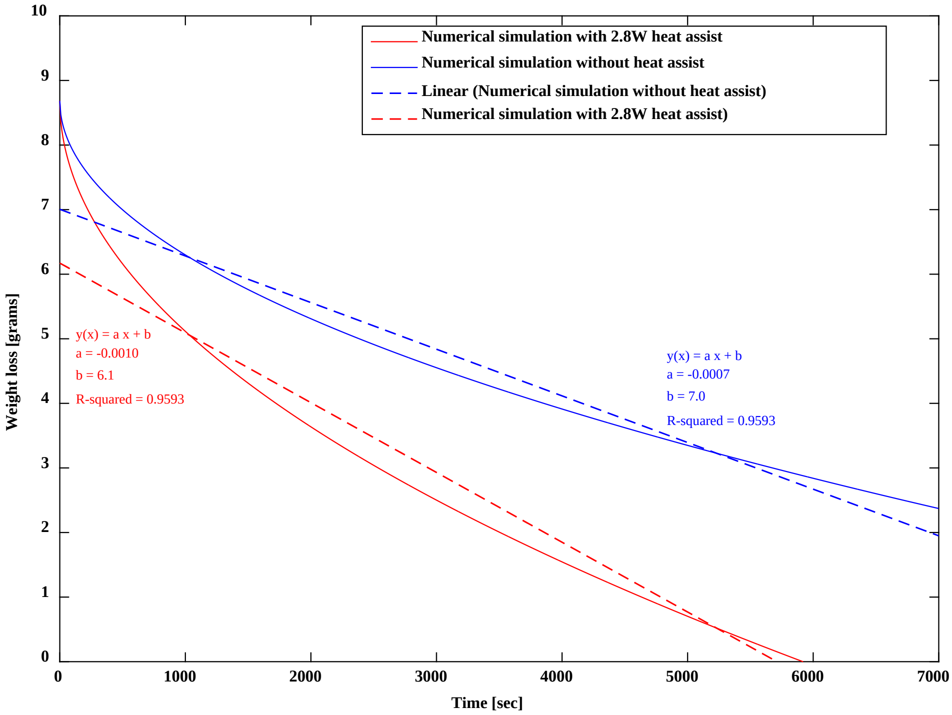


Figure 4.4.1: Moisture transmission rate KSS6T2E

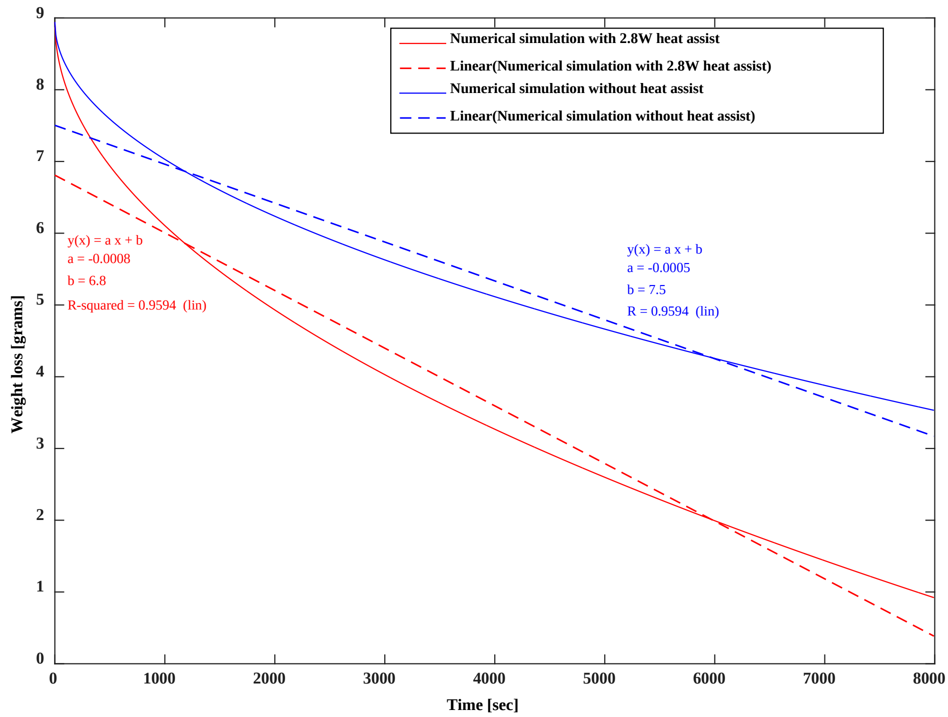


Figure 4.4.2: Moisture transmission rate KSS8T2E

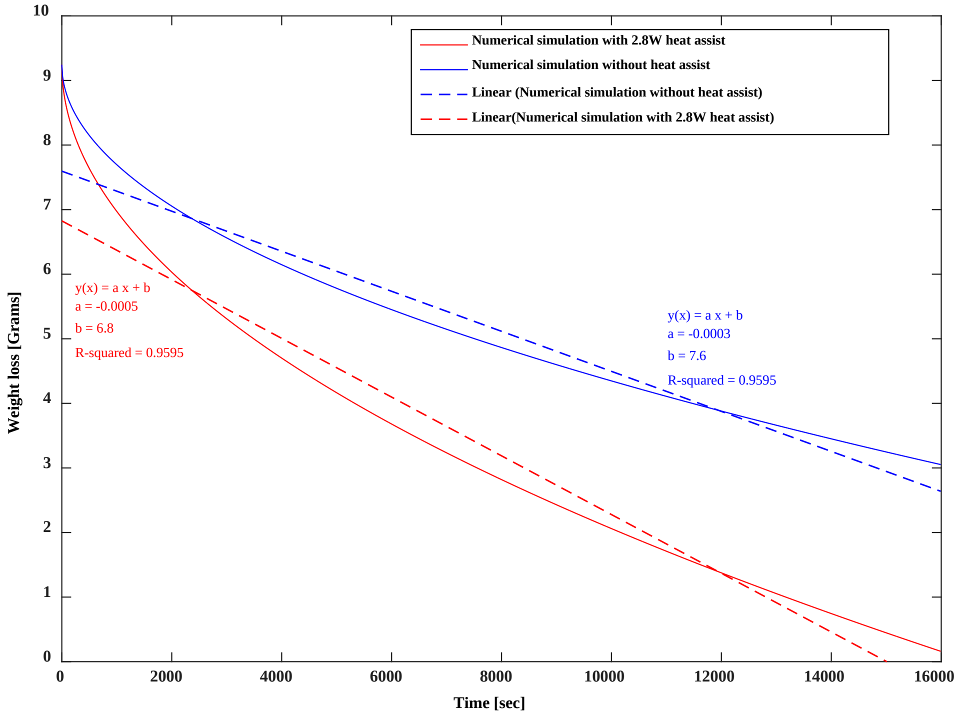


Figure 4.4.3: Moisture transmission rate KSS10T2E

4.5 Experimental validation of the new model

4.5.1 Concept

In the previous section a mathematical model which was developed to understand influence of creating a thermal gradient within the cross-section of a KSS would have on the transmission of moisture between the two outer knitted layers of the structure. The new model demonstrates the relationship between the capillary radii and the moisture transmission rates of a KSS at different environmental conditions, different fabric and fibre properties and at variable input heating rates was explained. In order to validate the new model, a novel measurement system has to be developed. In this system, the test sample (KSS) is positioned vertically between two mini environmental chambers and the change in weight of the test sample (moisture change) is measured. The temperature and humidity of the two mini environmental chambers can be varied and also measured. A schematic illustrating the concept of the measurement system is given in figure 4.5.1.1;

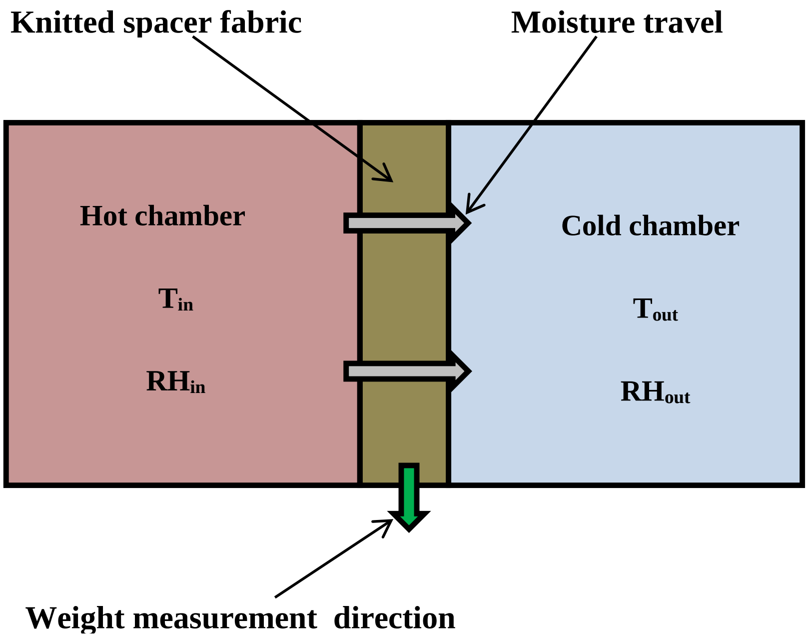


Figure 4.5.1.1: Schematic of the conceptual design of the measurement system

A test rig was designed, built and commissioned to gather the data required to validate the new mathematical model

4.5.2 Heating mechanism

During the testing heat has to be introduced on to one side of the surface of the test samples (KSS), which would increase the vapour pressure on that side of the sample; this would result in increasing the hydrostatic pressure gradient between the hot and the cold sides of the test samples. The derived mathematical model shows that higher the temperature gradient between the outer-surfaces of a KSS is more moisture should be transferred within it. Therefore, a plain knitted fabric with integrated knitted heating patches was placed on top of one surface of the test sample (KSS). The base fabric of the plain knitted fabric was manufactured from polyester yarn and FabRoc yarn to provide heating and silver coated (plated) nylon to provide the electrical power required to heat the FabRoc patches. The working principle of the knitted heated patches is that the stitches made of FabRoc yarn, which is made from silicone and carbon nano particles, represents an electrical resistive network powered by two knitted bus bars made from a conductive yarn such as silver plated nylon yarn (see figure 4.5.2.1 below);

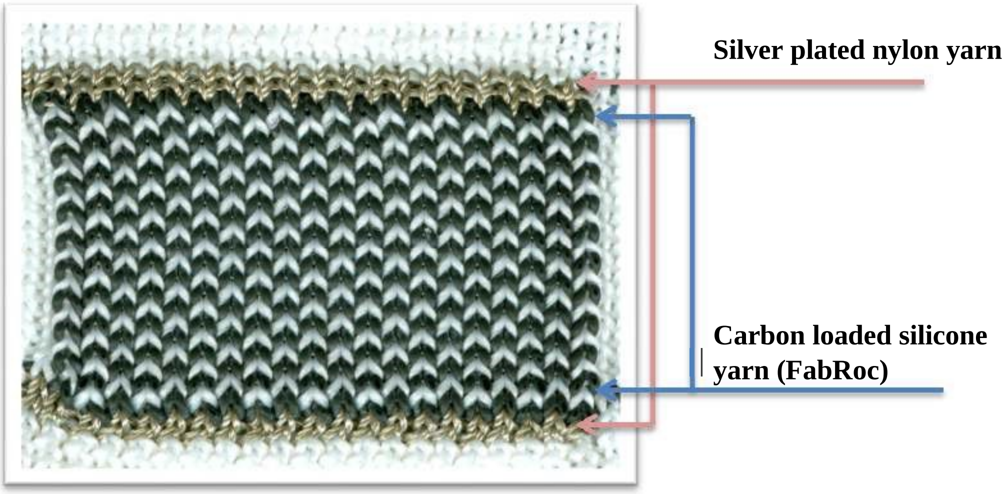


Figure 4.5.2.1: Photographic image of a heater patch

The fabric used for providing heat energy to the test KSS samples during testing were knitted with four heating patches. The specifications of the knitted heating fabric are given in Figure 4.5.2.2 below;

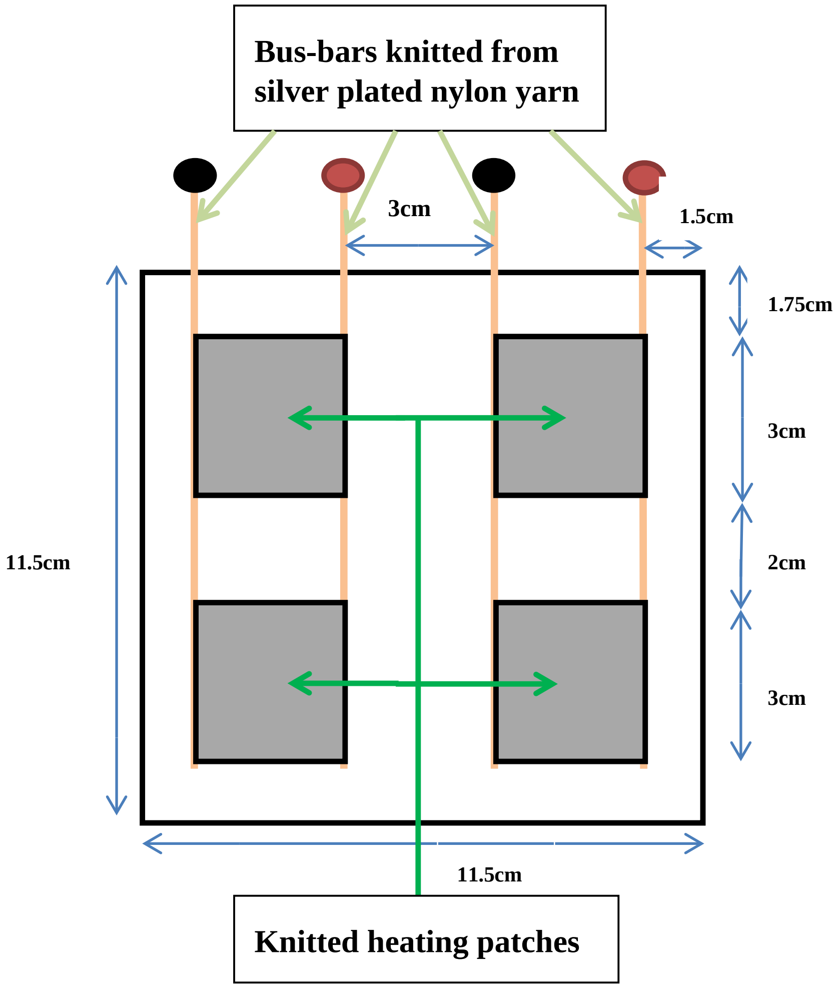


Figure 4.5.2.2: Heat fabric structural dimensions

The figure 4.5.2.2 above displays the dimensions of heating patches knitted on the single jersey fabric. The total number of heating patches are 4 with each having an area of 3.0 cm X 2.0 cm = 6.0 cm^2. So the total area covered by heat patches will be 6.0 cm^2 X 4 = 24.0 cm^2. The total area of the KSS that will be covered is 10cm X 10cm = 100cm^2. This is to exclude 1.5 cm on each edge which is used as supporting area on the plate holder. The total area not covered by the heat patches is 100cm^2 – 24cm^2 = 76cm^2 (76%). This is aimed as the moisture absorption and transmission area.

The heating patches were arranged in the knitted heating fabric to distribute the heat energy equally to all parts of the knitted heating fabric as well allowing moisture to pass between the heating patches.

Figure 4.5.2.3 below illustrate the heat patch connections.

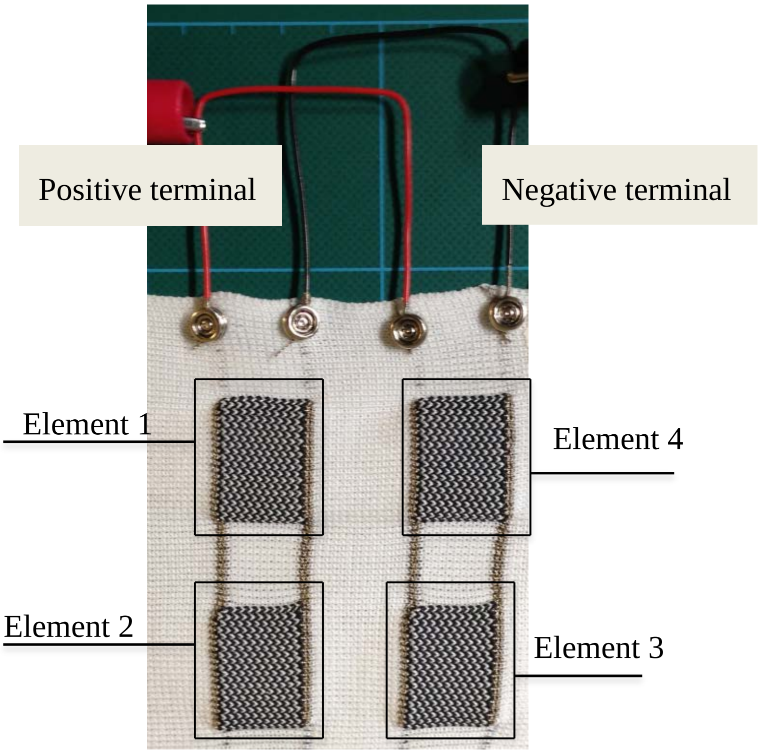
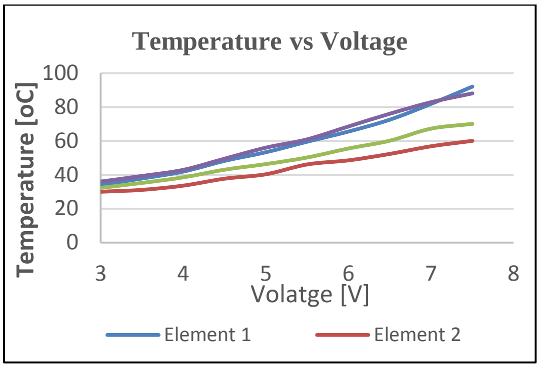


Figure 3.5.2.3: Parallel connection

Electrical power to the heating elements was supplied from a variable power supply in which the supply voltage and current could be adjusted; the specifications of the power supply is given in the Annex 2. Prior to testing of the KSS samples with the new test rig the heater fabric was tested for different voltages and currents and the corresponding temperature values were read by using a Raytek Rayngerr MX (see annex 3) laser temperature reader. The results are given in Figure 4.5.2.4.



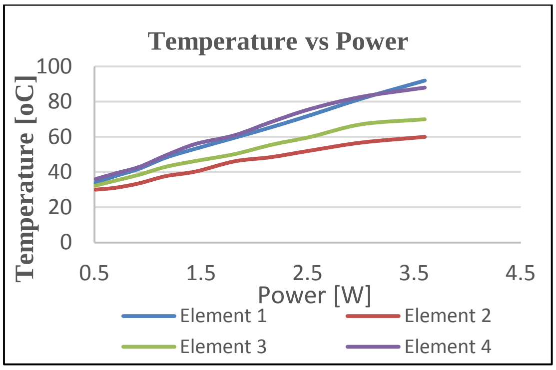
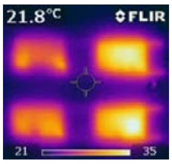
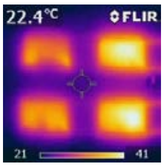
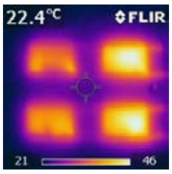
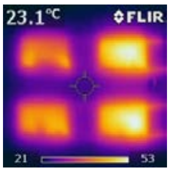
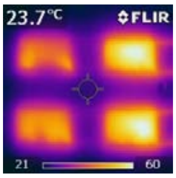
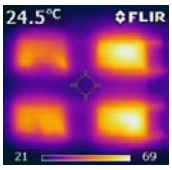
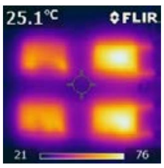
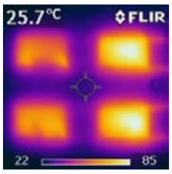
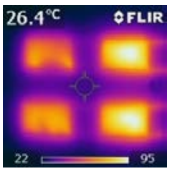
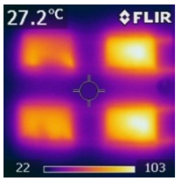


Figure 4.5.2.4: Performance of knitted heating fabric

Further to this, thermal images of the knitted heating fabric at the various temperature ranges were taken by using a FLiR i7 thermal image camera. The heating performance of the knitted heating fabric between 3.0 – 7.5V is given in Table 4.5.2.1 below;

Table 4.5.2.1: Thermal images of heating fabric

Voltage [V]	3	3.5	4	4.5	5
Current [A]	0.19	0.22	0.25	0.29	0.32
Image					

Voltage [V]	5.5	6	6.5	7	7.5
Current [A]	0.35	0.38	0.42	0.46	0.49
Image					

4.5.3 Design and construction

As stated earlier the test rig design consists of two mini chambers, one for heating and one for cooling. The design is illustrated in Figure 4.5.3.1 below;

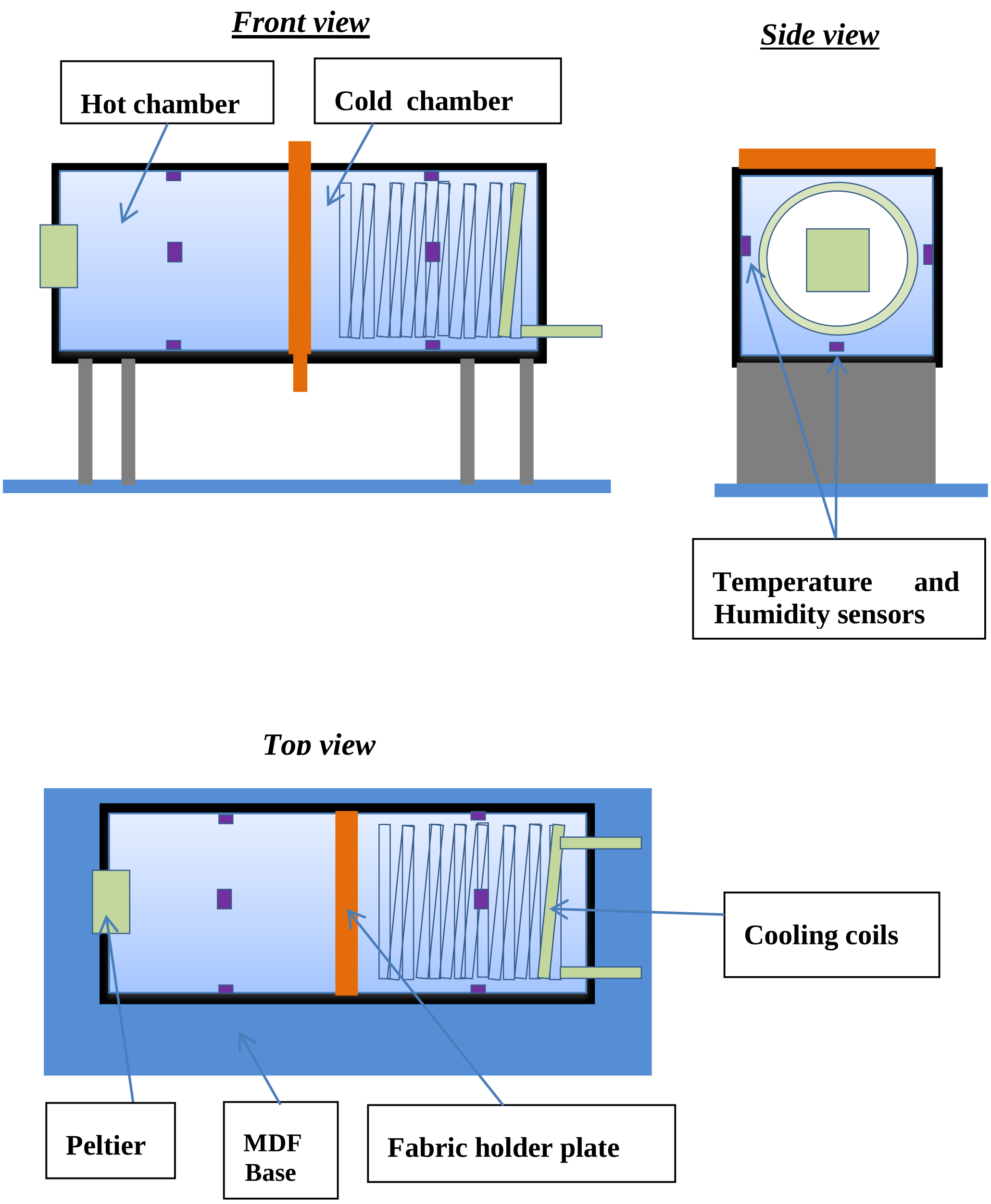


Figure 4.5.3.1: Test rig design layout

The two mini chambers were created by using acrylic sheet material. The mini chambers were produced with *210mm (L) X 210mm (W) X 4mm* (H) acrylic pieces which were glued together with a special industrial grade adhesive (specifications given in Annex 1). This glue insured a reliable joining of the acrylic pieces together. In order to ensure no heat loses the walls of the mini chambers were insulated with a 4mm cardboard-aluminium foil.

The same acrylic material was used to create a plate for holding the KSS test sample. In this case two acrylic plates of *164 (L) X 250 (W) X 4 (H) mm*, were glued together, and this plate (the sample holding plate) was slotted in vertically between the two mini chambers (see figure 4.5.3.2) in a manner that its bottom end lies on top of a digital weighing scale with a RS232 interface from Adams Equipment, model PGW753i.

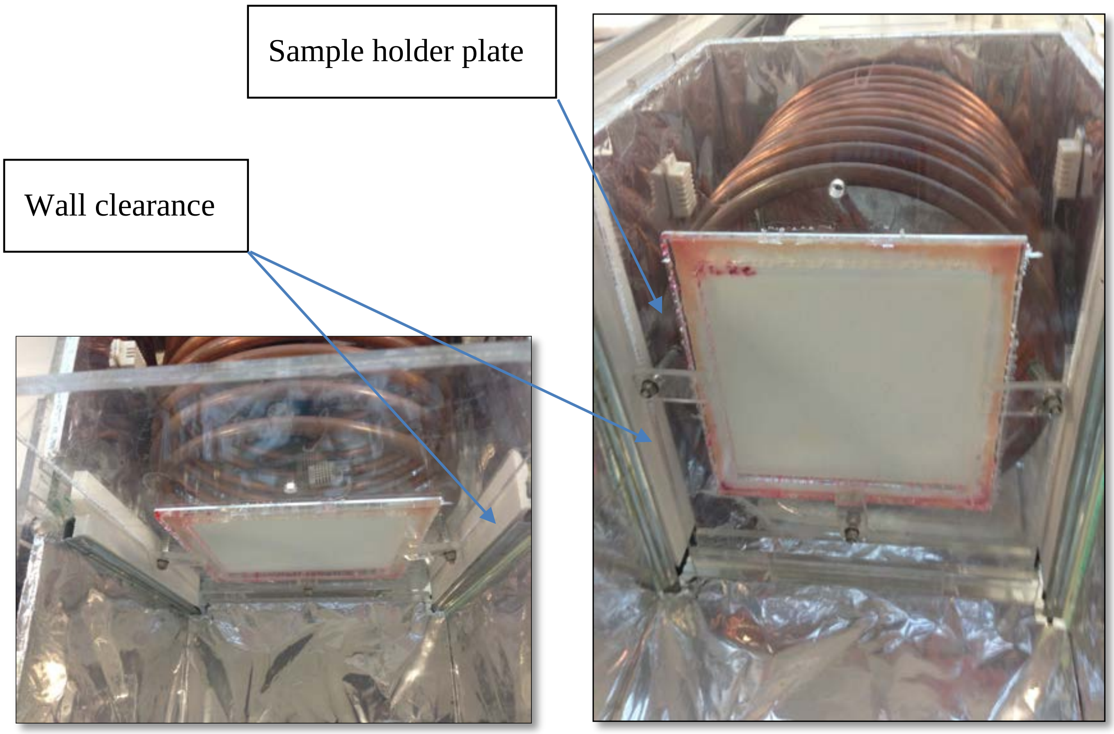


Figure 4.5.3.2: Sample holder plate placement in the test rig

At the centre of the sample holding plate, a *100 X 100mm* hole was created for the KSS samples. The KSS sample was secured in place with a thin acrylic frame and three spring holders (see figure 4.5.3.3)

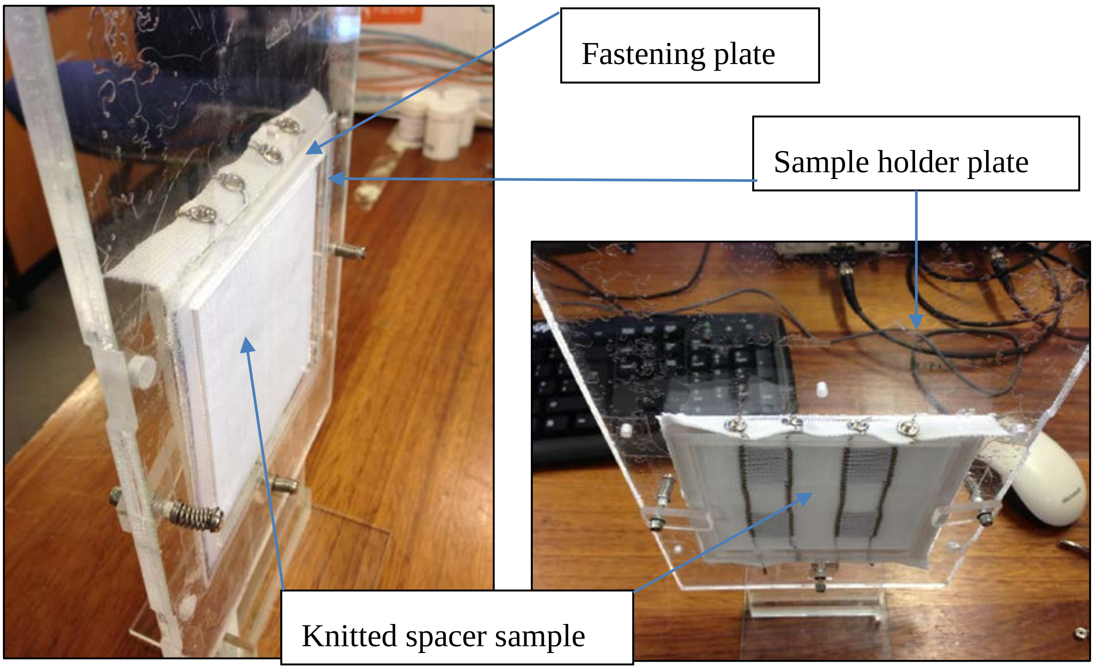


Figure 4.5.3.3: KSS holder plate

Heating of the hot mini chamber was achieved with a 200W Peltier element of 50mm X 50mmX 3.5mm (see Annex 4 for further details). The Peltier was fixed placed on the wall of the mini chamber so that its hot side was facing to the inside of the mini chamber and the cold side outside the mini chamber. Cooling fins with two 12V fans (not shown in figure 4.5.3.1) were placed on both sides of the Peltier, in order ensure efficient heat transfer from the Peltier into the mini chamber. Power to the Peltier was supplied from a TTi EL155R variable voltage power supply.

Similarly, on the cold mini chamber, cooling was achieved by using a heat exchange systems, consisting of two sets of *8 mm* diameter copper coils, each having 10 coils. One set of coils was placed inside the cold mini chamber and the second set in an ice bath. The principle is that, the heat is removed from the cold mini chamber and dissipated in to the ice bath. A Watson Marlow variable speed peristaltic pump, model 503U was used to circulate the cooling liquid between the two coils accurately. The cooling liquid used was a mixture of water and ethanol. Ethanol prevents freezing of water in the copper pipes. The ice box consisted of *210 X 210 X 210 mm* dimensions.

In order to monitor the temperature and the humidity in the mini chambers, six DHT22 high accuracy temperature and humidity sensors were used (see Annex 5 for further details of the sensors). Three temperature and three moisture sensors were used in each mini chamber (see figure 4.5.3.1). Signals from the sensors were collected by using an Arduino nanoV3 microcontroller board. The weight of the sample holder plate was measured using an Adam PGW753i precision digital weighing scale with 1.0mg sensitivity. LabVIEW software was used to acquire, display and export data from the sensors and the Adam weighing scale. A dedicated LabVIEW software program (see Appendix 2) was created to perform the above functions.

The test rig was placed on top of a *360 X 480 X 18 mm* base made from MDF material with the mini chambers being supported by side pates. This arrangement facilitated the weighing scale to be placed underneath the mini chambers. As the test rig was very sensitive to vibration it was placed on anti-vibration inflatable tubes. A level meter was used to ensure that the test rig was operated in an appropriate levelled position. The complete test system is shown in Figure 4.5.3.4 below;

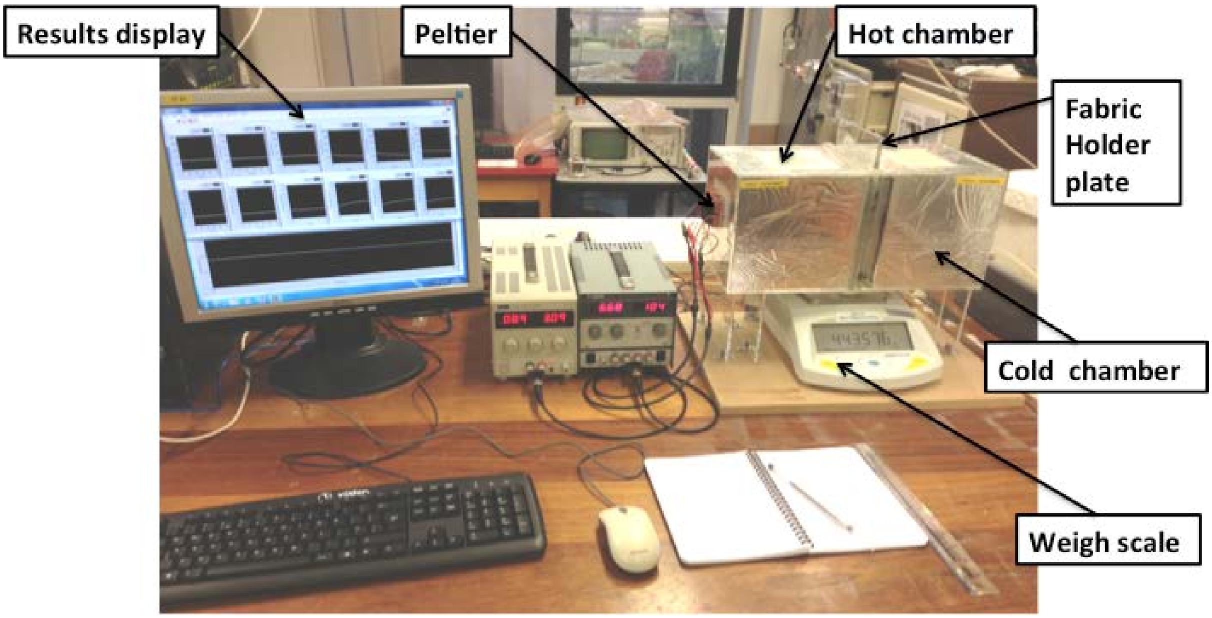


Figure 4.5.3.4: Moisture transmission test system

4.5.4 Experimental procedure

The test procedure adopted during the evaluation of fabric samples is described in the following steps:

Ice preparation: the ice bath is filled with fresh ice. The top of the ice bath must be covered at the top to prevent heat losses. The peristaltic pump is on switched on to start the circulation process;

- The peltiers and fans are switched on according to required settings;
- Weighing scale must be calibrated;
- Sample preparation: *115 X 115 mm* samples are cut from a large KSS and weighed;
- Sample Fixing: the KSS test sample is fixed to the sample holder plate and secured using spring loaded clips;
- Water spraying: after cutting, one side of the sample was sprayed with a predetermined amount of distilled water; this side of the test sample was placed in the test rig facing the heated mini chamber;
- Fixing: the holder plate containing the fabric sample was placed between the two mini chambers as described in the previous step. It was ensured that the bottom edge of the KSS test sample did rest on the digital weighing scale;
- Data acquisition software was initiated;

The above procedure was applied for evaluating all the fabric samples and the results were plotted against the time of data acquisition period. Also results representing number of repetitions performed on each test are shown below as well. This included both without heat and heat assisted tests.

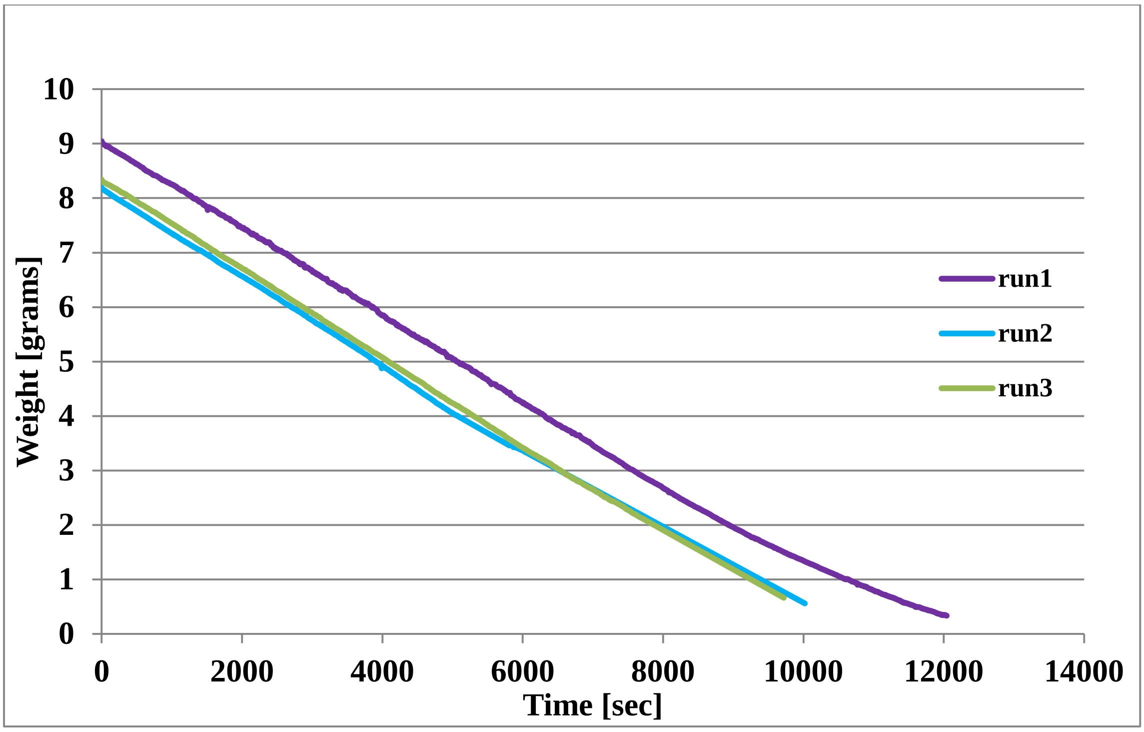


Figure 4.5.4.1: Moisture transmission rate for KSS6T2E without heat assist test runs

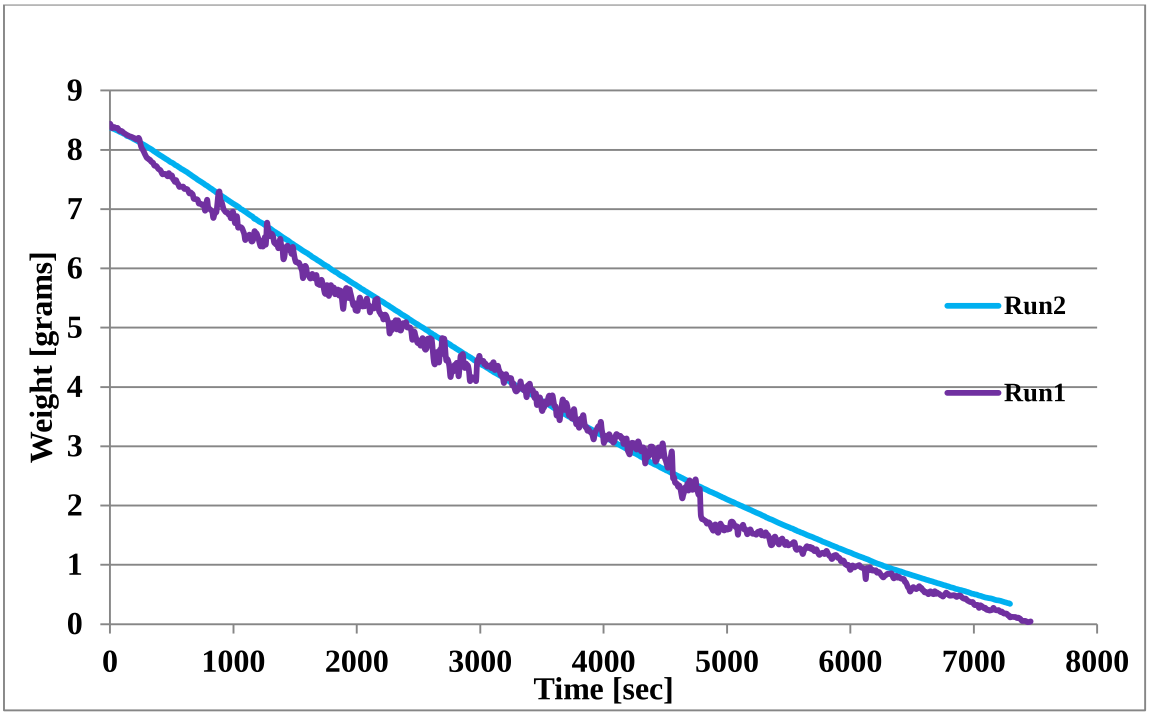


Figure 4.5.4.2: Moisture transmission rate for KSS62TE with heat assist test runs

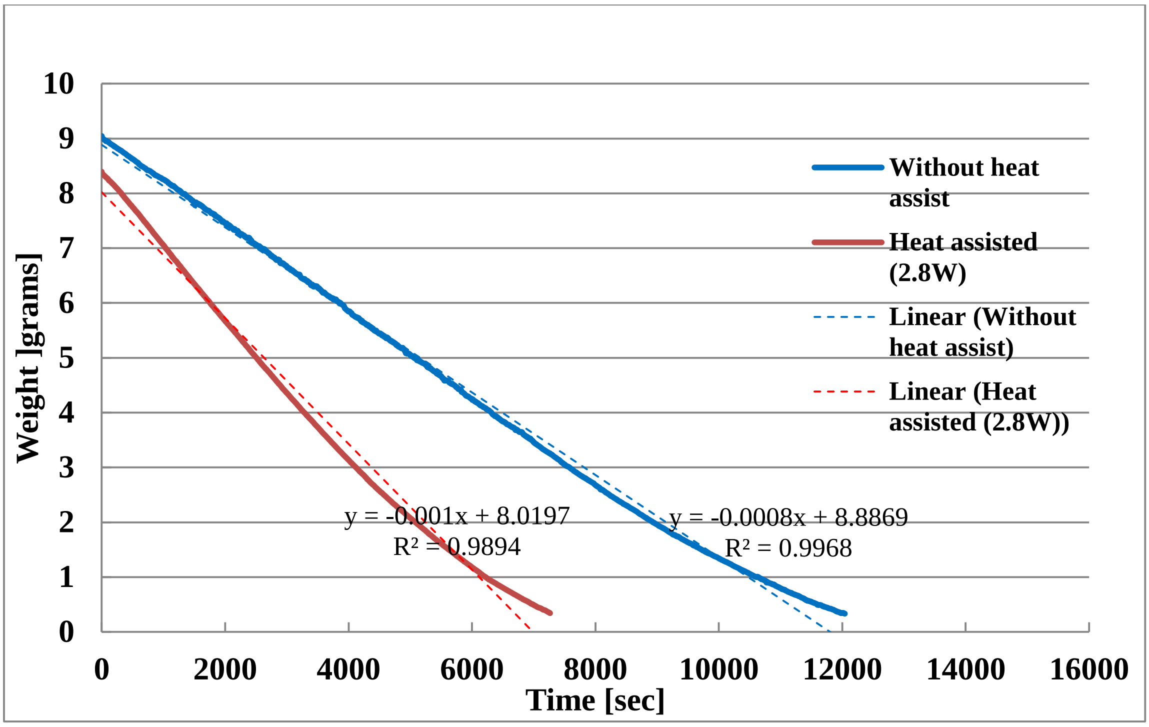


Figure 4.5.4.3: Moisture transmission rate for KSS62TE with and without heat assist comparison

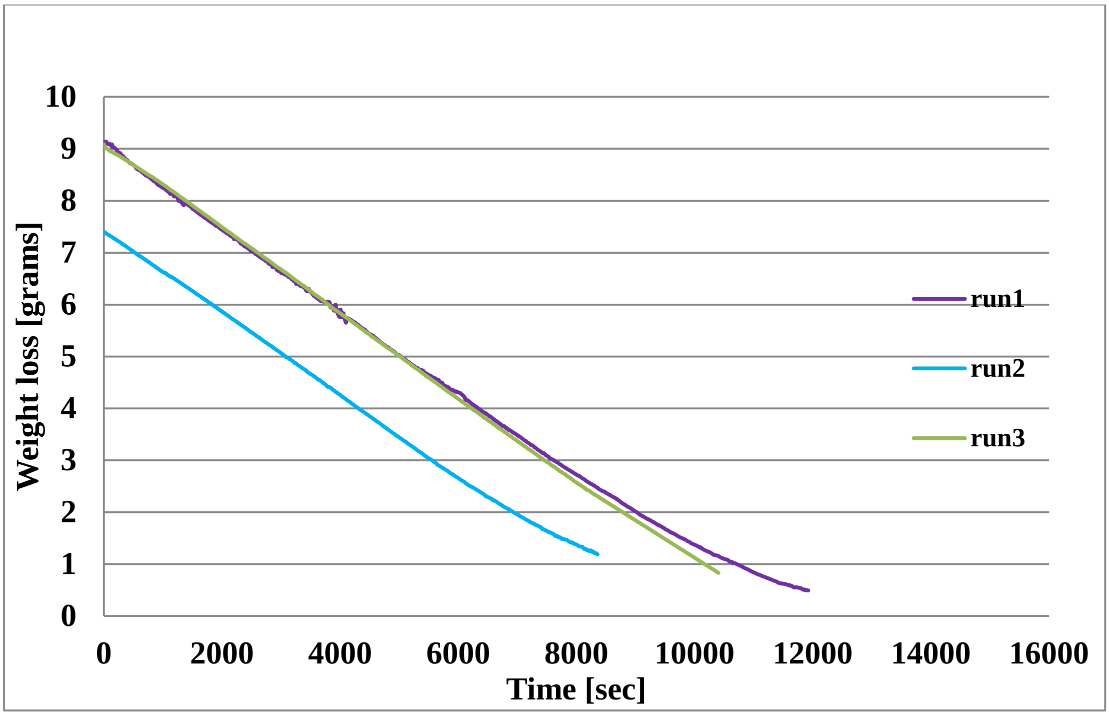


Figure 4.5.4.4: Moisture transmission rate for KSS8T2E without heat assist test runs

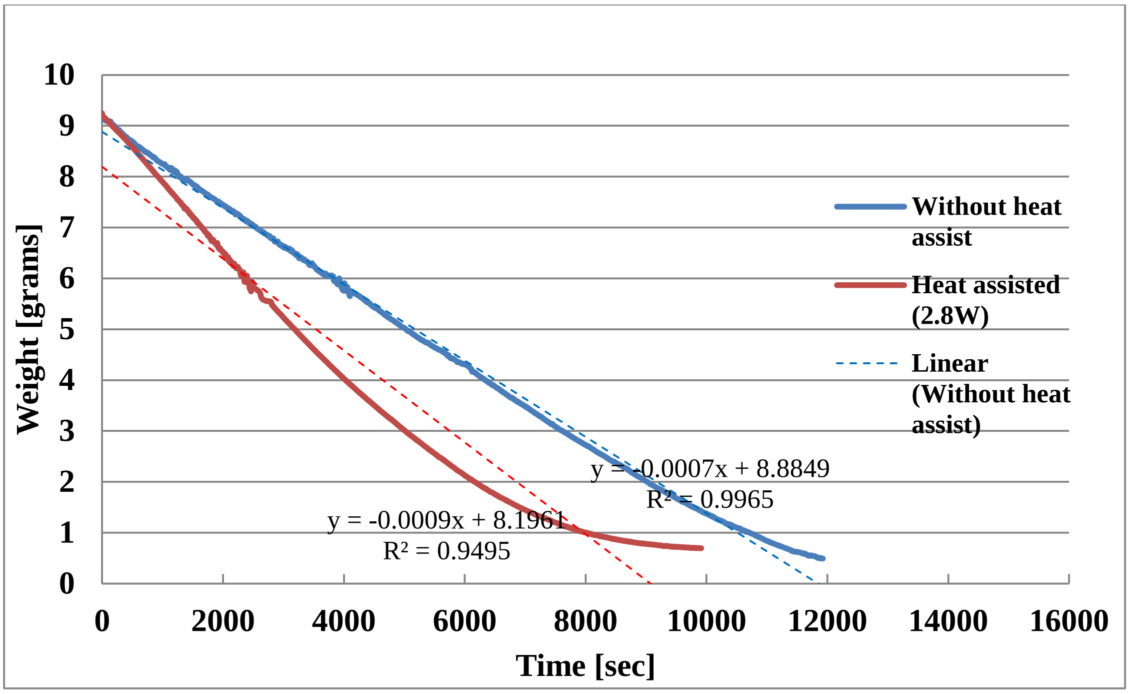


Figure 4.5.4.5: Moisture transmission rate for KSS8T2E with and without heat assist comparison

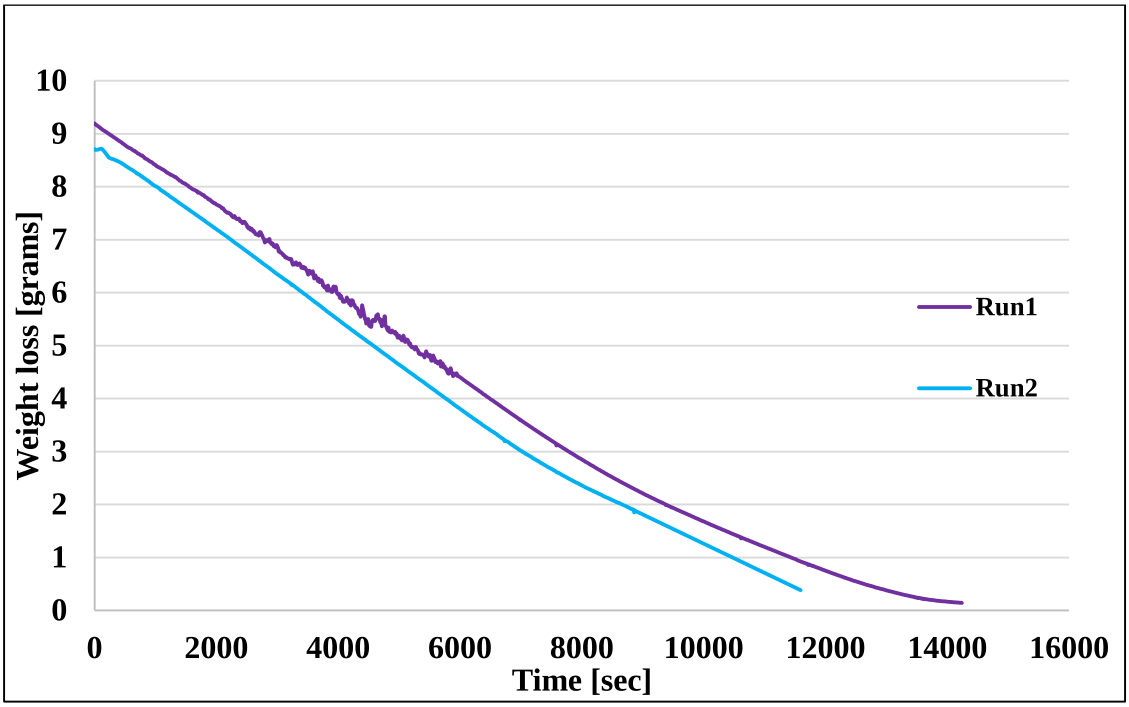


Figure 4.5.4.6: Moisture transmission rate for KSS10T2E without heat assist test runs

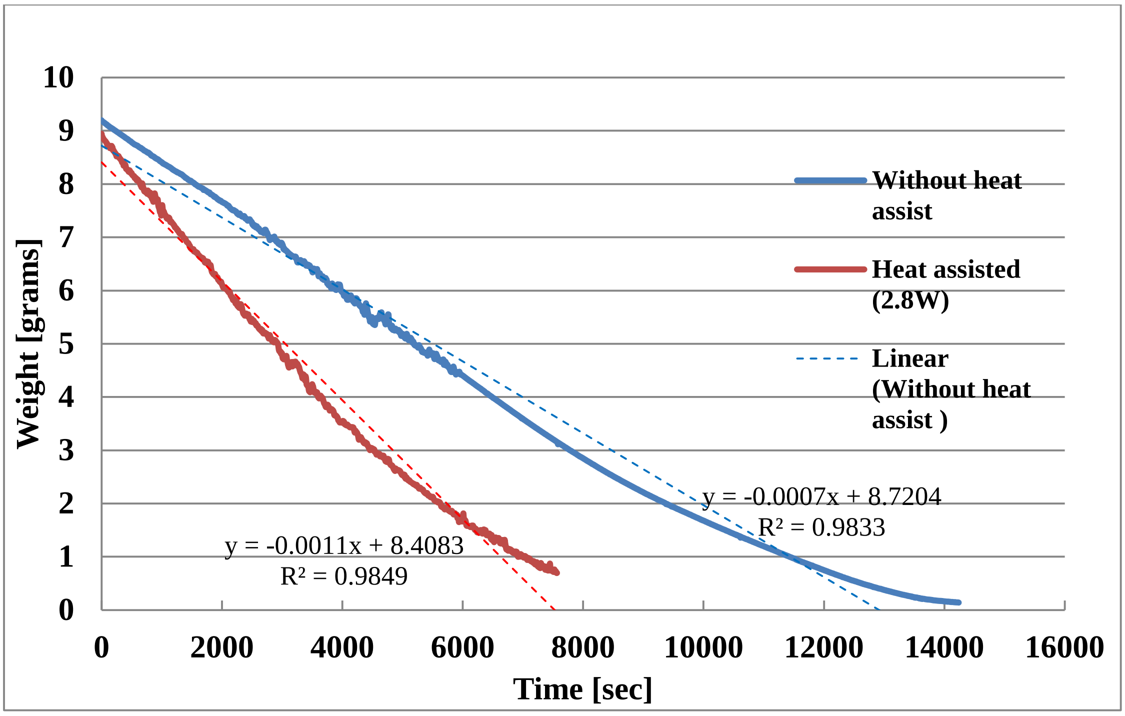


Figure 4.5.4.7: Moisture transmission rate for KSS10T2E with and without heat assist comparison

4.6 Discussion of results

It is apparent from the results of the experiments conducted that the effect of applying heating increased the moisture transmission rate, see figures 4.5.4.3, 4.5.4.5 and 4.5.4.7. They show an increase of moisture transmission by approximately 30%. A similar improvement in moisture transfer is observed from numerical simulation results shown in figures 4.4.1, 4.4.2 and 4.4.3. This moisture transfer increase can be explained by the increase in vapour pressure due to heat assist on the inner microclimate resulting in increasing the hydrostatic pressure gradient across the fabric. The higher the pressure gradient is, more moisture is transferred across the fabric.

Another observation from the results on figures 4.5.4.3, 4.5.4.5 and 4.5.4.7 is that, KSS6T2E showed a higher moisture transfer rate of 0.001g/s compared to KSS8 and KSS10 which showed 0.0009g/s and 0.0011g/s respectively when a 2.8W heat assist was used. This could be due to the low thickness of the fabrics which could be due to the shorter distance of travel of the liquid. In other terms, thinner spacer fabrics have shorter capillary lengths resulting in much higher transfer rates. Also, KSS6T2E had fewer spacer yarns in a repeat; this creates higher capillary radii compared to other sample (see figure 4.4.1). As such it is possible that the structure and the geometrical arrangement of spacer yarns in the structure contributed to the higher transfer rates than KSS8T2E and KSS10T2E.

Another important observation is that, the KSS10T2E showed 0.0002g/s higher transfer rate than KSS8T2E. This can be explained by considering structural differences. KSS10T2E has longer capillaries than KSS8T2E, and this would allow more moisture to be accommodated compared to KSS8T2E. Since KSS10T2E is thicker than KSS8T2E one can expect it to demonstrate low transfer rates. However, the test results indicate that the combination of structural factors can result in higher moisture transfer rates. The structural factors are the number of spacer yarns and the distance between the successive needles tucks which defines the angle of capillaries.

Heating fabric used in the experiments produced heating as evident from figure 4.5.2.1. Efficient heat production was obtained with parallel connection of the bus bars, as this configuration resulted in more current flow due to the low resultant resistance of the heating system. This connecting configuration will be useful when a larger number of heating patches have to be powered from one power source. Looking at thermal images given in Table 4.5.2.1, one can see that the heating is not uniformly distributed in the heating patches. Also the areas not covered by heating patches have lower temperatures compared to areas covered by heating patches. This effect was considered in the mathematical model by reducing the amount of heating areas provided by the patches. This allowed approximate by 75% of the spacer fabric samples to receive the heating produced by the heating patches.

Looking at graphs of figures 4.5.4.1, 4.5.4.2 and 4.5.4.3, one could conclude that the fluid transfer rates for KSS samples appear to be dominated by a constant rate of moisture transfer during almost 70% of the drying period. This may be due to the type of fibre used to produce the spacer fabrics. All KSS samples were produced exclusively from polyester fibres; polyester fibre is hydrophobic, hence, the moisture absorption could occur only between the fibres and minute insignificant amount will be absorbed by the fibres. This would facilitate moisture to be transferred through the fabric structure rather than absorbing it(Backpacklight, 2006, Saeed, 2006, Mohamed Hamdaoui, 2013). This is evident from the graphs as they exhibit an almost constant rate of moisture transfer compared to the exponential moisture transfer rate curves of other non-spacer natural fabrics. This shows that KSS have the ability to absorb moisture and release it at constant rates compared to fabrics made of natural fibres.

4.7 Experimental and numerical results comparison

In this section the results obtained from the numerical simulation of the new mathematical model is compared with the experimental results obtained with the test rig. In model simulation the same properties of the knitted structure (KSS), the fibres, and water were used as for the testing of the KSS test samples in the new test rig. Therefore the experimental results can be compared with simulated values obtained with the mathematical model. The comparison are showed on figures 4.7.1 to 4.7.3 below;

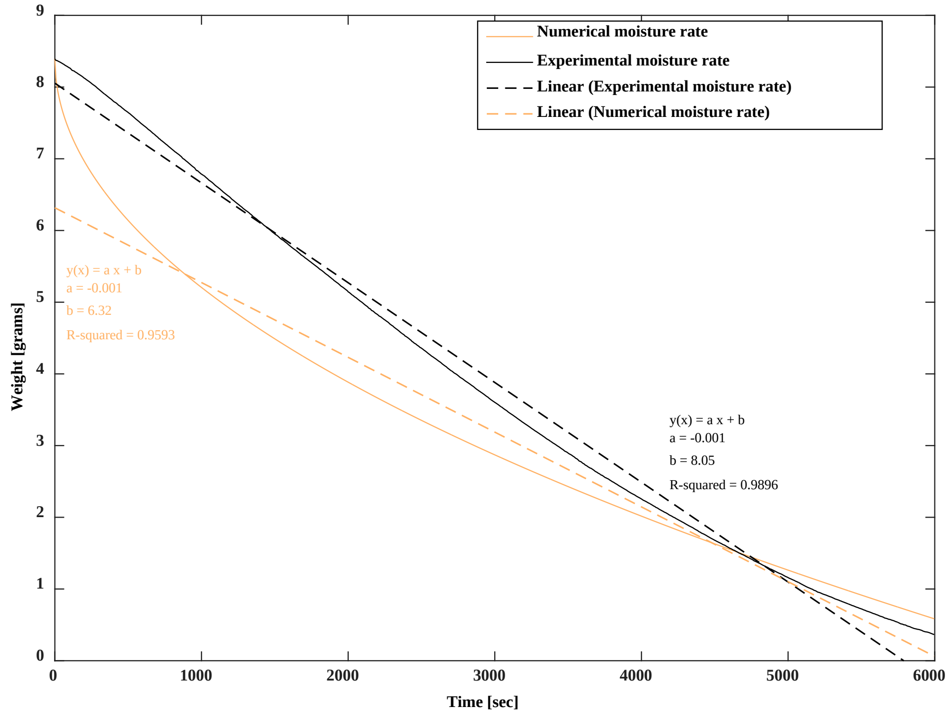


Figure 4.7.1: Moisture transmission rate comparison for KSS6T2E

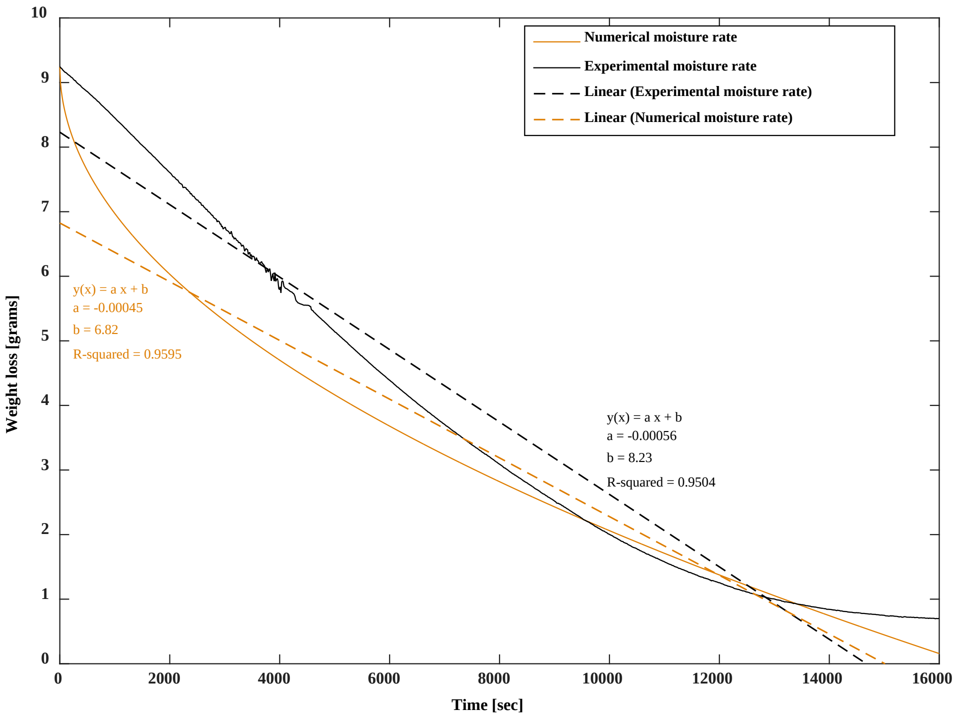


Figure 4.7.2: Moisture transmission rate comparison for KSS8T2E

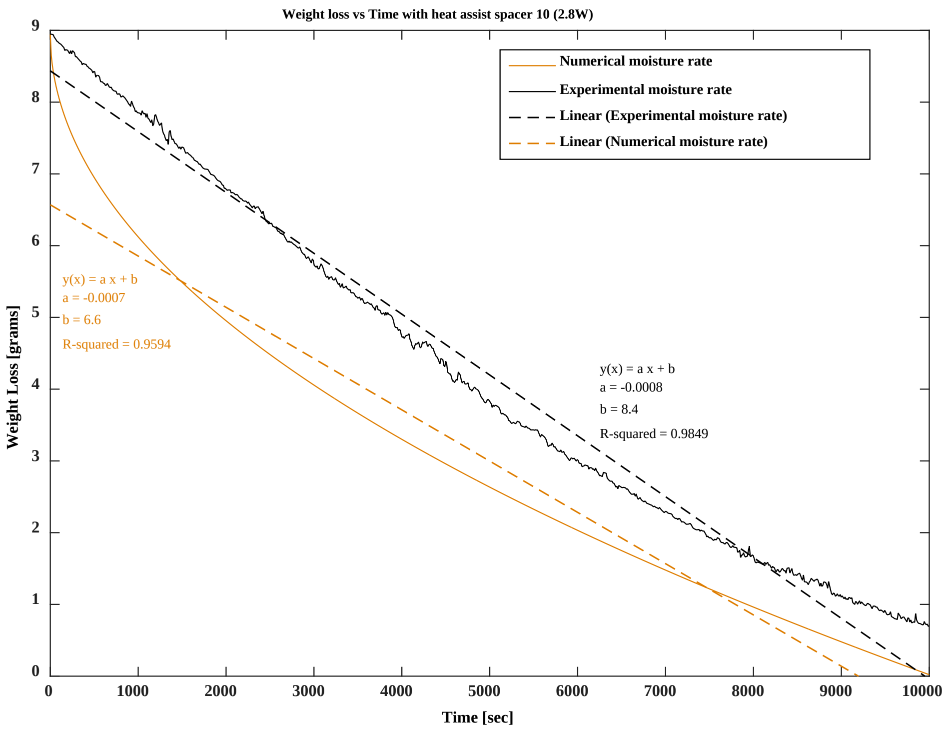


Figure 4.7.3: Moisture transmission rate comparison for KSS10T2E

Observation of the figures 4.7.1, 4.7.2 and 4.7.3 some important information can be drawn;

The moisture transmission rates of both numerical and experimental results were close as can be seen on the 0.9 regression fitted graph rates of 0.001g/s, 0.004/0.006g/s and 0.007/0.008g/s for KSS6T2E, KSS8T2E and KSS10T2E respectively. This shows that model prediction are in line with experimental results and the model could be used to study and understand different types of KSS and at various operating conditions. One issue to be raised is that the model results are closer to experimental results after 1/3 of the total time mark. Before this mark, model result predicts less rate compared to experimental results. After this mark, model result prediction is closer to experimental. This could be explained by the way moisture was introduced to the structure. Moisture was initially sprayed onto one side of the KSS and then moisture transfer rate was observed by monitoring the weight change of the KSS. The assumption made is that moisture would travel by capillary forces in one direction from the inner to the outer surface. But ideally some moisture would travel outwards along the fabric and this could reduce the amount of moisture traveling through the capillary and produce and the initial differences observed on the results. After the 1/3 of total time mark, both results appear to be the same. This could be at this instant more moisture is traveling inside the capillaries than across the fabric.

Another observation from the results is that model graphs show sharp weight loss within the first 3000 seconds and then almost a straight line. The first 3000 seconds are out of sync with the experimental results. This may be due to the contact angle used in calculating the numerical values by using the mathematical model (equation 4.3.2.12). In the model, a single contact angle of 75 degrees was used. But Delkumburawatte, Pan and Lukas (G.B.Delkumburawatte, 2011, Lukas, 2003, Pan. N) reports that the contact angle varies as liquid progresses through the capillaries. The contact angle would change from static to dynamic state as moisture progresses through the capillaries of the fabric. It is envisaged that this may be the reason for the difference observed between experimental and model result.

4.8 Moisture transmission of spacer fabrics

The previous section shown was about mathematical modelling of spacer fabrics and we have seen that model results proved to be same as experimental results of spacer fabrics. The type of spacer fabric used in this experiment was of type KSS10T2E, KSS8T2E and KSS6T2E. However the results summarised in table 4.4.1 (page 67) show that they are too heavy to be considered as outdoor garments. Therefore a new set of experiments were conducted using thinner KSS fabrics described in chapter 2 section 2.6; page 43 and the results are tabulated in table 4.8.1 below;

Table 4.8.1: Spacer fabric properties for moisture transmission

Sample	Weight/ 11.5X11.5cm^2 [grams]	Average thickness [mm]	Number of spacer yarns	Distance between needles	Number of courses per cm	Number of wales per cm
6T3E	10.665	3.73	3	6	11	8
6T2E	9.454	3.51	2	6	10	8
6T1E	7.662	3.15	1	6	11.1	8.2
4T3E	9.171	2.71	3	4	13	9.2
4T2E	8.167	2.62	2	4	12.2	9
4T1E	6.695	2.47	1	4	11	8
2T3E	7.609	1.95	3	2	12	10
2T2E	6.739	1.90	2	2	11	9
2T1E	5.859	1.85	1	2	13	9

Procedure and testing conditions for this set of fabrics was the same as the one used in section 4.5.4. Results for these experiments are displayed below;

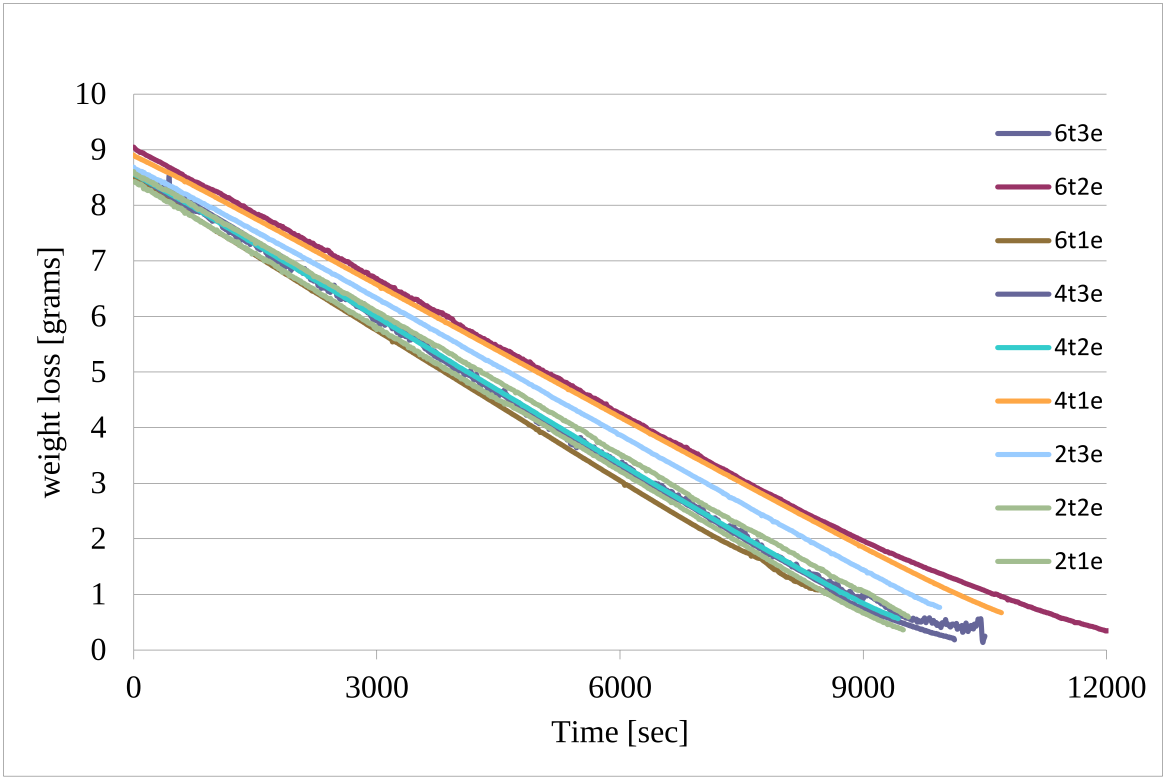


Figure 4.8.1: Moisture transmission on spacer fabrics

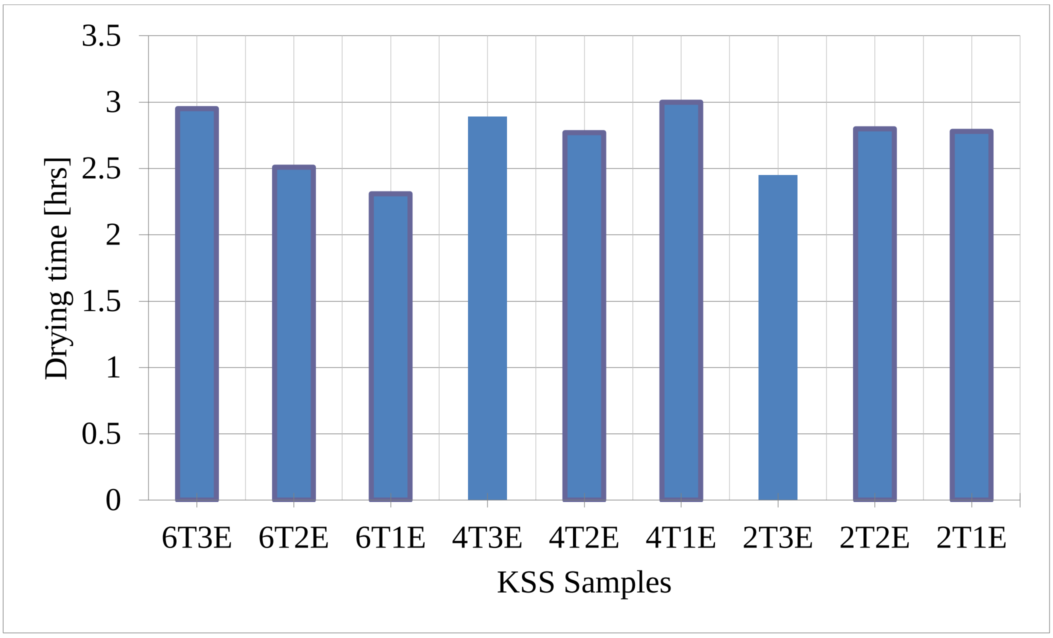


Figure 4.8.2: Spacer fabric drying time

The mathematical model created can be used to explain some useful technical properties of KSS like capillary radii and spacer yarn angle of inclinations. These properties define and predict ways in which moisture can be transmitted across a KSS. The capillary radii and angles of inclination for all the samples were calculated by using fabric properties tabulated in table 3.8.1and the results are displayed below;

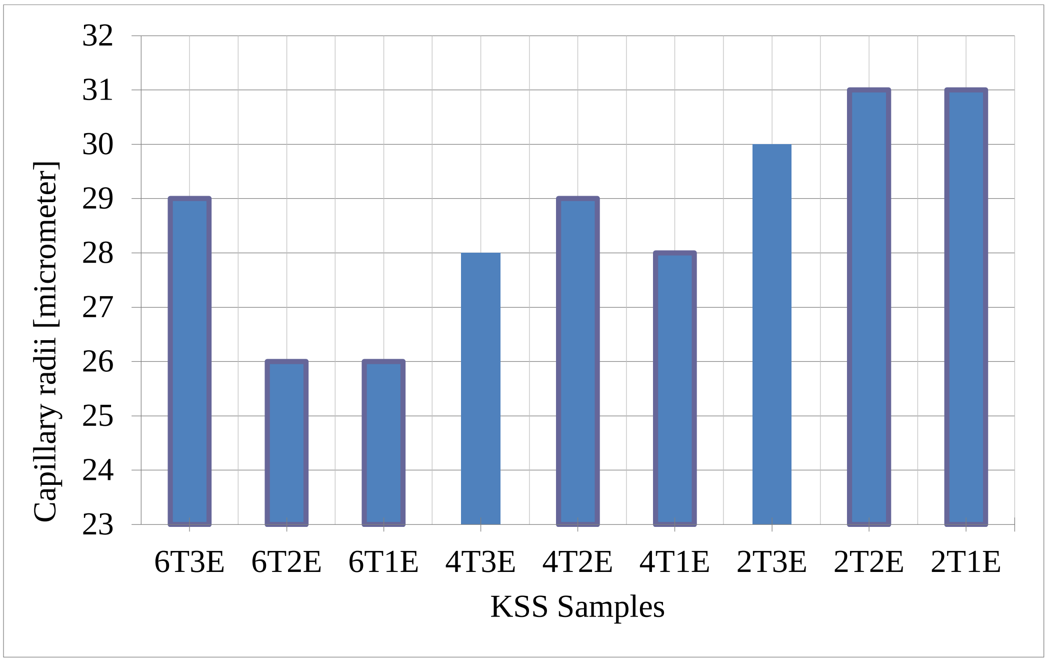


Figure 4.8.3: Spacer fabric's capillary radii of different KSS

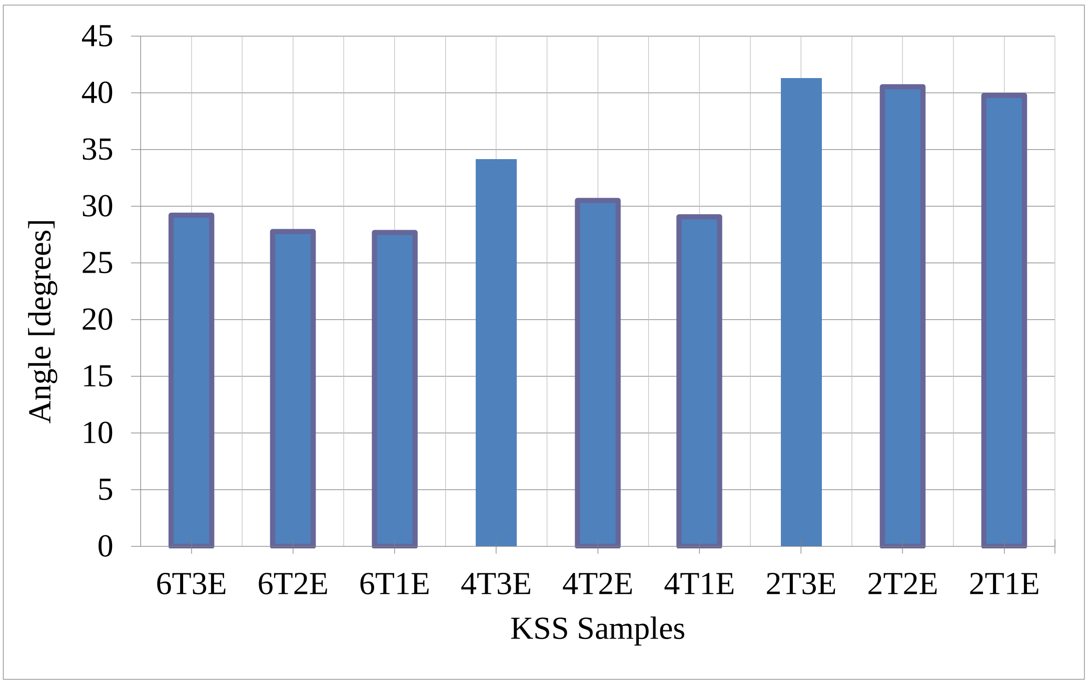


Figure 4.8.4: Spacer yarns angle of inclination

Moisture transmission of KSS by using test rig and important observation could be drawn. The above simulated results can be used to explain the test results shown in figures 4.8.1 and 4.8.2;

Figure 4.8.1 indicates the moisture transmission of 9 different test samples whose fabric properties are shown on table 4.8.1. The first thing to observe is that, transmission of fluid in KSS is almost linear which is due the micro channels in the structure which would promote capillary fluid flow. This pattern could vary in real applications due to its dynamic process however this provides a base to understand how dissimilar various knitted structures could behave in a controlled environment. The figure also indicates heavier structures like KSS6T3E take longer times to dry compared to lighter samples such as KSS2T1E. This is supported by the experimental results obtained for moisture absorption in KSS showed that heavy structures would hold more water affecting the transmission moisture mechanism. Figure 4.8.2 shows the drying times of spacer samples. KSS2 appears to have lower time than KSS6 and KSS4. This could be due to structure differences as explained earlier. The variants of KSS2 samples too showed differences. KSS2 with 3 ends had faster drying time compared to others. The reason could be explained by how the spacer yarns are arranged and their angle of inclination. These are explained below.

Figure 4.8.3 shows simulated results of knitted spacer samples capillary radii. This is the resultant radii consisting of all individual radii of the specific structure of knitted sample. This is an indicator of ideal amount of water which could be contained on the capillary. Results show that KSS6T had lower capillary radius than KSS4T and KSS2T. This could be explained from Lucas-Washburn equation, that larger capillary radius has less capillary flow compared to lower capillary radius. KSS6T had considerably high moisture flow that’s why it had good capability of holding moisture and took longer drying times. KSS2 however, had larger capillary which entailed its lower moisture handling but quicker drying times. For KSS2 variants; one with 2 ends had higher capillary compared to 3 ends. In this sense it has an advantage in terms of moisture transmission but a disadvantage in terms of moisture holding as compared with 3 ends. But however KSS2T3E is heavier and thicker than KSS2T2E. Therefore KSS2T2E was selected for the creation of an active moisture management sample (AMMS) for outdoors activities.

Figure 4.8.4 shows simulated results of knitted spacer samples indicated in table 3.8.1. This explain how the spacer yarns are oriented as they stretch from one single jersey layer to the other. This angle is important as it affects the overall length of the spacer yarn which in turn affects the capillary length formed. These knitted samples will have different orientations and had significant effect on spacer yarn length. The shorter spacer yarn would be efficient for water transmission and would have quicker drying times compared to longer ones. This means the larger the angle of inclination the shorter the capillary would be. Results shows that KSS2T spacer samples had shorter capillary length compared to KSS4T and KSS6T samples. This could be explained as to why KSS2T samples had quicker drying times compared to KSS4T and KSS6T.

4.9 Chapter summary

This chapter reported the development of a numerical mathematical model for KSS and using a specially designed test rig validated the model. The numerical simulation of moisture transfer was in line with experimental results despite some discrepancies due to water contact angle which was assumed to be static but dynamic in reality. Another reason for this could be the manner into which water was sprayed onto the KSS. During the experiments distilled water was sprayed onto the sample prior to measuring and recording of the sample weight. However literature depicts when moisture comes into contact with a fabric, a wetting process occurs which could allow moisture to spread along the fabric first before being absorbed by capillaries and travel across the fabric.

This process was difficult to simulate mathematically and the author believes that this is the cause why initially the experimental results are slightly different to the calculated numerical values. A much better correlation is evident after 3000 seconds. KSS6T was superior to all other samples due to its structural and dimensional properties. The new set of knitted samples (as shown on table 4.8.1) were investigated in terms of moisture transfer by using the new test rig. Results from the experiments showed that KSS2T is the most suitable structure for making a smart outdoor garment. This is because it is lighter, thinner and has good drying and moisture absorption characteristics.

Chapter 5

5.0 Textile heating fabrics

5.1 Introduction

In this chapter a broad overview and investigation of flexible heating textiles is reported. In chapter 2 and 4, knitted heating textiles were used as a source of heat to improve hydrostatic pressure gradient across the knitted spacer fabric. Therefore a good understanding of textile heating is important as its integration with knitted spacer fabrics (KSS), is necessary as the aim of the research is to develop a quick dry fabric.

5.2 Knowledge base

Flexible textile heating system is an important development in heating technology. The main advantage of such systems is the ability to bend and flex and, hence, provide heating effects for irregular geometries like tubular and round structures, such as formula one tire heating systems and popular heating blankets (figures 5.2.1 and 5.2.2)

Figure 5.2.1: Tire warmers(dmracing)

Figure 5.2.2: Heating blankets(target)

Heating systems are used to provide necessary warmth to individuals from cold environments. This is important, as warm conditions are required to keep an individual's body warm as it is important for the proper functioning of vital body systems (Sampath et al., 2012). The human body has to be maintained at a temperature of 37^{o}C as far as possible. It is reported that at temperatures below 37^{o}C organ dysfunction could occur, and the individual would experience what is known as hypothermia (Au, 2011, Kar et al., 2007, Kissa, 1996). Since most of the current heating systems are stiff and regular shaped, textile based flexible heating systems are required for wearable applications. Such systems have an added advantage of efficient heat delivery as, generally, heat is lost in non-flexible wearable heating systems due to less contact areas between the heating systems and the area required to be heated. With wearable heating systems heat delivery can be assumed to be by conduction and convection (Ding-Hua Xu1, 2011, Hsieh, 1995, Luiza. H. C. D. Sousa, 2004) as the contact areas can be increased with a wearable system.

5.3 Types of textile heaters and development

Current textile heating systems can be subdivided into two categories; polymer based and metal based textile heaters. As the names imply they are categorized according to the construction of the heating elements. In metal-based heating textiles metals are attached to the textile fabric as heating elements (Altmann et al., 1990). In these designs, metals wires and sometimes sheets are used to produce the heating (Figure 5.3.1 below)

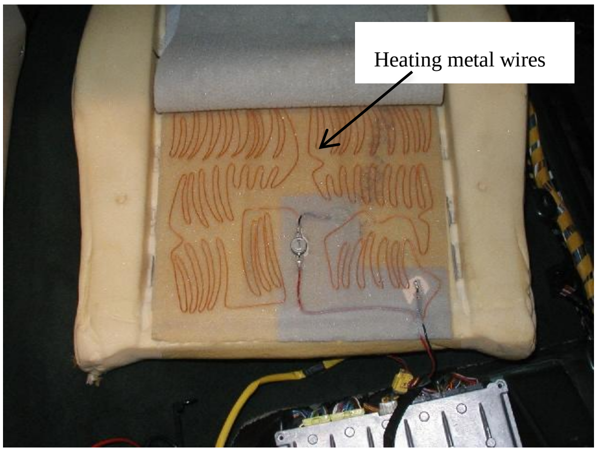


Figure 5.3.1: Metal based textile heaters in car seats(infrafloor)

Polymer based textile heating systems electrically conductive polymer yarns are used to produce heat when DC power is applied. Electrically conductive yarns are made by plating a micro layer of metal such as silver, gold or copper onto the filaments of a synthetic yarn (e.g. Shieldex, X-Static, Amberstrand etc.) or by extruding a mono filament yarn from a mixture of silicone and carbon (e.g. FabRoc yarn). An example of a flexible heating system made from a sheet of FabRoc by EXO Technologies is shown in Figure 5.3.2 below.

Figure 5.3.2:Flexible polymer based heated fabric by EXO2(EXO2theheatinside)

5.4 Heating theory

Technology behind heating systems stretches from the basic principle of Ohm's law in which current supplied from a voltage source through a resistor, causes resister to heat-up and dissipate power as heat (Paynter and Boydell, 2011) (see figure 5.4.1 below).

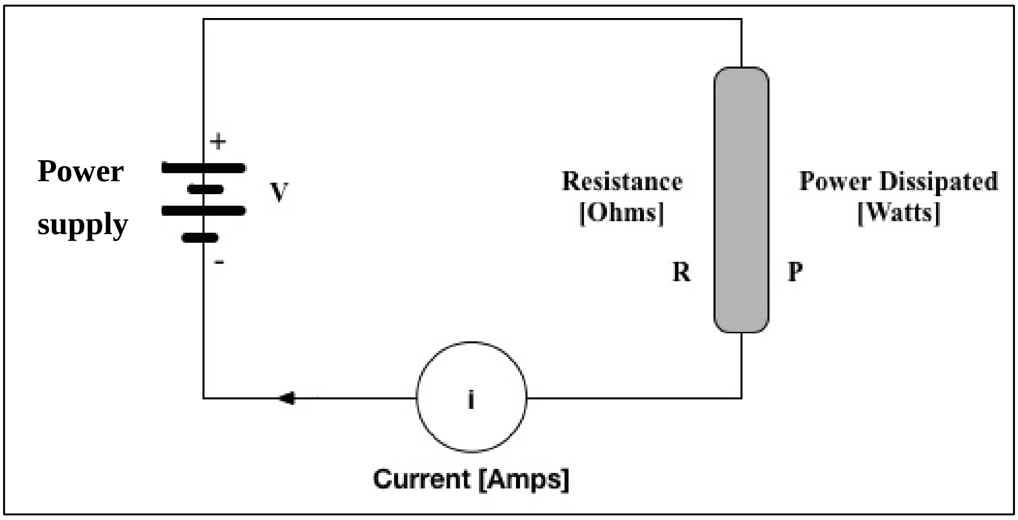


Figure 5.4.1: Ohm's law illustration

Numerically, ohms laws can be expressed as follows;

The voltage is the product of current, i flowing through a resistor, R;

$V = i\,R$……………………………………………………………………(5.4.1)

Power, P dissipated by the resistor can be calculated as follows;

$P = iV = i^2R$…………………………………………………………………..(5.4.2)

An electrical heating system requires three key components; the power source, the resistor and the interconnection between them. The power source would generate an electric current and force it to pass through the resistor which, as the name implies, would attempt to impede its flow generating heat in the process. The resistor and the interconnections have to be made from conducting materials to facilitate the current flow. Generally, metals are used for the interconnects due to their superior electrical conductivity. In wearable heating systems the resistors and the interconnects have to be sufficiently thin to allow flexibility, strong enough to prevent breakage during use, and provide efficient heating. Another important key requirement of a wearable heating system is the power source, which must be portable and capable of providing power for a long time. Batteries are the most popular option today, however, for wearable heating systems they need to be small and light weight and capable of providing power for an extended period of time. Most efficient systems use detachable power supplies so that they could be recharged easily when required.

In the case of heated garments the key challenges are the attachment of the heating system and power supply with the textile of the garment. In many systems the heating unit is attached onto the textile material or sandwiched between two or more textile layers.

However, such solutions influence the aesthetics of the garment and/or increase the weight of the garment. On the other hand in non-wearable applications such as heated car seats the above factors may not be an issue.

5.5 Applications of metal based heaters

Current applications of metal based heating systems are in automotive and construction industries, sports and recreations activities. Heating systems have been integrated in to vehicles, and is a common feature in vehicles supplied to the northern hemisphere market. The vehicles developed for this market will provide a premium luxury environment for the driver and the passengers during cold seasons. Getting into the car in cold morning to go to work would be much comfortable with heated seats and heated steering wheel.

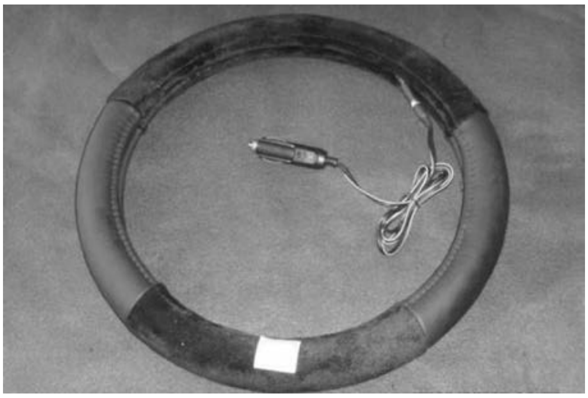


Figure 5.5.1: Heated steering wheel cover(weiku)

The above heating effects have been achieved with textile based flexible, reliable and controllable heating systems. In the most common design metallic heating elements are inserted into a woven fabrics (Weiss, 2013), in order to combine the required heating effect produced by the heating elements and the flexibility of the textile structure. Generally, thin copper wires are used as heating elements. The heating systems are coupled with appropriate controls (Buie and Buie, 1997) to provide different heating levels. A comfortable heating environment is provided by regulating the heating time and the cut off times, thus preventing overheating.

5.6 Polymer based textile heaters

The issues of aesthetics and the conformability of metal-based heating systems can be addressed with polymer based textile heaters. In these systems the heating elements consist of electrically conductive yarns which can be processed on conventional fabric manufacturing techniques such as weaving and knitting. This section describes the major considerations required in the design and manufacture of polymer-based heated textiles.

5.6.1 Types of yarns

An important aspect in the development of polymer-based heating systems is the type of conductive yarns that could be used to create the heating elements. In this research carbon loaded silicone (FabRoc) yarn was used to develop knitted heating elements. FabRoc yarn has been developed by EXO Technologies in the UK for the manufacture of polymer-based heating textiles. According to EXO Technologies, it is made by mixing a fine carbon powder with a silicone polymer material prior to the extrusion of the mixture to produce FabRoc yarn.

Figure 5.6.1.1: FabRoc yarn packages

It is a low modulus single filament yarn and behaves similar to elastomeric yarn such as Spandex or Lycra. Mixing ratios of carbon and silicone are important as they determine the overall resistance for the filament yarn. According to the manufacturer FabRoc yarn has more heating power which consist of far infrared energy which can be used to provide much needed therapeutic treatment of human skin (EXO2theheatinside, MCANDREW, 2006). Generally heating textiles would consist of electrically conductive yarns for heating, which is integrated according to a predetermined pattern within the textile structure made from conventional non-conductive yarn. In some designs, it is required to integrate the electrically conductive yarn to create localised heating zones which could be achieved by developing textile based heating elements by using different type of yarns, i.e. at least two conductive yarns with different electrical conductivity and non-conductive textile yarns for heating and bus-bars to power them which are integrated into conventional textile fabric during manufacture. The selection of conductive yarns are important in such developments.

Due to its low cost and strength Polyester is widely used in heating textiles. Black polyester yarns can be used to retain heat due to the ability of a black body to retain heat. In a fabric produced with back polyester yarn the heating elements will produce heat at localised areas of the fabric and in non-heating areas the heat would be retained/transferred due to black body effect of the base fabric. This would allow using fewer heating elements resulting in less power consumption of the heating fabric. In other cases combination of colours used in heating elements and non-heating elements can be used in the overall design of the textile.

Another type of yarn used in heating fabrics is elastomeric yarn. This yarn can be used to enhance the stability of the heating fabric. The heating fabric produced from FabRoc yarn tends to bend in one direction due to the elastomeric nature of FabRoc yarn, and an elastomeric yarn can be used to counterbalance this effect.

The electrical properties of FabRoc yarn are important for generating heat, however, its mechanical properties such as breaking strength, elongation at break and evenness are necessary for knitting.

5.6.2 The development of knitted heating fabric with localised heating

As the aim of the programme of research is to introduce a temperature gradient across a knitted spacer fabric it was necessary to study the development of heating fabric with localised heating elements. Due to the availability of FabRoc yarn and the technology for producing knitted heating elements (Thermoknit) (MCANDREW, 2006) it was decided to develop a knitted fabric with heating elements with FabRoc yarn. The heating fabric was knitted from PE yarn for the base fabric, FabRoc yarn for localised heating elements and high conductive yarn to create the bus-bars for powering the knitted heating elements. Two conductive yarns were studied for creating the bus-bars; i.e. silver plated nylon yarn from Statex GmbH and copper yarn made from fine copper wire of 25 micron diameter. A good heating fabric will need to have smooth flow of fabric design. Heating and non-heating areas must have enough efficient fabric flow to provide a good end product. As such the count of yarn used to produce the base fabric has to be selected carefully. Table 5.6.2.1 below show vital properties of yarns to be used to produce the heating fabrics.

Table 5.6.2.1: Yarn properties

Name		Diameter [mm]	Linear density [dTex]	Yarn type	Colour	Resistance [Ohms/cm]
Polyester		Approx. 0.02	167/48	Filament	White	Approx. 10^{17} (Minges and Committee, 1989)
FabRoc		0.50	Approx. 37.5	Filament	Black	0.48
Copper		0.20	Approx. 7.2	Filament	Brown	0.16
Double covered Elastane	Nylon66	Approx. 0.015	44/13	Filament	Black	Approx. 10^{17} (Minges and Committee, 1989)
	Elastane	0.25	310	Filament	White	Approx. 10^{17}
Statex		0.50	234/34	Filament	Grey silver	1.0

5.6.3 Production process

Flat-bed knitting process was utilised to produce the heating fabric and the dimensions of the heating elements were selected to reduce the overall electrical resistance. The dimensions of the heating elements can be selected by varying the number of wales and courses in a knitting element. Knitting of polymer based heaters can be done on a flat-bed, circular and warp knitting machines, however, due to the availability of computerised flat-bed knitting machines in the Advanced Textiles Research Group of the Nottingham Trent University the research on developing heating fabrics was based on flat-bed knitting technology. An example of a computerized flat-bed knitting machine is shown in Figure 5.6.3.1 below. Important features of such machines are the individual electronic needle selection, knitted loop transfer, fabric take-down tension, yarn carrier selection and carriage transverse speed, which all are independently controlled and programmable.

Figure 5.6.3.1: Stoll CMS 822HP computerized flat-bed knitting machine

All the above functions can be programmed via CAD/CAM systems and the digital information then down loaded on to the machine for knitting. Current technology is very versatile and enables knitting 2D and 3D structures including producing seamless garments.

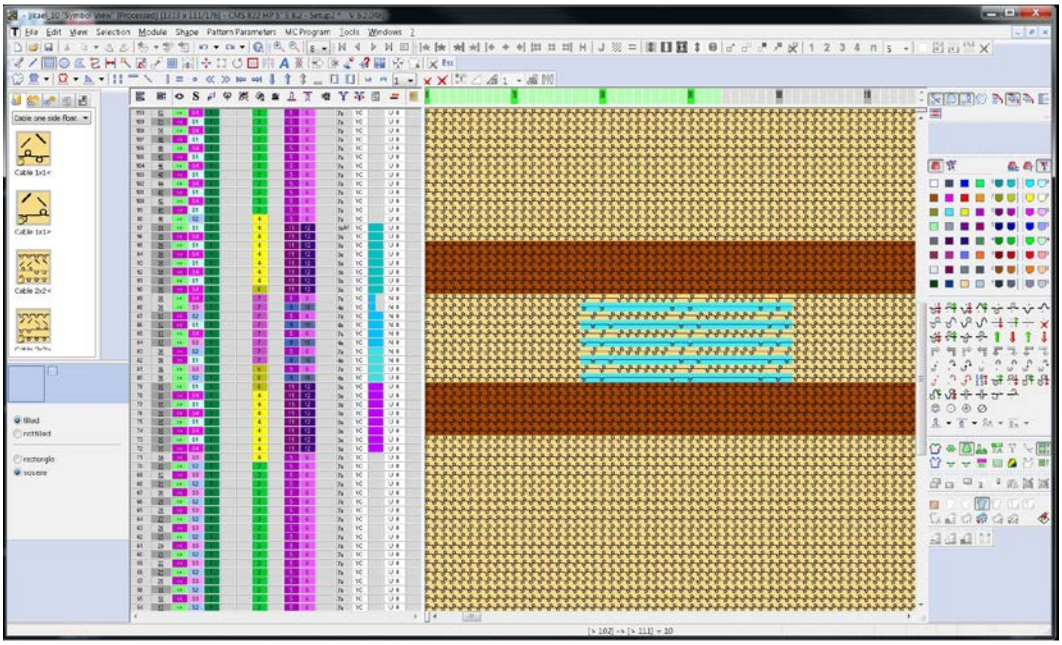


Figure 5.6.3.2: Stoll M1 Plus CAD system(Stoll)

Knitting FabRoc yarn is challenging due to its elastic nature, which causes it to stretch during the stitch formation process. Therefore, special yarn delivery system, EFS80 produced by Memminger GmbH (Memminger et al., 1988) was utilised for feeding FabRoc yarn to the knitting machine (Figure 5.6.3.3) this system allowed FabRoc yarn to be delivered to the yarn carrier with minimum stretch.

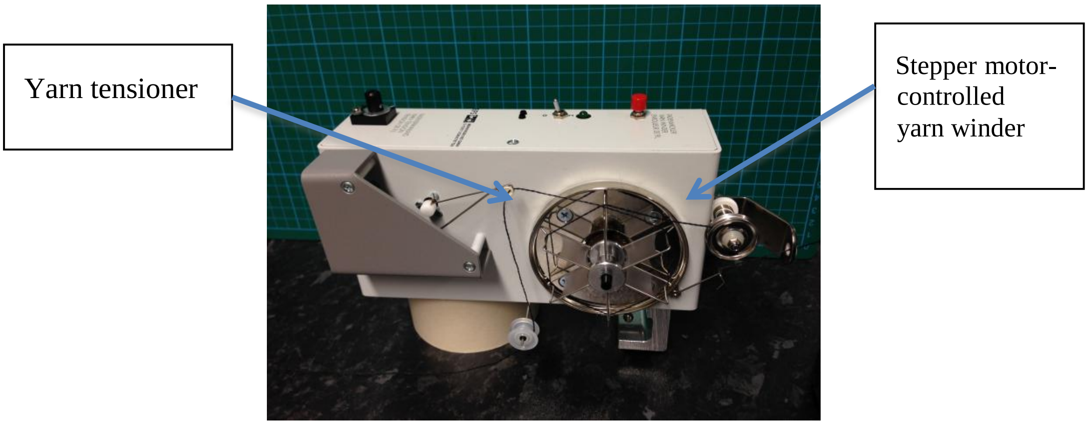


Figure 5.6.3.3: Yarn EFS80 delivery system(Memminger et al., 1988)

The structural design (knitting pattern) of the heater elements will influence the heat generated. As shown in Table 5.6.2.1 the electrical resistance of FabRoc yarn is 0.48Ω/cm, which is three times higher than the copper thread (0.16Ω/cm), and one would need to use higher voltages to generate heat. Therefore, three different structures using Statex yarn as bus bars, where designed and the stitch formation diagrams are illustrated in figures 5.6.3.4, 5.6.3.5 and 5.6.3.6 below;

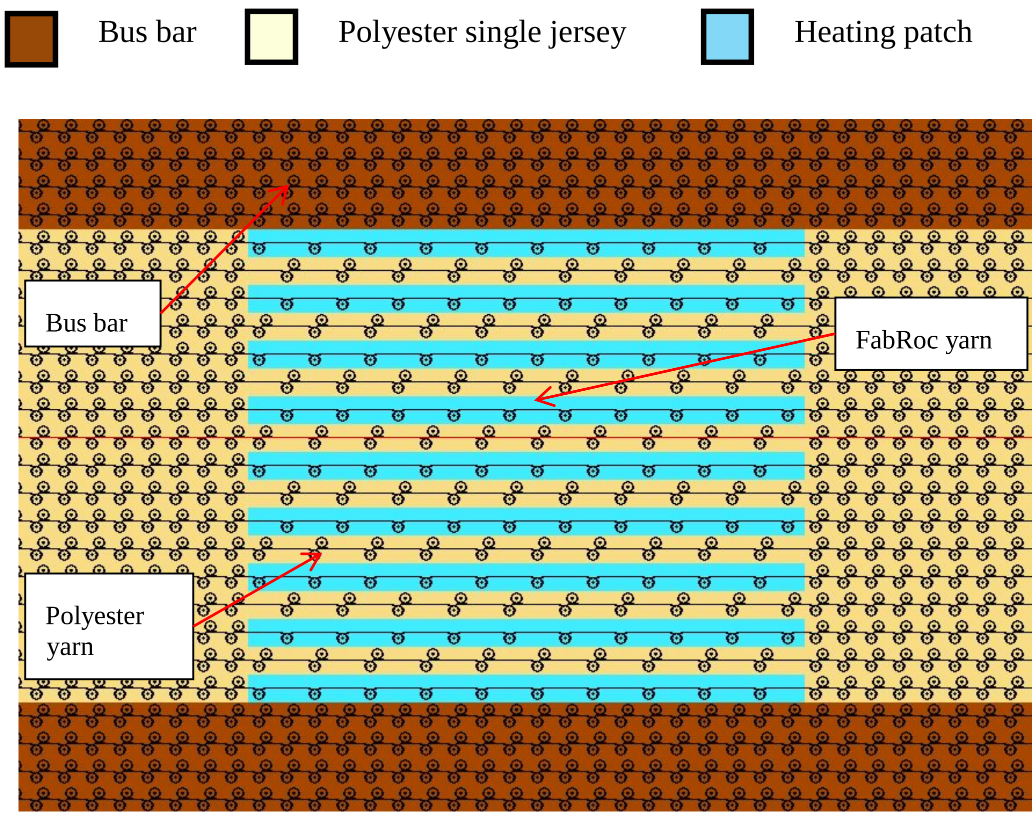


Figure 5.6.3.4: Stitch formation diagram of structure A

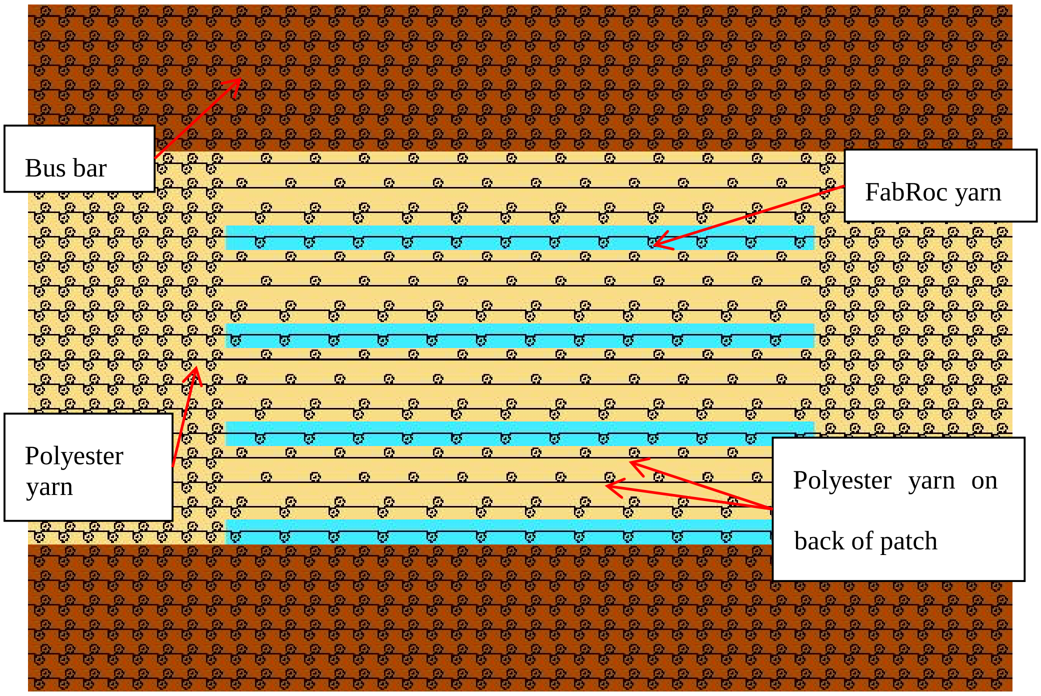


Figure 5.6.3.5: Stitch formation diagram of structure B

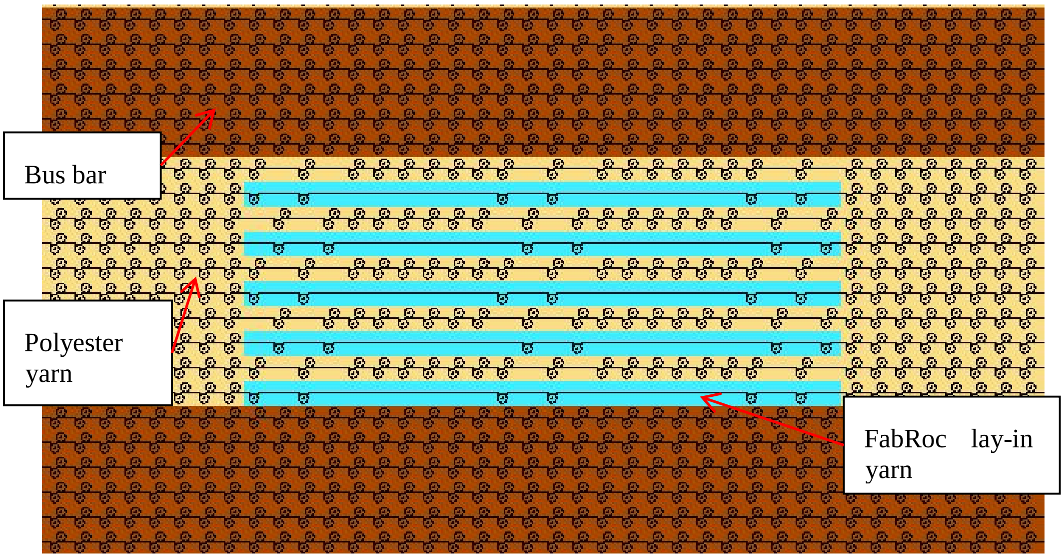
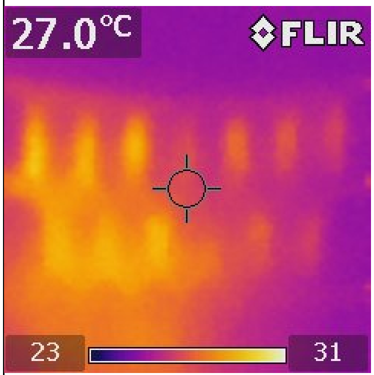
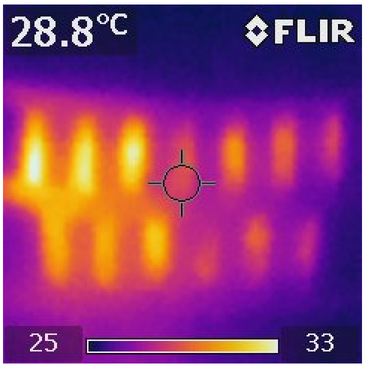
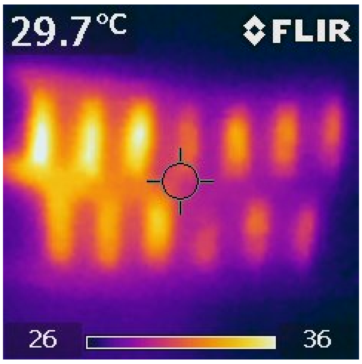


Figure 5.6.3.6: Stitch formation diagram of structure C

The above knitted structures where produced and powered from a laboratory bench power supply from TTi, tested for heating efficiency at different voltages; the thermal images were captured by using FLiR i7 thermal imaging camera. The results are displayed below;

Voltage	Current	Electrical power	Image
[V]	[A]	[W]	
3	0.05	0.15	
4	0.07	0.28	
5	0.08	0.4	

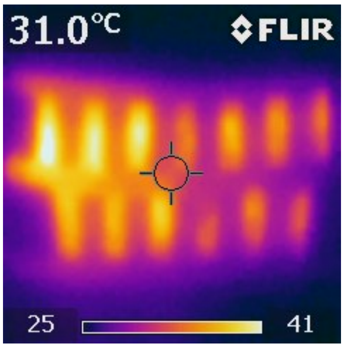
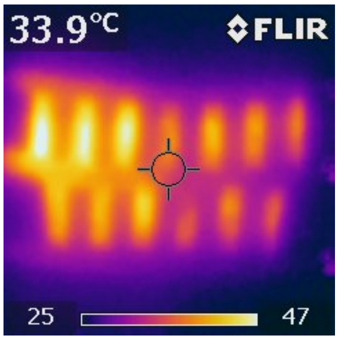
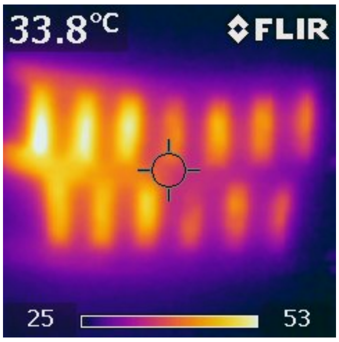
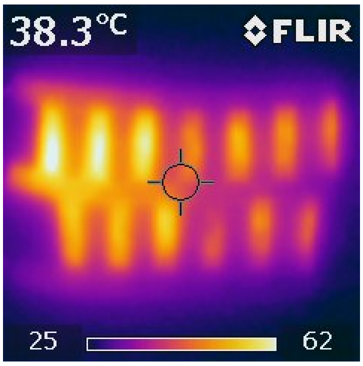
6	0.1	0.6	
7	0.12	0.84	
8	0.14	1.12	
9	0.16	1.44	

Figure 5.6.3.7: knit structure C thermal image

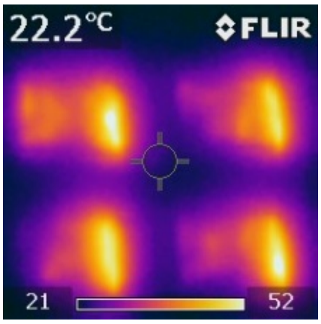
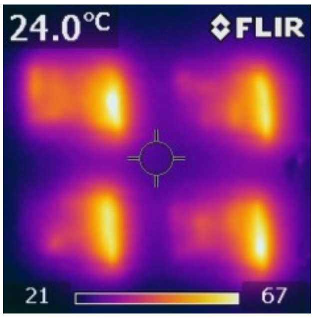
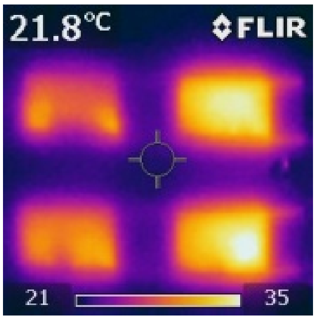
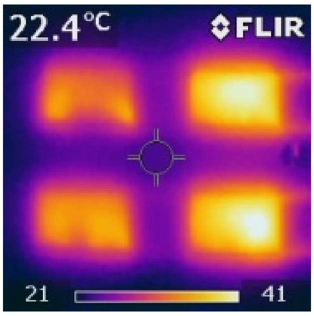
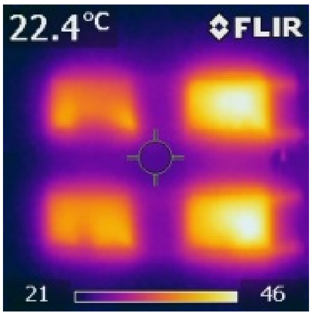
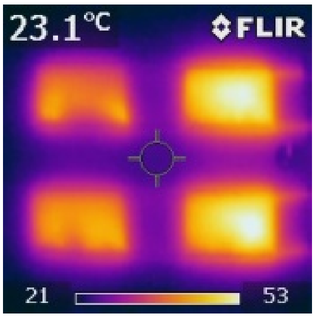
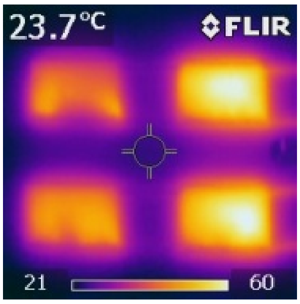
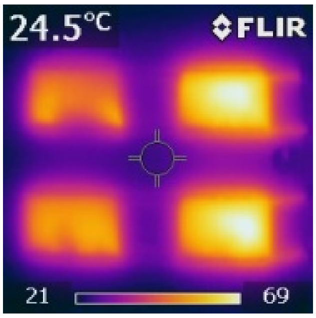
Voltage	Current	Electrical power	Image
[V]	[A]	[W]	
10	0.01	0.1	
12	0.1	1.2	

Figure 5.6.3.8: Knit structure B thermal image

Voltage	Current	Electrical power	Image
[V]	[A]	[W]	
3	0.19	0.57	

3.5	0.22	0.77	
4.0	0.25	1.00	
4.5	0.29	1.30	
5.0	0.32	1.60	
5.5	0.35	1.92	

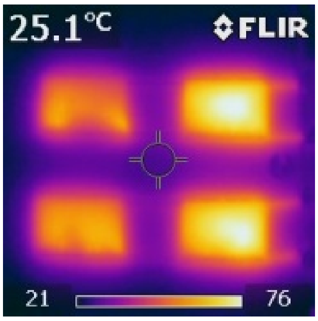
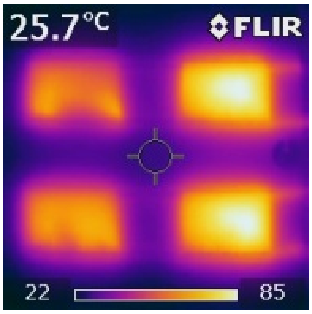
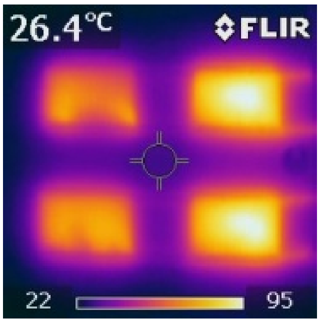
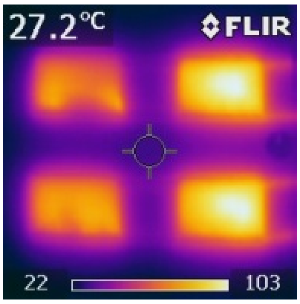
6.0	0.38	2.28	
6.5	0.42	2.73	
7.0	0.46	3.22	
7.5	0.49	3.67	

Figure 5.6.3.9: Knit structure A thermal image

Observation of above heating results; showed that knit structure A proved to be efficient than the others by having an ability to use less power and provided reliable heating effect. However, the heating pattern for individual elements showed variation; this could be due to yarn properties variations which could provide variation in resistance for the heating elements. Also this effect could be due to the location of heater elements on the structure. Heater elements closest to the power terminals appeared to heat more than those further away. This could be due to increase in resistance of the elements further away from the power supply at one side. This could be eliminated in future by powering from both sides of the structure to reduce current resistance and enhance heat uniformity.

Structures B and C used higher voltages than structure A to provide heating effect. An efficient heating element would require less power consumption to provide heat. Also observing the thermal images between the three structures; structure A had a consistent heat pattern than B and C which showed uneven heat patterns which could be not less useful in most heating applications.

In view of the above results it was decided to study the structure A in detail. It was decided to examine the change in electrical resistance (effective resistance) of the FabRoc yarn when it was knitted to create heater element. . The dimensions of the rectangular knitted area was determined to be 7.0 X 2.0 cm and then the resistance between the two bus bars was measured by using an Agilent 34410A precision digital multimeter. Then the FabRoc yarn in the knitted heater element was carefully unravelled and the resistance of FabRoc yarn measured. Results are shown on table 5.6.3.1 below;

Table 5.6.3.1: Resistance variation on heat element with size 7.0 X 2.0 cm

FabRoc length [cm]	304.0
Resistance before unravelling [Ohms], i.e. between the bus bars of the knitted heater element	60.0
Total resistance of FabRoc yarn after unravelling [Ohms]	136,000
Reduction in Resistance [Ohm]	135,940

The above results show that a significant reduction in electrical resistance of the heating element knitted with FabRoc yarn can be achieved with the structure A as explained by Dias et.al.(T. Dias, 2008)

5.6.4 Dimensions of the heaters

In design and production of knitted polymer based heater elements, the size and the knitted structure would influence the heating efficiency. The design of the polymer based knitted heater element in terms of size is crucial. It affects the way the electrical connections are made with the electrically conductive yarns, and as the table 5.6.3.1 shows, knitting polymer based yarns in a predetermined manner will reduce the overall resistance enabling the use of low voltage batteries to power them. However, the size of the heating elements have to be determined for reliable heating effect. As such several heater elements of different dimensions were knitted and tested. A set of samples were knitted with 54 needles, but with different number of courses, and the results are summarised in Figure 5.6.4.1 and figure 5.6.4.2. It is evident from the thermal images in Figure 5.6.4.2 that, narrower sized heater elements have significant better heating effect compared to wider elements. (See Figure 5.6.4.1).

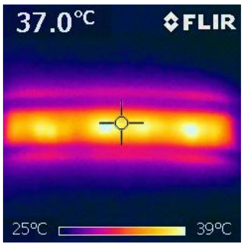
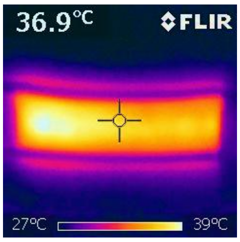
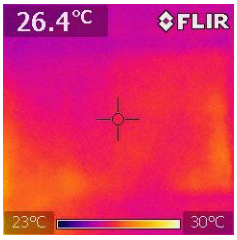
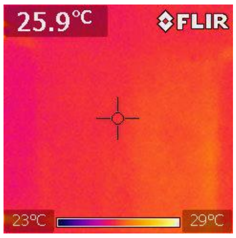
1cm	2cm	4cm	6cm
			

Figure 5.6.4.1: Width comparison thermal images at 3V power supply

A second set of samples were knitted with 11 courses but with different number of needles. Due to different sample sizes, the distance between the thermal camera and the test samples was varied to accommodate the full length of the test sample. This resulted in the thermal images of longer samples appearing narrower, however temperature profiles were accurate. Normally the camera was placed at 15.0 cm from the sample; but for 14 cm and 21cm sizes; the camera was positioned at 30.0 cm and 45.0 cm respectively. The results summarised in Figure 5.6.4.2 below demonstrates that the length of the heater elements has no significant effect in heating. These results showed that when designing knitted heater elements one has to consider their dimensions.

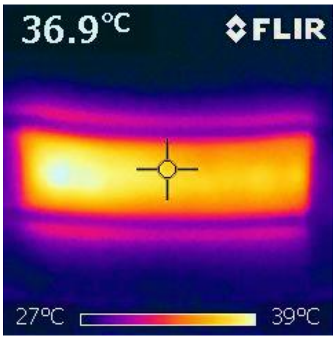
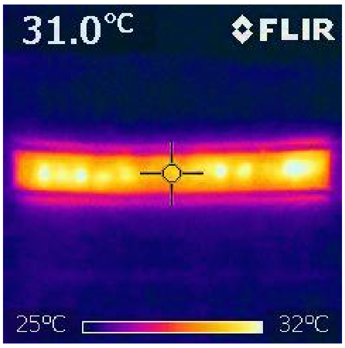
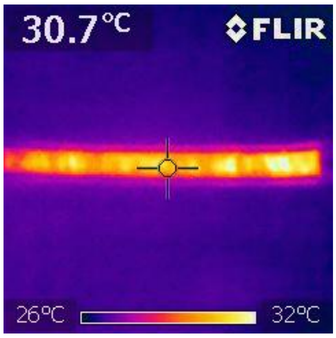
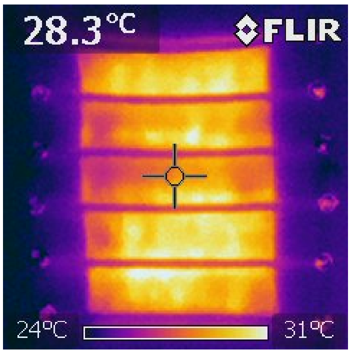
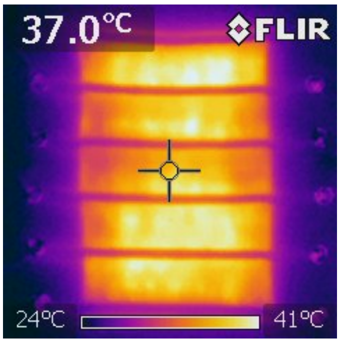
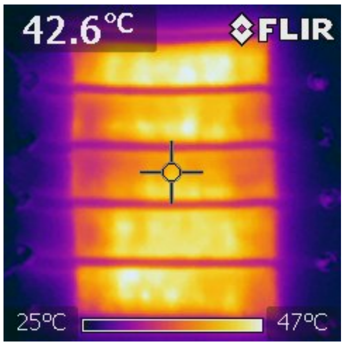
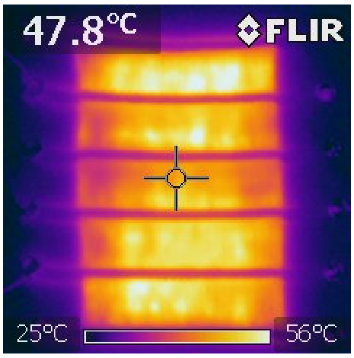
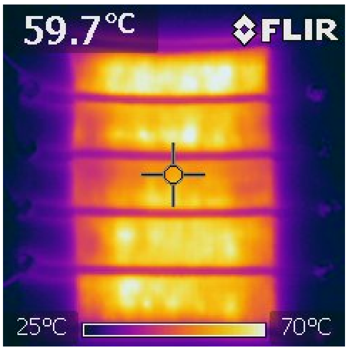
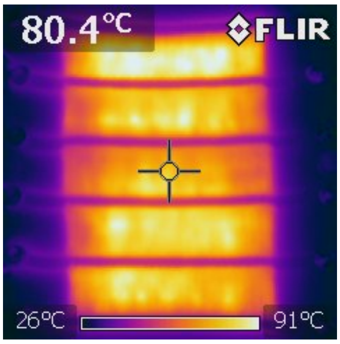
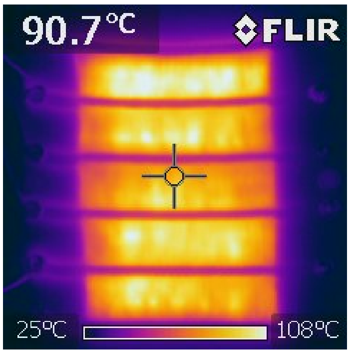
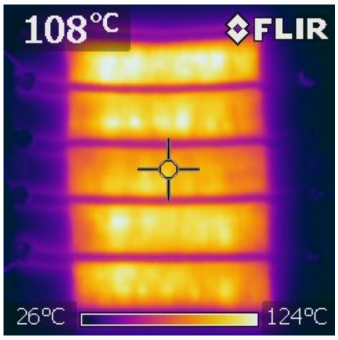
7cm	14cm	21cm
		

Figure 5.6.4.2: Length comparison thermal images at 3V power supply

All the above heater elements were of single element design; i.e. each heater element was powered by its own bus bars. The possibility of creating a textile with a large heating area using multiple heater elements were studied. A knitted structure with several heating elements arranged side by side was designed and analysed for its heating efficiency. The fabric was produced with five heating elements sharing common bus bars. The results shown in Figure 5.6.4.3 demonstrates that this could be an efficient way to produce large area heating fabrics.

Voltage	Current	Electrical power	Image
[V]	[A]	[W]	
3	0.31	0.93	
4	0.48	1.92	
5	0.64	3.2	
6	0.83	4.98	

7	1.06	7.42	
8	1.32	10.56	
9	1.59	14.31	
10	1.83	18.30	

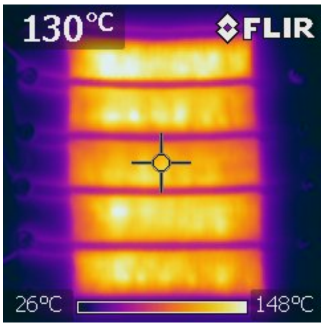
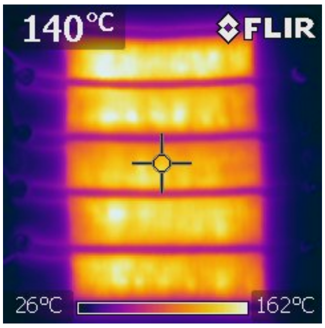
11	2.13	23.43	
12	2.36	28.32	

Figure 5.6.4.3: Thermal image of a large area heating fabric

5.6.5 Electrical connection network

Generally Polymer based heaters are powered by DC power source due to the use of batteries. The power supply will force a current to flow through the knitted heating elements resulting in generation of heat. The knitted heating elements are powered by two bus bars connected to the powers supply and for efficient heating, the voltage drop in the bus bars has to be very low. Hence, high conductive (very low resistance) yarn was utilised for knitting the bus bars. The selection of conductive yarn is important. Although there are different kinds of conductive yarns commercially available two different types of conductive yarns were used in the research to knit the bus bars:

1. Shieldex; a nylon yarn plaited with a thin layer of silver, produced by Statex GmbH;
2. Copper thread, which is produced by multiple strands of fine copper wires.

An example of knitted heater element is shown in Figure 5.6.5.1.

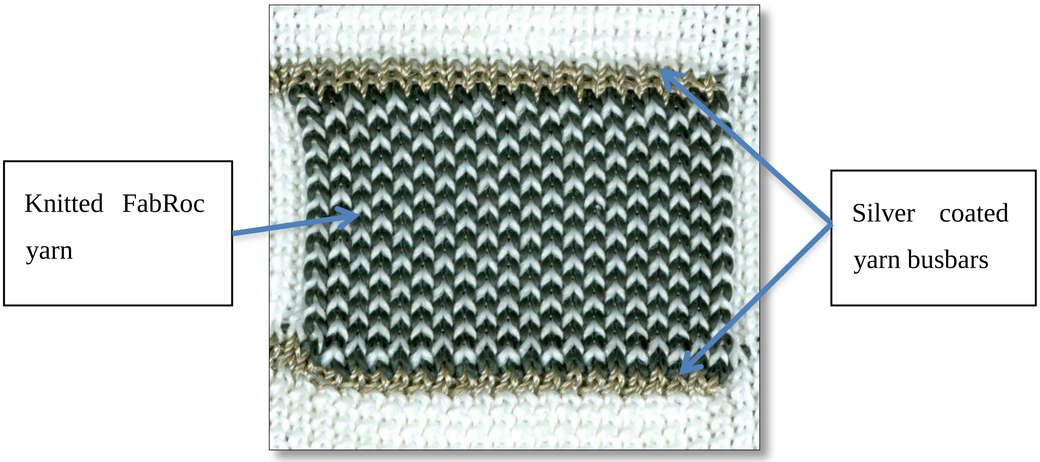


Figure 5.6.5.1: Knitted heater elements produced with FabRoc, PE and conductive yarns

As stated earlier Statex yarn is produced by twisting 34 PA (nylon) filament fibres with a thin layer of silver together. The electrical resistance of Statex yarn would be influenced by the number PA-Ag filaments and the thickness of the silver layer. However, the thickness of the silver layer that is plaited onto the surface of a PA filament would impact on the overall flexibility of the Statex yarn. The Statex yarn used in the research could easily be processed in flat-bed knitting machine. However, it is important to use a yarn with a low electrical resistance as this would affect the voltage drop of the bus bars. The ambition of the research is to design a textile fabric with enhanced moisture management by creating a temperature gradient within the fabric with the help of localised heating elements. Once developed such a fabric could be used to produce outdoor garments, and this would require the design of heating elements of low overall resistance in order to use low voltage batteries. Connections from the power supply to the heater element, which is produced with FabRoc yarn, are achieved with two courses knitted from either Statex or copper yarn at either end of the heater element, named as bus bars in Figure 5.6.5.1. Care have to be taken to avoid contact between the two bus bars to prevent an electrical short circuit. As knitting more courses of Statex or copper yarn to create a bus bar should reduce the total resistance and, hence improve the conductivity of current conductivity. Therefore, this was studied in detail by producing samples with 10cm long bus bars consisting of different number of courses (Figure 5.6.5.2). Resistance of each bus bar was measured individually by using an Agilent 34410A precision multimeter. The procedure is summarised as follows;

1. Sample preparation: this involved measuring the bus bar length to precisely 10cm by using a meter rule and then press studs were placed at these ends. Press studs also act the measuring points as they provide reliable hard part for the multimeter connectors.
2. Multimeter preparation: settings for measuring resistance were selected on the menu and connections for the measuring leads properly connected on the device.
3. Measuring: the two connecting leads were touched (with reasonable pressure) against the two press studs placed at 10cm apart on each bus bar and the corresponding reading was recorded. This step was repeated 5 times to ensure reliable recorded results. The same procedure was performed for the remaining bus bars for both copper and Statex samples.

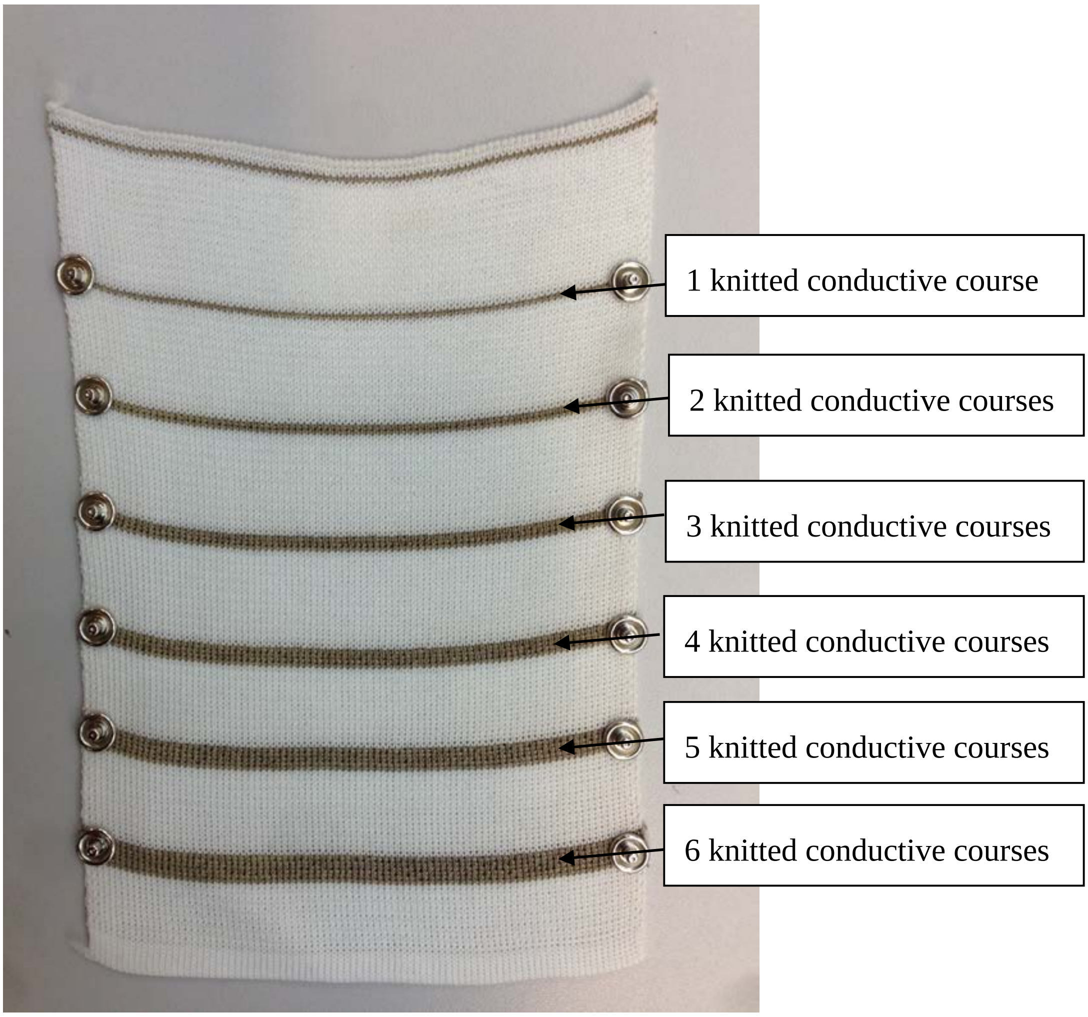


Figure 5.6.5.2: Statex yarn bus bar courses

The study showed (Figure 5.6.5.3) that in the case of Statex the resistance dropped significantly when the number of conductive courses were increased to three and four, and a significant change in resistance was not observed beyond four conductive courses.

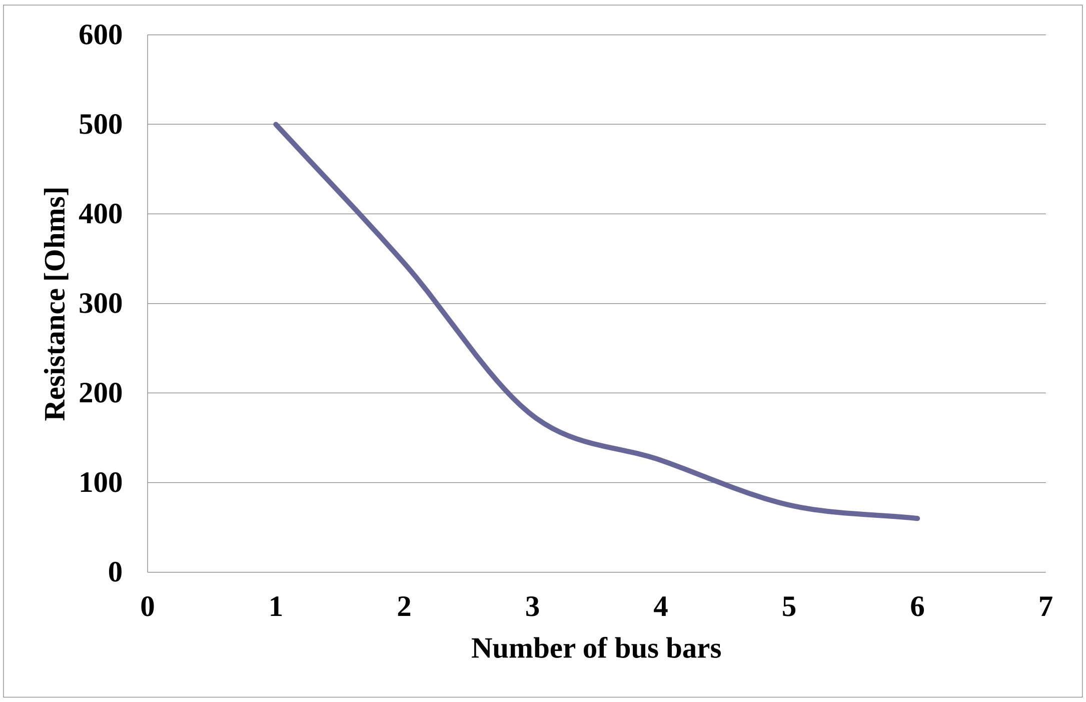


Figure 5.6.5.3: The influence of the number of Statex courses on the electrical resistance of a bus bar

The above experiment was repeated with bus bars knitted with copper wire see figure 5.6.5.4 below;

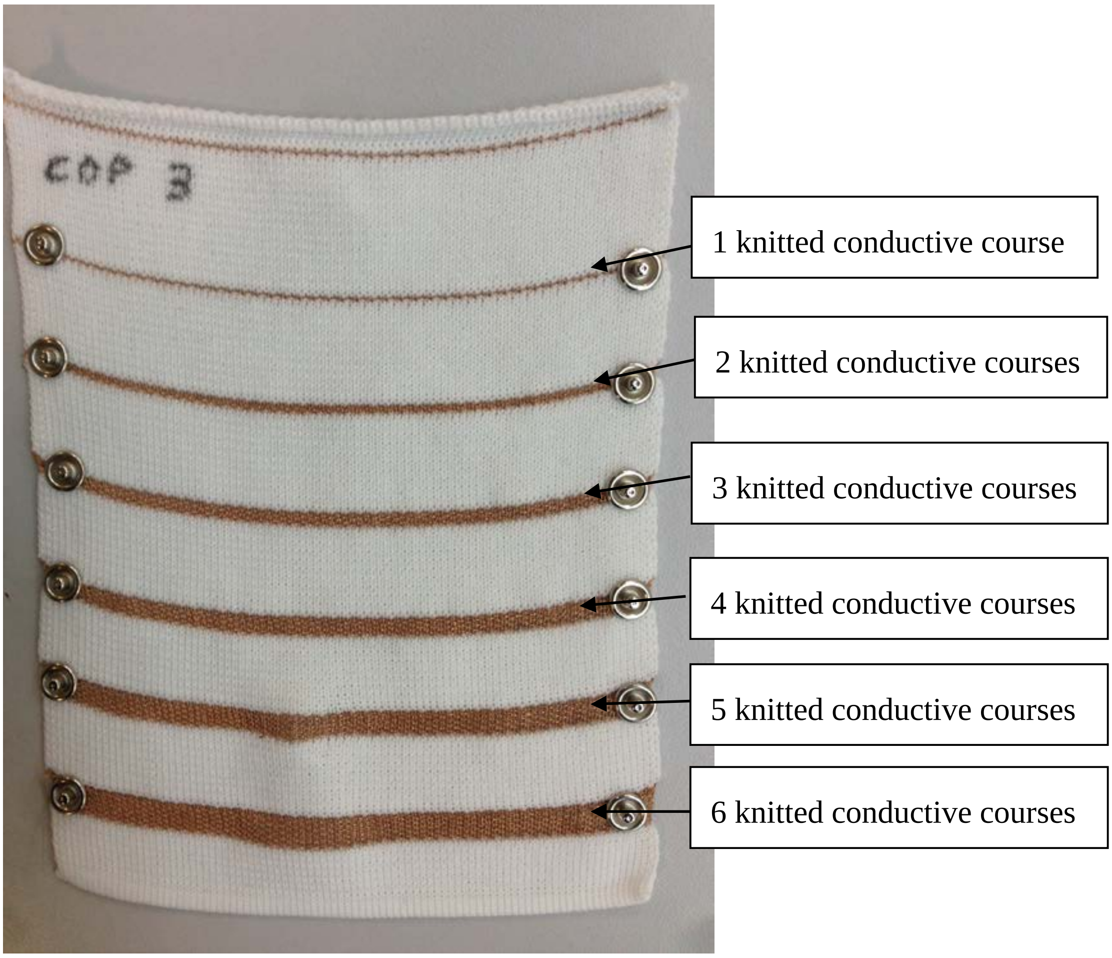


Figure 5.6.5.4: Copper yarn bus bar courses

Copper is widely used in electrical and electronic industry due to its efficient and reliable conductivity and due low resistance. Knitting copper yarn is a challenge, especially due its low breaking strength and very little stretch (high modulus). The copper yarn used has been produced by twisting eight copper strands of 25µm diameter, see Table 5.6.2.1. For further details. The results for bus bars produced with copper yarn is given below in figure 5.6.5.5 below

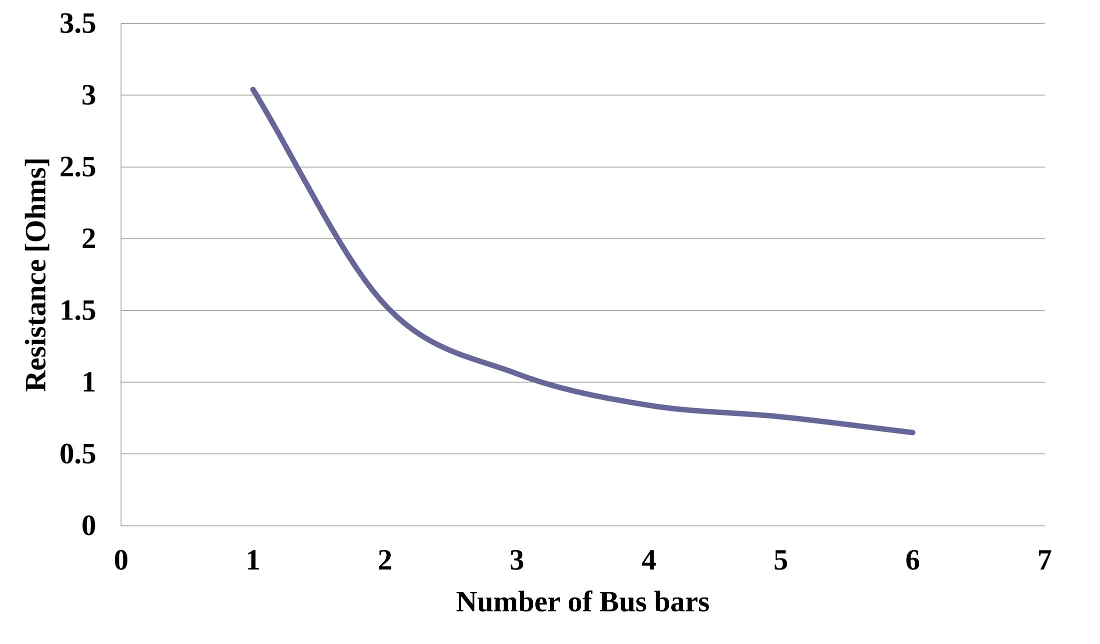


Figure 5.6.5.5: The influence of the number of copper courses on the electrical resistance of a bus bar

The study of the bus bars made from Statex yarn and copper produced interesting results; generally they all showed that the more bus bars used the less the electrical resistance becomes. This shows that more electrical channels are created by addition of knitted courses and this would reduce resultant resistance of the bus bar. Statex yarn had higher resistance than copper per unit length. From this copper yarn showed less resistance change after just 2 bus bars compared to 3 for Statex yarn.

5.6.6 Power supply system

Effective and reliable polymer based heaters has to be designed so that they use electrical power efficiently to produce heat. Generally, direct current power source, such as a rechargeable battery are used. Most rechargeable batteries are made by lithium ion technology which can be shaped in to different designs (Jha, 2012). This allows the battery power packs to be seemly incorporated into wearable products with less distraction. For instance the power source of EXO2 heated glove (EXO2theheatinside) are designed to be integrated into the pocket in the glove easily. In their design a controller has been integrated into the rechargeable battery in a manner that it can be regulated by the user, thus empowering the user to adapt the heating effect according to the outside temperature.

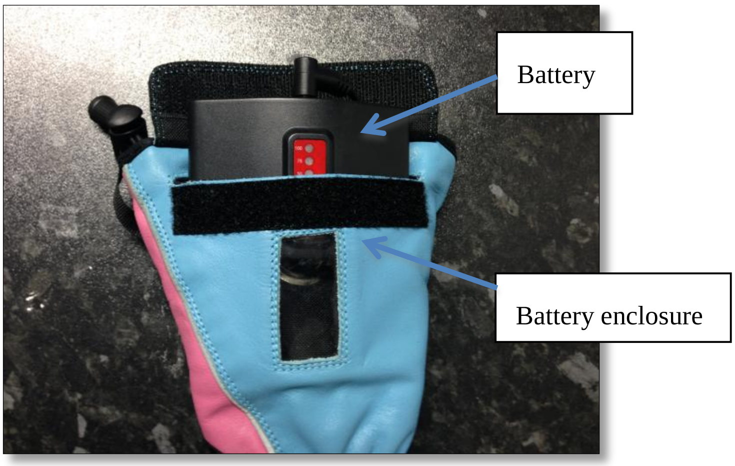


Figure 5.6.6.1: EXO2 power pack enclosure

The control unit changes the output voltage of the battery to adjust the current that would flow in the heater elements knitted with FabRoc yarn. This allows different heating effects to be achieved. In some applications heating for a longer period of time may result in a rise in temperature at concentrated areas, and the control circuit can be designed to prevent such situations happening by switching off power at predefined periods of time. Current trend is to incorporate such a control circuit in the power packs.

All the knitted samples with heating elements described in this chapter were powered from bench top laboratory power supply units, in which the output voltage could be adjusted. These power supplies could measure the current flowing in a connected circuit which could be read directly on the power supply (Figure 5.6.6.2).

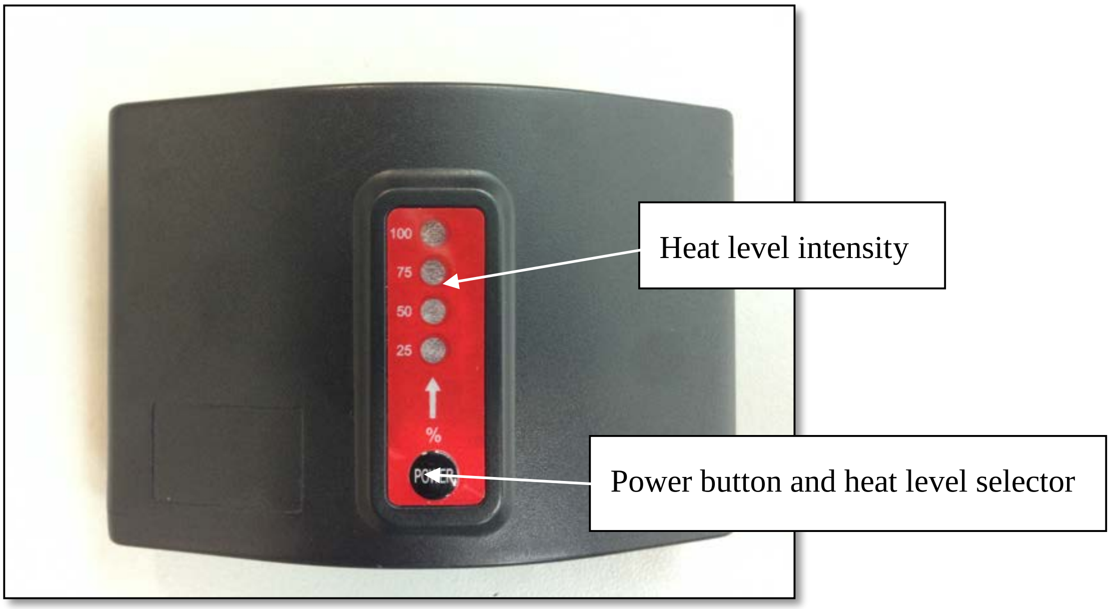


Figure 5.6.6.2: EXO glove battery

An outdoor heating garment has to be offered with its own power supply. The heater elements have to be designed with two bus bars to power them, and these could be connected to the two terminals (positive and negative) of the power supply for heating to occur. In case of multiple heating elements, this would mean multiple terminals which then need to be connected to the positive and negative terminals of the power supply. In order to reduce the number of terminals which need to be connected to the power supply, a knitted structure was designed in which the bus bars of the heating elements were connected to two central conductive knitted tracks. This design enabled number of knitted heater elements to be powered via two main conductive tracks when connected to the power supply. The two conductive tracks were created with two knitted wales, and an example of a heating fabric consisting of nine heating elements is shown in Figure 5.6.6.3.

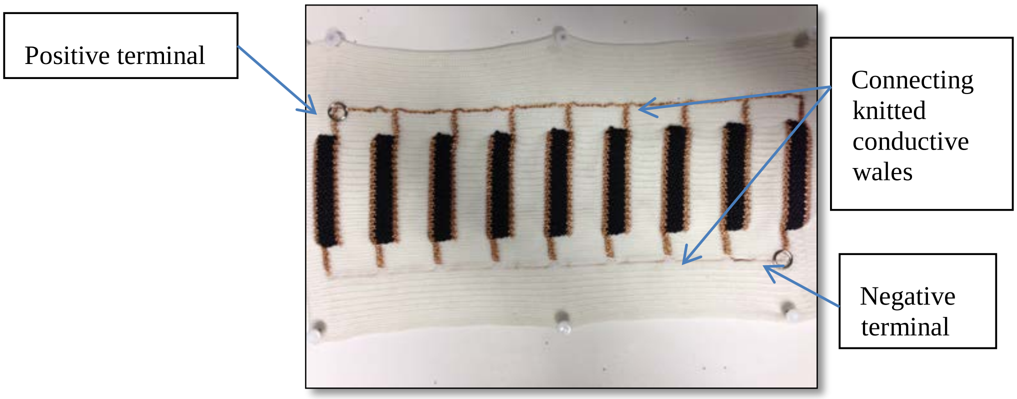


Figure 5.6.6.3: Knitted heating fabric with nine heating elements

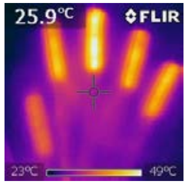
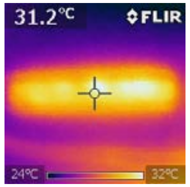
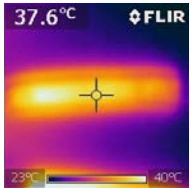
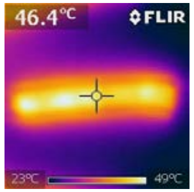
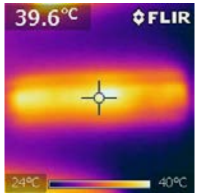
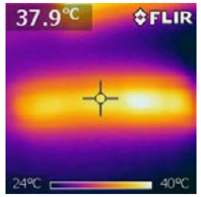
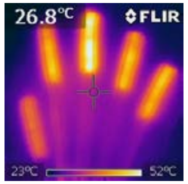
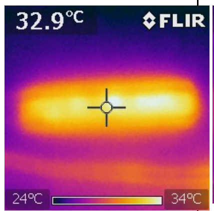
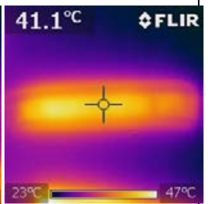
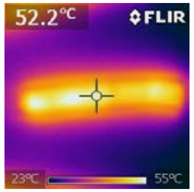
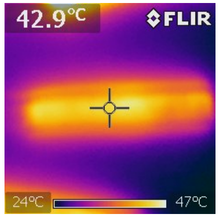
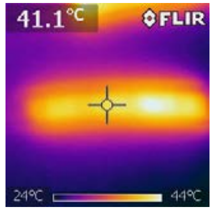
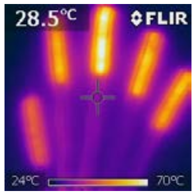
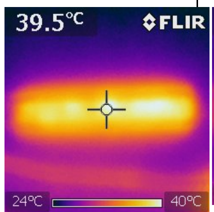
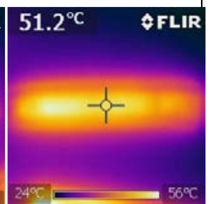
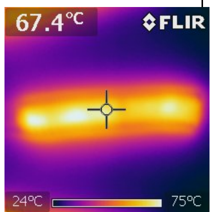
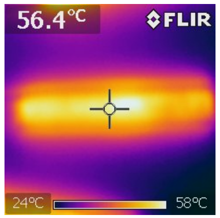
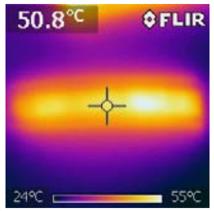
The heating elements can be considered as resistors which are connected in parallel. The Ohms' law described in section 4.4 can be used to determine the overall resistance of the heating system. In an electrical circuit when resistors are connected in parallel the same voltage will be applied across each resistor and the overall resistance becomes lower than individual resistors. The parallel connection of the heating elements would reduce the overall resistance of the heating fabric thus enabling the use of low voltage power supplies (batteries). Although more heat energy could be generated with this design the higher current requirement would reduce the heating time for a given battery capacity

5.6.7 Post processing of textile heaters

Processing of textiles during manufacturing process induces stresses and strains on the final product, which could result in dimensional stability of the finished products. Polymer based textiles main concern is during the knitting process. The yarns are subjected to high stresses during the knitting process due to the input yarn tension, which could be in the region of 15 – 25 cN and the fabric take-down (Spencer, 2001). Steaming of knitted fabrics is among one of the post processing techniques used in the manufacture of knitted garments. The exposure of a fabric soon after knitting would enable the stresses in the fibres of the yarn induced during the stitch formation process to relax quickly (Spencer, 2001). Apart from steaming, washing could also encourage the fibres in yarns to relax due to constant agitation and heating of the fabric.

As the shape and the size of the stitches of a knitted fabric could change due to the relaxation of the fibres in the yarn after knitting, it was decided to study its effect on the resistance of the heating elements.

A simple experiment was conducted on glove liners produced with five heater elements and bus bars. The heater elements were made from FabRoc yarn with copper yarn forming the bus bars. The test samples were washed in a household Bosch Logixx8 washing machine, at 90^{o}C, 2.35hrs and spin dried at 800rpm. The results showed that the resistance dropped after washing resulting in improved heating efficiency of the heater elements. A second wash test was conducted but no change in resistance was observed. This showed that washing can be used to improve the heating efficiency and doesn't significantly affect fabrics heating characteristics. Thermal images of the these results are illustrated in figures below;

Sample	Resistance [Ohms]	Voltage [V]	Current [A]	Thermal Image					
				Whole	Thumb	First finger	Second finger	Third finger	Last finger
3Cu	50.1	3.7	0.49						
		4	0.55						
		5	0.74						

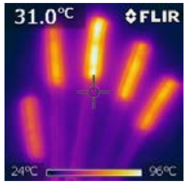
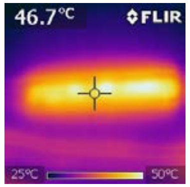
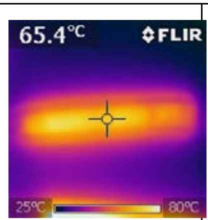
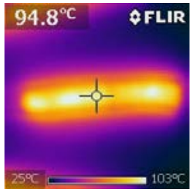
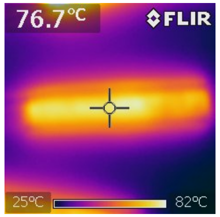
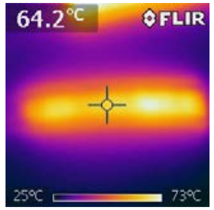
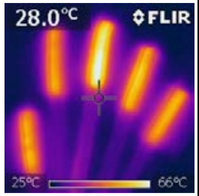
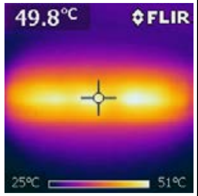
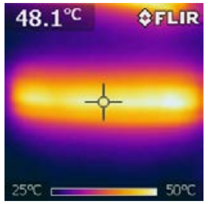
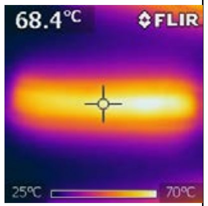
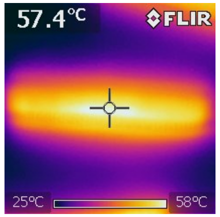
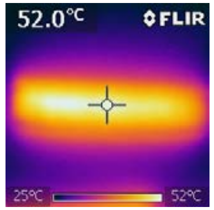
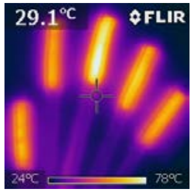
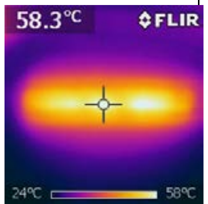
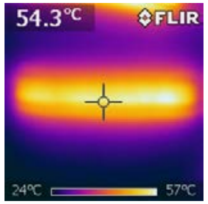
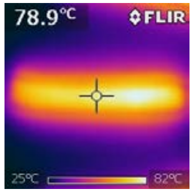
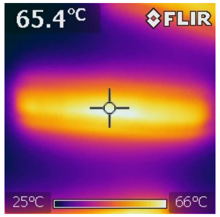
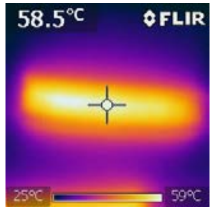
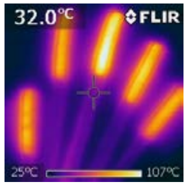
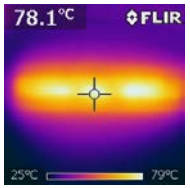
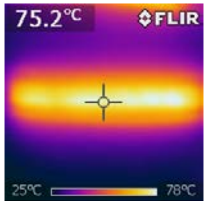
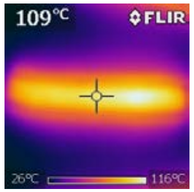
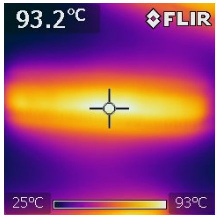
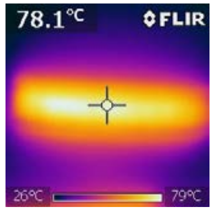
		6	1.00						

Figure 5.6.7.1: Thermal images for glove liner made from 3 ply 8 strand copper bus bars before washing

Sample	Resistance [Ohms]	Voltage [V]	Current [A]	Thermal Image					
				Whole	Thumb	First finger	Second finger	Third finger	Last finger
		3.7	1.02						
3Cu	16.5	4	1.14						
		5	1.58						

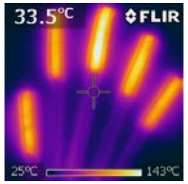
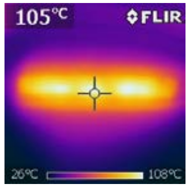
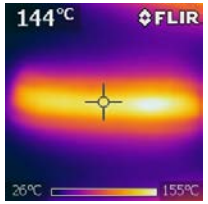
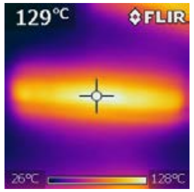
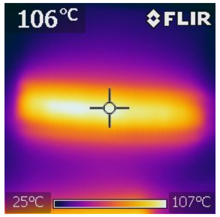
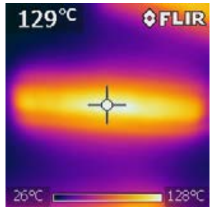
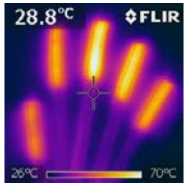
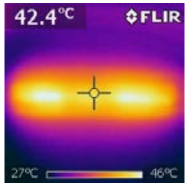
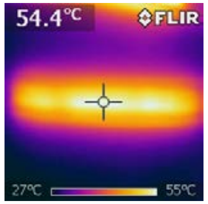
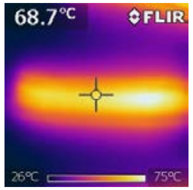
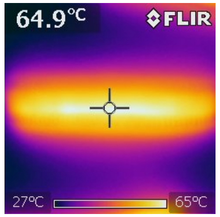
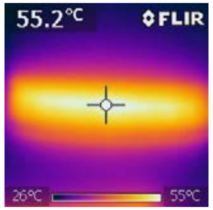
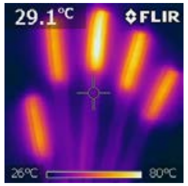
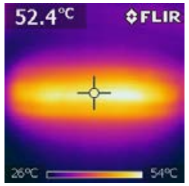
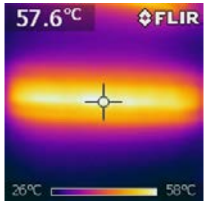
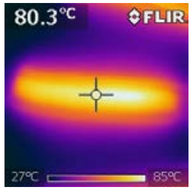
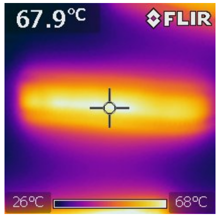
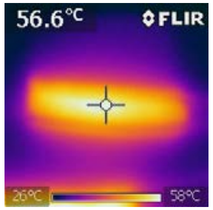
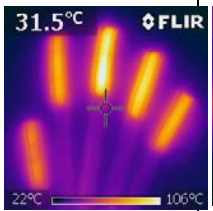
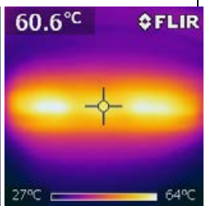
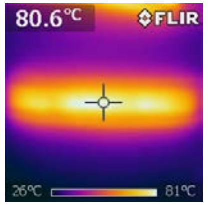
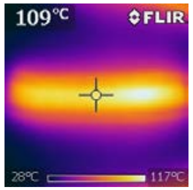
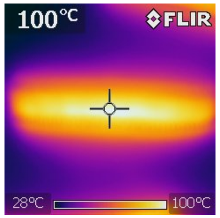
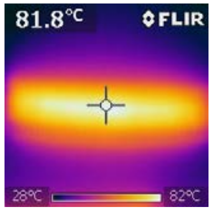
		6	2.07						

Figure 5.6.7.2: Thermal images for glove liner made from 3 ply 8 strand copper bus bars after washing run-1

Sample	Resistance [Ohms]	Voltage [V]	Current [A]	Thermal Image					
				Whole	Thumb	First finger	Second finger	Third finger	Last finger
3Cu	18.9	3.7	0.98						
		4	1.11						
		5	1.49						

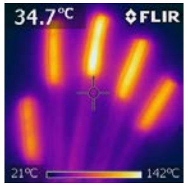
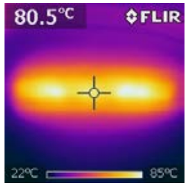
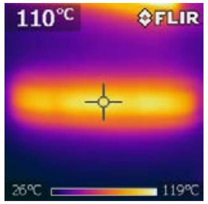
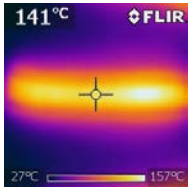
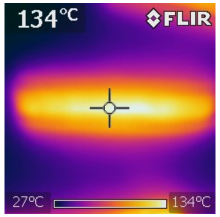
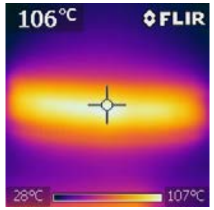
		6	1.97						

Figure 5.6.7.3: Thermal images for glove liner made from 3 ply 8 strand copper bus bars after washing run-2

Other post processing techniques like dyeing and colorations are rarely applicable for polymer based heaters as the fabric produced is solely for technical purposes. The final heating fabric can be used in between layer(s) containing carefully fashioned designs and together they can produce a good result. Sometimes it is important that the heating performance and the aesthetic of the final product are considered during the design process. This will help to create a good functional and fashionable product.

5.7 Applications of polymer based heating systems

The main applications of polymer based heating systems include heated gloves and heated fabrics.

5.7.1 Heated gloves

Heated gloves are considered as an entry point for the use of polymer based heated textiles. In heated gloves should be flexible to enable excessive bending of the arms and fingers. Good dexterity can be achieved with polymer based heated textiles. EXO2 Ltd has developed a heated glove to meet the above requirements. The EXO2 heating gloves are made by using three different types of yarns:

1. Carbon loaded silicone (FabRoc) yarn, which is one of the company's own inventions, and used to craft the knitted heater elements;
2. Shieldex yarn, which is used to form the bus bars to power the knitted heater elements;
3. Texturised PE yarn.

A seamless knitted heated glove liner is produced by the company (see Figure 5.7.1.1).

Figure 5.7.1.1: Thermoknit glove liner(EXO2theheatinside)

The glove liner is then used to produce a leather glove using the conventional cut-and-sew techniques for ski market.

5.7.2 Heating fabrics

Another application of polymer based heaters is the production of heated fabrics. A knitted heated fabric was developed by incorporating several heater elements, which were formed by using FabRoc yarn. By arranging the positions of the heater elements one could customise heated fabric depending on the end use. An example of a heating fabric consisting of four heater elements is given in figure 5.7.2.1 below).

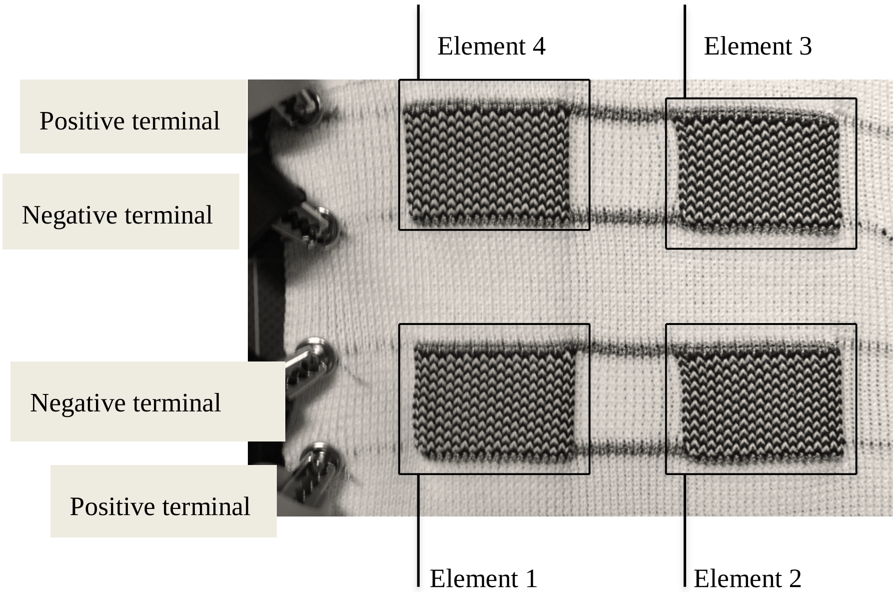


Figure 5.7.2.1: Heating fabric square-boxed design

There are many potential areas of applications for such fabrics, e.g. in the automotive sector one could utilise these for heating car seats, door panels, parcel shelves and the steering wheel. Another possible application area is in sportswear and recreation fabrics for outdoors activities. In car seats, polymer based heaters are sandwiched in between layers for protection against abrasion during climbing and seating actions. Designs for car seating are concentrated on the outer layer which will be in contact with the user which makes the heating layer to be free of aesthetic nature and can be tailored only for its performance. Polymer based heaters are flexible than metal based heaters so they could be used to provide heat even at confined places like glove boxes and centre consoles due to the good draping capabilities. This can be seen on adjustable seats where the cover fabric is constantly stretched. Outdoors activities like hiking, jogging requires the user to have a substantial body covering clothing to keep him/her warm and protect from wind. Human body has to be maintained at a constant body temperature, and textiles have been used for many thousands of years to help to maintain the body temperature, especially during outdoors activities. The use of textiles to keep one warm has helped man to survive in the coldest areas such as the Arctic and the Antarctic where the outside temperatures can reach -50^{o}C. Heated textiles and especially polymer based ones can be used to provide the necessary heating. An advantage of using polymer based heated textiles is their low power requirement enabling the use of lighter power sources which are easier to carry. Polymer based heaters can be folded and compacted when not in use without destroying their structure and performance due to their flexible nature. Polymer based heaters can be carefully designed to produce efficient knitted vest liners which could be worn in-between layers and provide heat when required. There are heated vest in the market but washing them seems to be difficult as they may lose performance.

5.8 Chapter summary

In this chapter, heating fabrics technology and application were discussed. Different types of heating mechanism structure, designs, manufacturing and experimentation were performed. This was to identify potential use with spacer fabrics (KSS2T2E) discussed in chapter 2 and 4.

Heating elements made by using structure A were found to be most suitable for creating the temperature gradient in a KSS. The use of copper bus bars would be an advantage due to improved heating efficiency.

The next task is to combine the two (KSS2T2E and structure A heating structure) technologies to create a smart fabric. This is discussed in the next chapter.

Chapter 6

6.0 Active Moisture Management Structure (AMMS)

6.1 Introduction

In chapter 2 a detailed literature review on fabrics for moisture management was carried out, in order to identify the state-of-the-art technologies and designs employed by the industry, and the findings were reported. Today, different technologies are adopted to manage moisture in fabrics ranging from synthetic membranes (Gore-tex) to modified fibres). One of the popular techniques used currently is the use of multi-layer textile structures to enhance moisture management in textiles. The purpose of this chapter is to describe the development of an active knitted spacer structure, and the scientific investigations which steered to its development. Generally, knitted spacer structures consist of three layers and their ability of absorbing significant amounts of moisture is reported in the latest literature (Dias and Delkumburawatte, 2007, Saeed, 2006).

How one could manufacture heated fabrics with heater elements on computerised flat-bed knitting machines was studied in detail within the research and the findings are detailed in the previous chapter. The investigations showed that, different kind of heating fabric designs can be produced with modern flat-bed knitting technology. The analysis of the performance of knitted heating fabrics demonstrated that efficient and reliable heating fabrics can be produced with flat-bed knitting.

As stated in chapter 1 the aim of this research project was to develop a smart fabric with high drying capabilities for outdoor activities. The basic concept of the development is to employ a temperature gradient between the two fabric surfaces of a spacer structure, and this can be achieved by integrating heating elements on to one of the fabric surface of the structure. The exposure of the fabric surface integrated with heating elements would enhance the moisture evaporation to the outer environment, thus influencing the hydrostatic pressure difference across the fabric which is the driving force of moisture transfer of a fabric. One of the limitations of current fabrics used for moisture management is that the moisture transfer within the fabric structure is dependent on the hydrostatic pressure difference between its two surfaces and is influenced by the evaporation of moisture to the outer atmosphere. However, if the evaporation is slow then this would hinder the moisture transfer in the fabric resulting in an accumulation of moisture within the fabric. The integration of heating elements on to one fabric layer of the knitted spacer structure could be used to force the moisture to evaporate even at higher relative humidity atmospheric conditions. Therefore, the new moisture management structure developed will be referred to as Active Moisture Management Structure (AMMS) in the thesis.

6.2 Development of AMMS

It is important in any new product development to identify the points of references for the development. The following design rules were considered in the development:

- The knitted spacer fabric has to be light and thin. This would allow moisture to pass quickly through the spacer structure. The knitted spacer structure would provide sufficient heat insulation due to is structure, which is an important factor to be considered as the new structure will be used in outdoor activities where the surrounding temperature is expected to be lower than the average skin temperature of the end user.
- The heating elements have to be ergonomically placed onto the fabric structure without destroying the aesthetics as far as possible.
- The AMMS has to possess a good degree of softness as it could be worn next to the skin of the human body. Another major important feature of that the AMMS is that

it has to be flexible to allow all bending and stretching it would be subjected to during its use. This is an important factor as this would influence the conformability of AMMS around a human body and comfort.

As stated earlier the AMMS is a knitted spacer structure with heating elements integrated on to one fabric layer of the spacer structure. The heating elements are knitted from FabRoc yarn and copper yarn forming the required bus bars. The heating elements are embedded into the structure of the spacer fabric in a manner that they will enhance the required hydrostatic pressure difference across the spacer structure. In chapter 3 different types of spacer fabrics which can be produced with computerised flat-bed knitting technology was discussed. The spacers demonstrated were knitted by altering the length of the spacer yarn by tucking them between different needles of two needle bed, and their ability to absorb moisture was evaluated, and the results reported. The increase of the length of spacer yarn influenced the weight and dimensions of the samples produced. The knowledge gained from the work reported in chapter 3 can be used in designing the AMMS. The knitted spacer samples were also investigated in terms of moisture transmission when situated between two contrasting environmental conditions by using the new test rig developed for the purpose. The results shown in figure 5.8.1 indicates different behaviour in terms of the transmission rate (drying times), weight and thickness as expected.

By considering the data reported in chapter 2 one can conclude that spacer 2 both in terms of absorption and transmission of moisture characteristics meet the requirements to develop the AMMS. It has the lowest weight and thickness, and demonstrated relatively good results in both absorption and transmission of moisture.

As the focus of the research is to enhance the moisture management of a knitted spacer structure by introducing a temperature gradient within the cross section of the fabric using heat, the number of knitted heating elements, their dimensions and their placement are crucial factors to be considered. The temperature gradient across the fabric will depend on the heat generated at the fabric layer integrated with heating elements. This means, ideally the fabric layer could be covered entirely by heating elements. However, such a design could compromise moisture absorption and evaporation ability, as less area would be available for moisture to be absorbed by the spacer structure. On the other hand several heating elements are required to generate the heat required to increase the hydrostatic pressure difference across the spacer structure. However, this could result in an increase of the surface temperature of the spacer structure. Therefore, a good balance between moisture transfer and fabric surface temperature has to be determined, and a mathematical model would be a useful tool. In chapter 5, it was concluded that, heater elements with narrow size were more efficient than wider ones. So this was considered in this section when integrating heater onto a KSS. However, integration of heater elements would require modification of one side of the KSS to accommodate the heater elements. See figure 6.2.1 below for details;

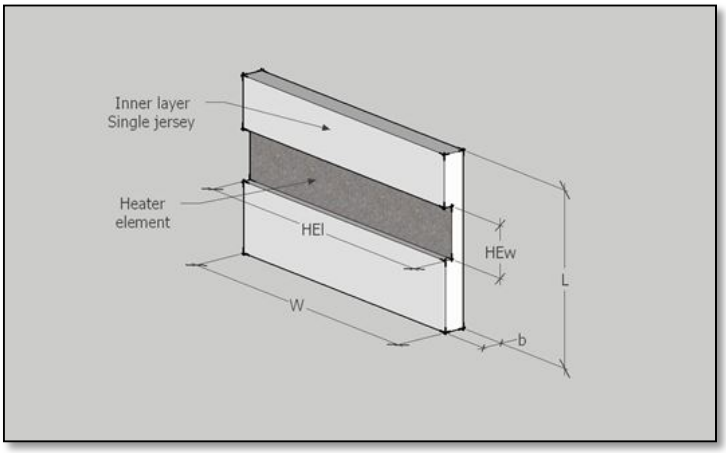


Figure 6.2.1: AMMS sample showing heater elements integration

This would change the surface of the KSS and in doing so, these changes had to be captured on the mathematical model developed in chapter 3. The two major aspects that required modification were;

1. The KSS thickness. The heater integration into KSS would be attached into the KSS single jersey layer. Previously, this was not affected as the heater elements was made separately and then placed on top of the KSS single jersey layer. As this is integrated onto the KSS, KSS thickness would be affected at areas that are covered by heater elements. So it was assumed that the effective fabric thickness would be reduced by 50%. For the KSS fabric thickness b, the effective fabric thickness would be;

   $b_{eff} = 50 * \frac{b}{100}$..(6.2.1)

   This modified KSS thickness was introduced into equation 4.3.1.1

2. The dimensions of the heater elements to be integrated into the KSS. This would have an effect to the total area into which the heat influences the KSS. So assuming number of heater element Nh will have a dimensions of length HEL and width HEW and KSS sample having dimensions of length L, width W and thickness b. The length influenced by the heater elements onto the KSS is Leff. This is calculated by;

   $L_{eff} = L - (HEW * Nh)$..(6.2.2)

   Thus the total area influenced by the heater elements would be;

   $A_{eff} = L_{eff} * W$..(6.2.3)

   This modified area is substituted into equation 3.3.2.4 in chapter 3;

The results simulated using Matlab is given in figure 6.2.1, which illustrates how different number of heating elements would influence moisture transmission and surface temperature in a spacer structure.

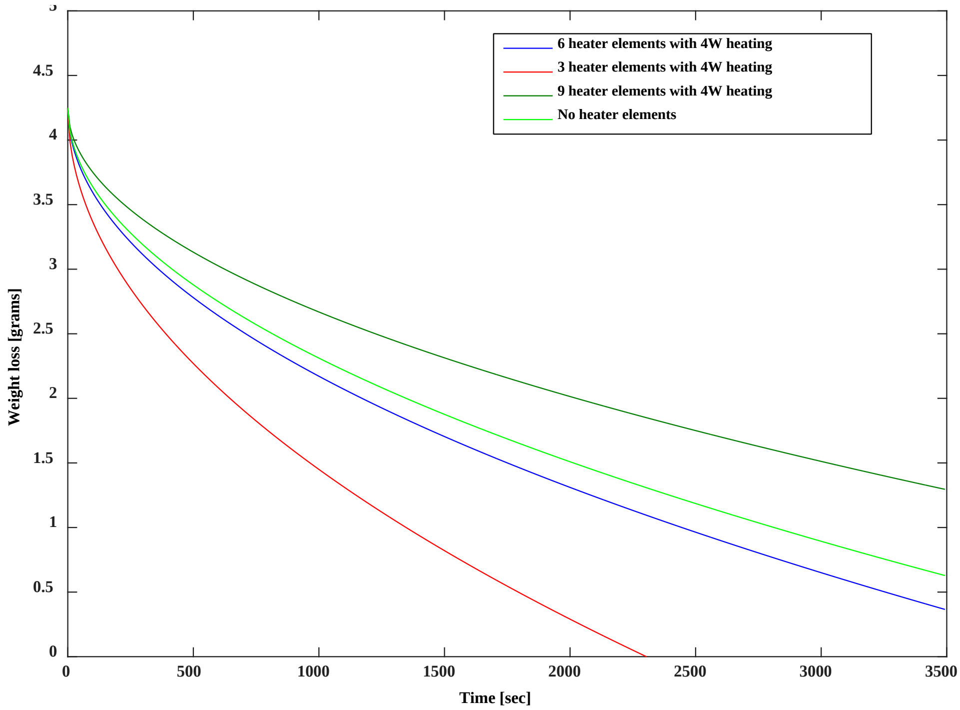


Figure 6.2.2: The influence of the number of heating elements on moisture absorbency of a spacer structure

The equation 4.3.2.12 derived in chapter 4, pages 62-66 was used to simulate how the number of 7.0 x 0.5 cm heating elements and the electrical power supplied would influence the temperature of the layer integrated with heater elements of AMMS, and the results are summarised below in Table 6.2.1.

Table 6.2.1: AMMS surface temperature when supplied with different electrical power

Power supplied [W]	AMMS inner surface temperature [K] (^oC)
1.0	311.67 (38.67)
2.0	313.33 (40.33)
3.0	315 (42)
4.0	316.67 (43.67)

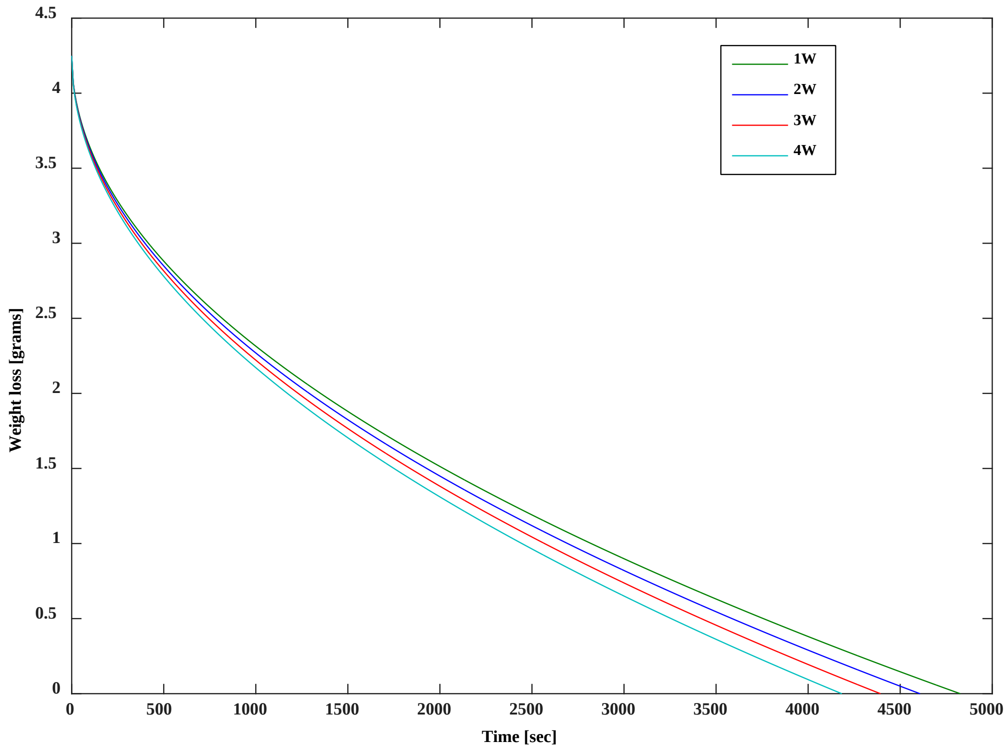


Figure 6.2.3: Moisture transmission of AMMS when supplied with different electrical power

Table 6.2.2: AMMS inner surface temperature simulations at 4W power supply

Number of heater elements	**AMMS inner surface temperature [K] (^oC)**
0	310 (37)
3	323.33 (50.33)
6	316.67 (43.67)
9	314.44 (41.44)

Similarly, considering a knitted fabric sample (KSS2T2E) with length and width dimensions of 11.5 X 11.5 cm respectively having heater elements each of size 7.0 X 0.5 cm; the total area covered by 3 heater elements can be expressed as;

Considering one heater element;

Area = Length of heater element X width of heater element

Thus, Area = 7 x 0.5 = 3.5 cm^2.

So for 3 heater elements; Area covered = 3 x 3.5 = 10.5 cm^2.

Then, the total area uncovered by heater elements would be;

Area uncovered= Area of AMMS – area covered by heater elements

Area uncovered = (10X10) – 10.5 = 89.5 cm^2

The same procedure was used to calculate the parameters considering 0, 6 and 9 heating elements and results are tabulated on Table 6.2.3 below;

Table 6.2.3: Heater elements influence of AMMS fabric area

Number of heater elements	Total area covered by heater elements [cm^2]	Total area uncovered by heater elements [cm^2]	Percentage area covered by heater elements [%]
0	0.0	100.0	0.0
3	10.5	89.5	11.7
6	21.0	79.0	26.6
9	31.5	68.5	45.9

This subsection concerned about the development of AMMS. The main aspects covered were the number of heater elements to use, location on the KSS and amount of heating to be used.

Figure 6.2.2 shows simulated results using the mathematical model developed in chapter 4 to investigate the number of heating elements to be used on the AMMS. Results show that 6 heater elements would be significant per area of the KSS. Although 3 heater elements show a much quicker moisture transfer than 6 and 9; but this compromised in terms of temperature generated on the inside surface of the AMMS as indicated on table 6.2.2 with 3 heater elements, much higher inside temperature was generated compared to 6 and 9. Also table 6.2.3, shows that AMMS integrated with 6 heater elements contains more surface area for moisture absorption and transmission as only 26% of AMMS is covered by heating elements resulting in 74% remaining for moisture absorption and transmission. This is advantageous compared to 3 and 9 heater elements AMMS area coverage.

After establishing 6 heater elements would be sufficient to provide heat effect for required pressure gradient across the AMMS sample, other aspect was to establish how much heat would be efficient required to ensure significant pressure gradient across AMMS with 6 heater elements. Figure 6.2.3 and table 6.2.1 demonstrates amount of heating effect applied. Results showed 4 watts of heating had significant application as reasonable temperatures are generated on the inner layer of the AMMS necessary for creating pressure difference for moisture transfer.

6.3 Manufacturing process

The intention of this section is to explain the manufacture of AMMS by using computerised flat-bed knitting technology. The design rules for developing AMMS were explained in the previous section. The conceptual design of the AMMS is to use multiple fabric layers of different functionality; a porous hydrophobic fabric layer, a heated textile fabric layer and a sandwich structure consisting of capillaries to facilitate the moisture transfer. The modern computerised flat-bed knitting technology provides an ideal manufacturing platform to create the AMMS due to the ability to produce a single textile structure integrated with above mentioned characteristics; the key features of the technology are summarised in chapter 2, pages 37-43 of the thesis.

As the AMMS is based on a knitted spacer structure a detailed study was carried out to select the suitable, which is summarised in chapter 2 and 4. Based on the knowledge obtained the spacer 2 (2 tucks of spacer yarns and 2 ends of spacer yarn). Similarly the previous chapter demonstrated how single layer heated fabrics can be produced on computerised flat-bed knitting machines. Therefore, the AMMS for this research was produced on a modern computerised flat-bed knitting machine from Stoll GmbH, who is one of the leading manufactures of flat-bed knitting machines; the machine employed was a gauge 16 CMS830 generation.

The focus was to create an AMMS of minimal weight and thickness while retaining flexible characteristics of textiles. See figure 6.3.1 below (all dimensions in cm);

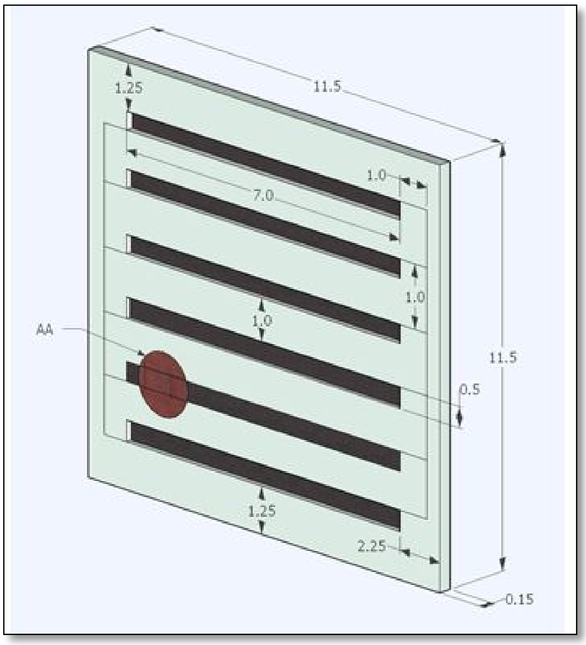


Figure 6.3.1: AMMS sample schematic dimensions

Therefore, heating elements of 7.0 x 0.5 cm dimensions were used as they would portray less disturbance on the spacer structure as minimal area is used by the heating elements making more area being available for moisture handling. Chapter 5 also documented the use of knitted bus bars to connect individual heating elements to a power source. Since the design concept is to use number of small heater elements it is necessary to connect the bus bars of all heater elements to two central electrical terminals to power the heater elements. For the AMMS this was achieved by forming two wales on either end of the heated fabric layer with conductive yarn; the number of stitches per wale has to be selected according to the current draw in the central electrical terminals. This design is advantageous, as electrically all the heating elements are connected in parallel resulting in the reduction of the equivalent resistance of the electrical circuit enabling the use of low voltage power supplies such as batteries.

The stitch formation diagram represented by projection AA in figure 6.3.1 above is given in figure 6.3.2 below demonstrates how the knitting heating elements and bus bars of the AMMS samples of the research. This is a section of the entire stitch formation diagram used to produce the AMMS samples, which is given in Appendix 6.

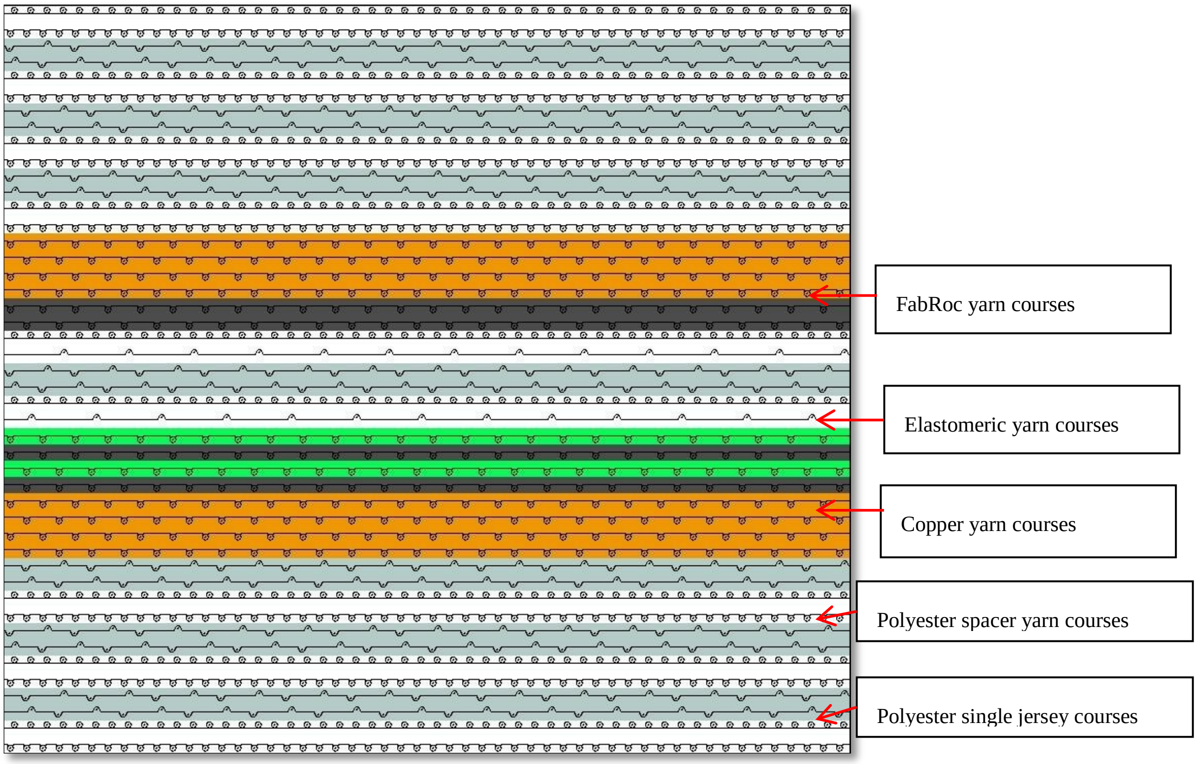


Figure 6.3.2: The repeat of the stitch formation diagram for producing the heating elements of the AMMS(Stoll)

The repeat shows the knitting of 2 tuck–2 yarn spacer structure with PE yarn including heating elements. The heating elements were designed as explained in chapter 5, however, of smaller dimensions due to their efficiency and ergonometric.

Test samples of two different dimensions were made as they were required for the evaluation of AMMS for moisture absorbency and transmission experimental investigations. The testing of moisture absorbency required smaller samples of 5 x 5cm dimensions whereas somewhat larger samples of 11.5 x 11.5cm were required for moisture transmission tests. The absorbency tests were carried out with the MKS GATS System, described in chapter 2, pages 43-47 of the thesis. The details of the samples used are summarised in Table 6.3.1, and figure 6.3.2 shows examples of knitted test samples.

Table 6.3.1: Fabric samples structural properties

Property	Small sample		Large sample	
	With heaters	Without heaters	With heaters	Without heaters
Size [L X W]cm	5 X 5	5 X 5	11.5 X 11.5	11.5 X 11.5
Weight [grams]	2.95	1.1012	9.1612	5.9242

Also figure 6.3.2 below shows completed knitted samples with both the sizes.

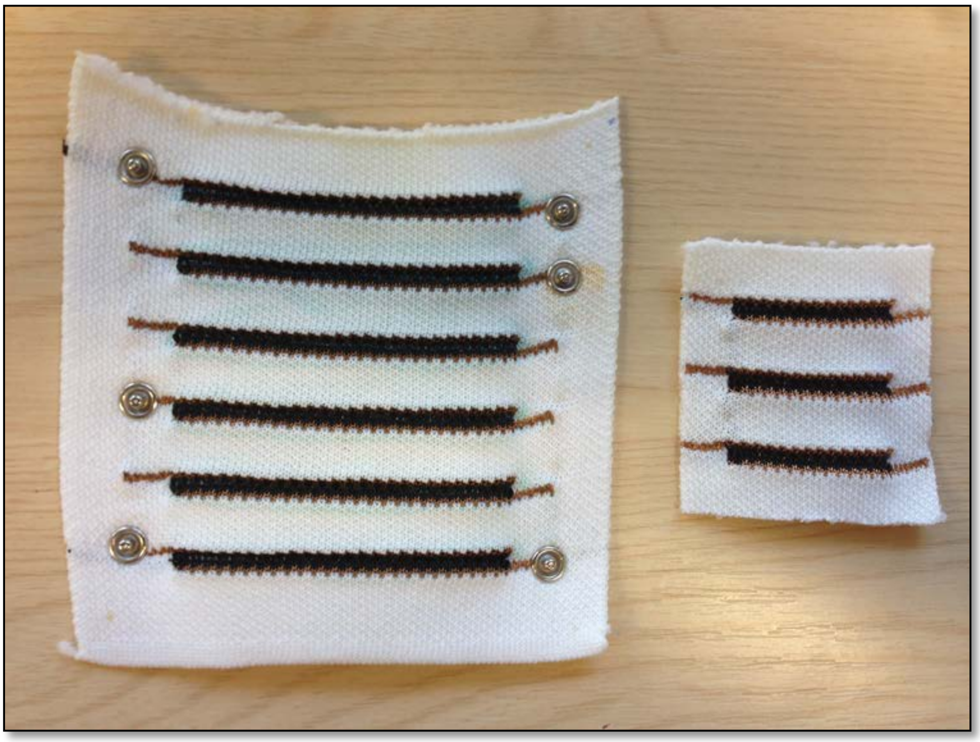


Figure 6.3.3: AMMS test samples used for evaluation of moisture absorbency and transmission

6.4 Experimentation

The intention of this section is to report the experimental procedures conducted to capture the behaviour of the AMMS. In the previous chapters three and five the moisture absorbency and transmission of knitted spacer structures and knitted heated fabrics were investigated. The AMMS is a created by fusing these two technologies together and, therefore, it is important to study the behaviour of AMMS for its moisture management capabilities. The study of the characteristics AMMS would be helpful to understand how its performance could be improved without any risk to the end user. Generally, any product would function at its optimum performance within defined limits, and the main objective of this section to identify theses limits and define the overall performance of the AMMS. The two types of AMMS samples would have same properties as they were manufactured in same manner. However, samples of different dimensions were produced to suit the different test methodologies to determine the moisture absorption and transmission, wash tests, fabric wettability tests and the rate of fabric temperature increase.

6.4.1 Moisture absorption

The moisture absorbency of AMMS was evaluated to determine the effect of heating elements in the structure. The MK GATS system was used to compare absorption capabilities of test samples with and without heating elements. The figure 6.4.1.1 shows the samples used in this experiment.

Figure 6.4.1.1: Fabric samples with and without heating elements

The procedure described in chapter 2, pages 43-47 was used to test the moisture absorption of AMMS samples. A total of 5 samples were tested for each group, i.e. with and without heater elements, and the results are summarised in figure 6.4.1.2 below.

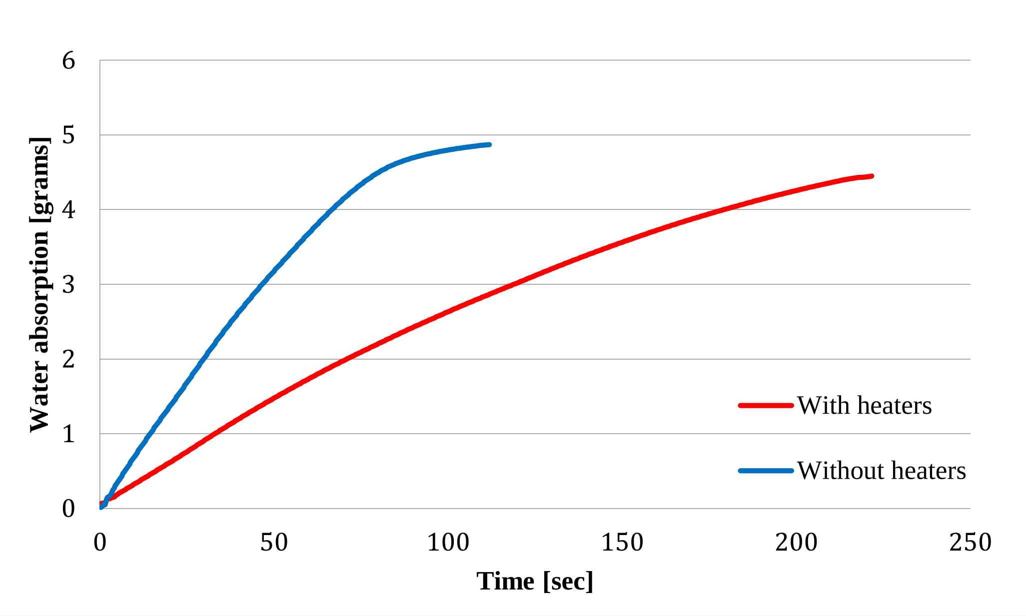


Figure 6.4.1.2: The effect of heating elements on moisture absorption; test sample size is 5 x 5 cm

The above test was conducted to explain the effect of heating elements into spacer fabric absorption characteristics. Results show that, although there is a reduction of moisture holding capacity and increased absorption time; still the heating system could be introduced into the knitted spacer fabric for increased moisture handling as the heater elements would provide the necessary hydrostatic pressure control across the knitted fabric. The test was conducted while the heater elements were not operating, and heater elements could affect the moisture absorption due to its yarn characteristics. Heater elements yarns are non-absorbent which means absorption occurs only on non-heater areas and not in the heater area. This could explain the drop in moisture absorption characteristics. Table 6.3.1 compares the weight change after the introduction of heating elements. We saw about 45% increase in weight per area. This shows an increase in weight gain but as new technologies emerge; this could be improved and a much lighter development could be introduced.

6.4.2 Thermal characteristics of AMMS

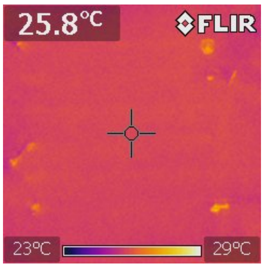
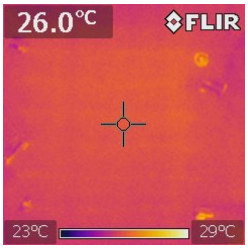
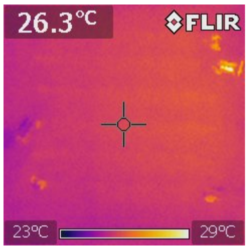
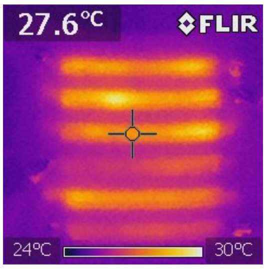
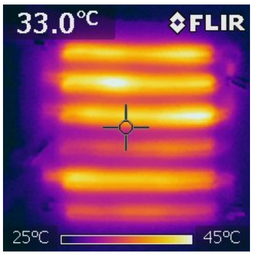
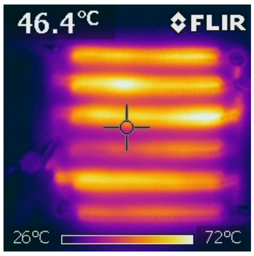
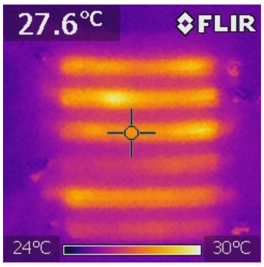
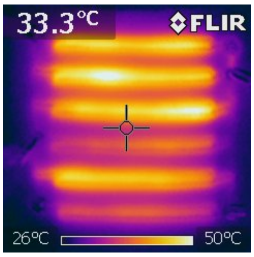
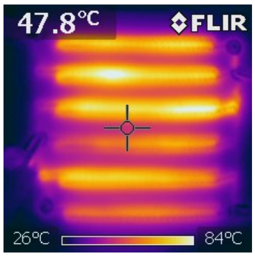
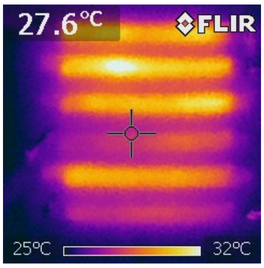
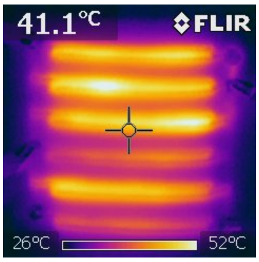
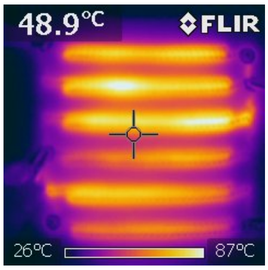
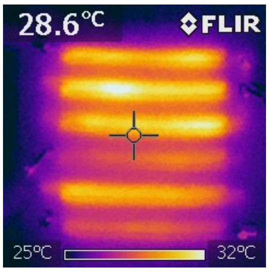
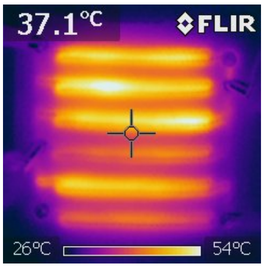
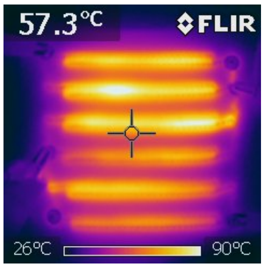
The heat generation and electrical power consumption of AMMS was studied to determine the power requirements for efficient functioning of moisture transfer within the structure. The knowledge gathered would also assist in the selection of suitable power source. The 11.5 X 11.5 cm sample was used, and thermal images were obtained using an infrared camera, FLIR i7. The sample was connected to the TTi laboratory bench type power supply, by connecting suitable power leads to the press studs of the samples. The samples were powered at different voltages and the output current of the power supply noted. The power consumption of the samples were calculated with the voltage supplied and the current flow (see Table 6.4.2.1).

Table 6.4.2.1: Fabric power supply at various voltages

Voltage [V]	Current [A]	Power [W]
1.0	0.38	0.38
2.0	1.02	2.04
3.0	1.85	5.55

The temperature distribution in the samples and the maximum temperatures of the heating elements were established from the thermal images of the camera. Thermal images of the samples were captured at predefined times in order to ascertain the heating rate of AMMS samples.

Results of this investigation are summarised in figures 6.4.2.1 and 6.4.2.2 below;

Time [min]	Thermal image		
	1V: 0.38A	**2V: 1.02A**	**3V: 1.85A**
0			
1			
2			
3			
8			

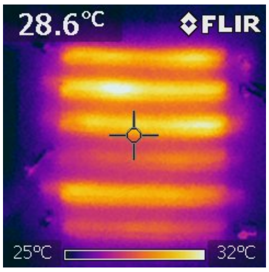
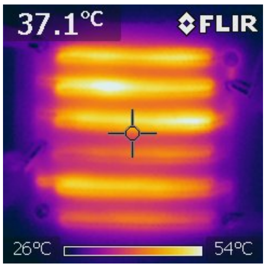
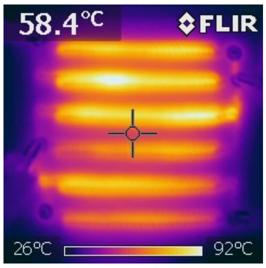
13			

Figure 6.4.2.1: Thermal images of AMMS samples when powered at three different voltages

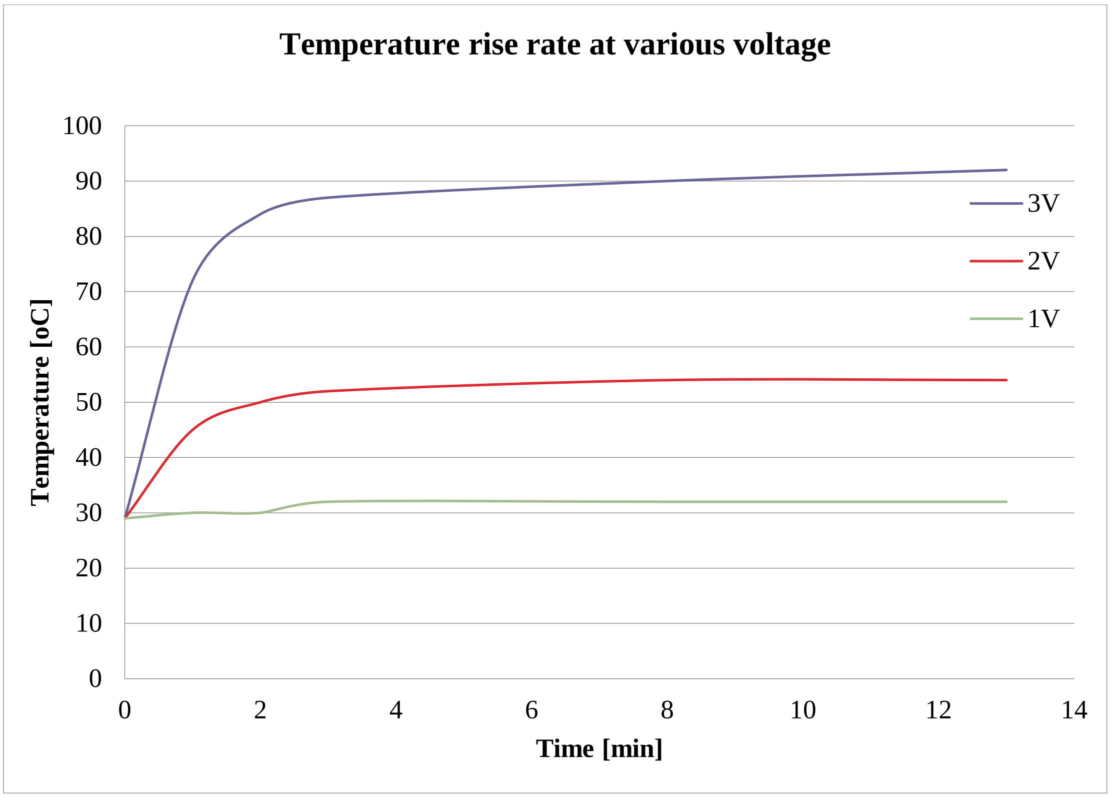


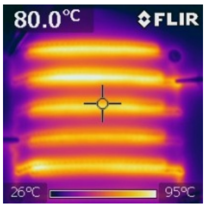
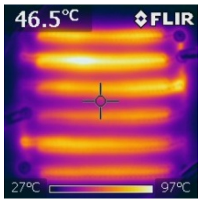
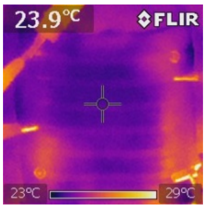
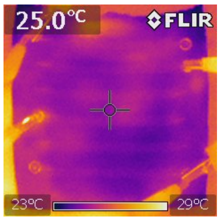
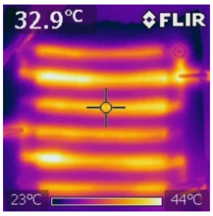
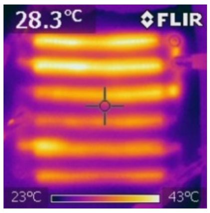
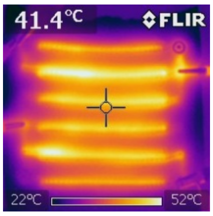
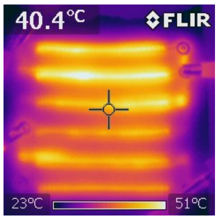
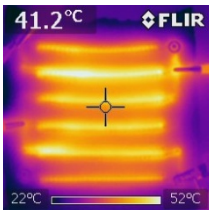
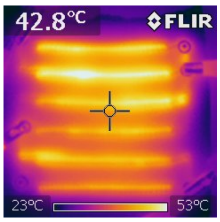
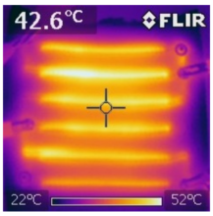
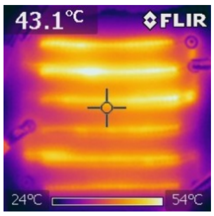
Figure 6.4.2.2: Thermal characteristics of AMMS when powered at different voltages

Results from this experiment could be explained below; in figure 6.4.2.2, the rate of temperature of heating elements on the AMMS fabric rise at 1.0, 2.0 and 3.0 volts. It indicates clearly temperature at all three voltages rose sharply within the first two minutes and then stabilized to maintain the constant value. This is important as heat application needs to be quick when needed to avoid moisture build up on the fabric and create discomfort to the wearer. Also the test shows that, temperature of heating element is stable for a long period (after 2.5 min); which could be useful safety feature to avoid excessive temperature raise or unpredictable heat rise which could cause harm to the wearer or damage to the system. Figure 6.4.2.1 show thermal images of heated spacer fabric with heating elements attached. The temperatures achieved at these voltage ranges are within the range that could be needed to create the hydrostatic pressure difference across the fabric to improve moisture transfer. For instance at 1.0V just a maximum of 32^{o}C was recorded which is below the skin temperature so the wearer could not feel the heat but feel the drying state of the fabric.

6.4.3 Moisture wettability test

It is also important to study how the moisture absorbed by the knitted spacer structure of the AMMS would affect the generation of heat by heater elements. When using AMMS to produce outdoor garments the heating elements could be surrounded by sweat (moisture), and this could result in a change in the electrical conductivity of the knitted heated system. Therefore, the performance of the knitted heater elements of AMMS samples when they are saturated with distilled water were analysed. The mathematical model developed to study how the creation of a temperature gradient in a knitted structure would influence the moisture transfer of the fabric was validated by placing test samples in the experimental rig that was designed and built for testing (chapter 4, pages 83-96). Although the samples were sprayed with distilled water prior to testing it was difficult to determine the heating performance of the heater elements. Therefore, a different method was adopted to evaluate the performance of heater elements when they are wet, and the test procedure is explained below.

The 11.5 x 11.5 cm AMMS samples were saturated with 15g of distilled water and powered at different voltages. The infrared camera, FLIR i7 was used to capture thermal images of the samples at predetermine times and the results are displayed on figures 6.4.3.1 and 6.4.3.2 below;

	Voltage [V]		Current [A]		Thermal Image	
	Run1	Run2	Run1	Run2	Run1	Run2
Before wetting after 10min	3.0	3.0	2.56	2.26		
After wetting 0min	0.0	0.0	0.0	0.0		
After wetting 1min	3.0	3.0	2.55	2.45		
After wetting 5min	3.0	3.0	3.2	2.87		
After wetting 10min	3.0	3.0	3.2	2.94		
After wetting 20min	2.8	3.0	3.2	2.93		

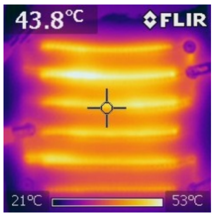
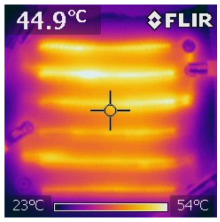
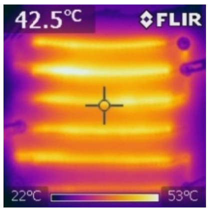
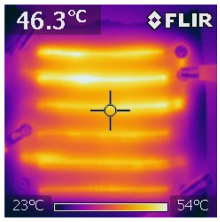
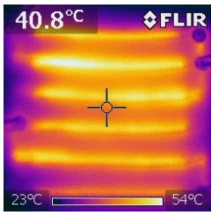
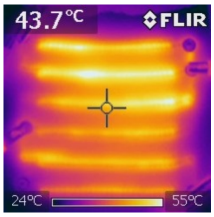
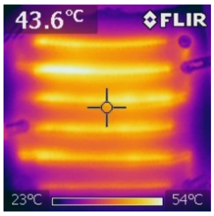
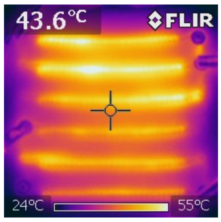
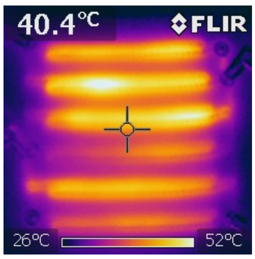
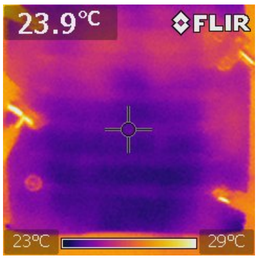
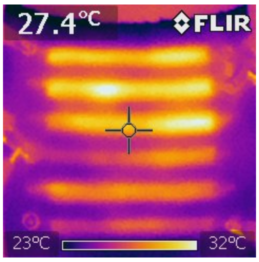
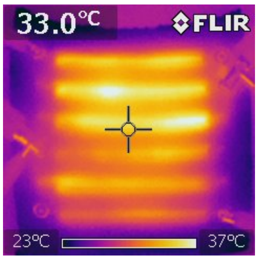
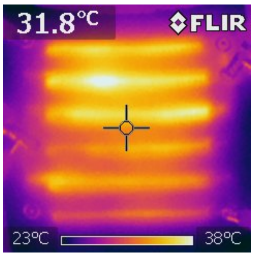
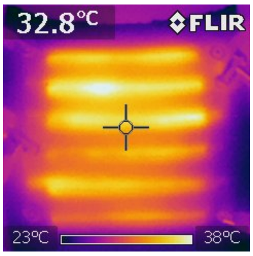
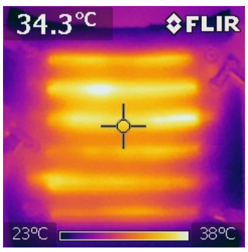
After wetting 30min	2.8	3.0	3.2	2.91		
After wetting 40min	2.8	3.0	3.2	2.89		
After wetting 50min	2.7	3.0	3.2	2.87		
After wetting 60min	2.7	3.0	3.2	2.85		

Figure 6.4.3.1: Performance of heater elements of 11.5 x 11.5 cm AMMS samples saturated with distilled water when powered with 3.0V

	Voltage [V]	Current [A]	Thermal Image
Before wetting 0 min	2.0	0.86	

After wetting 0 min	0.0	0.0	
After wetting 1 min	2.0	0.93	
After wetting 5 min	2.0	1.15	
After wetting 10 min	2.0	1.22	
After wetting 20 min	2.0	1.23	
After wetting 30 min	2.0	1.24	

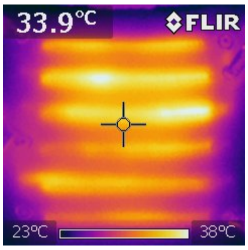
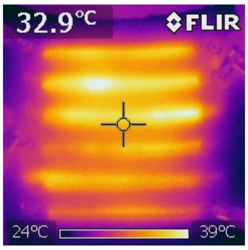
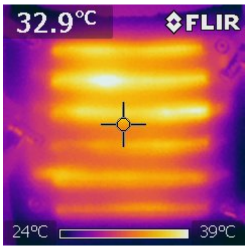
After wetting 40 min	2.0	1.23	
After wetting 50 min	2.0	1.23	
After wetting 60 min	2.0	1.23	

Figure 6.4.3.2: Performance of heater elements of 11.5 x 11.5 cm AMMS samples saturated with distilled water wettability test when powered with 2.0V

This step was to investigate the properties of the technical fabric operating in a wet state. This is the state believed to occur when a fabric is worn besides a sweating skin of an individual. It was conducted at 2.0V and 3.0V. At 3.0V as indicated on figure 6.4.2.1, a decrease in temperature after wetting was observed but gradually increased with time. This shows that the fabric is operating well at wet conditions and fabric heat could be a source of moisture evaporation from the surface of the fabric. However at 3.0V, temperature is much higher than human body skin temperature but this could be improved and instead a lower voltage could be used as can be seen on figure 6.4.3.2 with 2.0 voltage supply. Another observation from the results show how the technical fabric operates whilst still wet. Water is regarded as a good electrical conductor and since the heater elements on the technical fabric consist of positive and negative connection; the thought was an electric short circuit could be created once in contact with water. There is an increase in current once water in presented into the fabric however due to less amount of power required on the heater elements, this reduces risk of electrical shock. This is important as the combination could safely be used for human body protection without causing potential danger.

6.4.4 Wash tests

Generally textiles, especially those used in garments, would undergo washing during their lifespan. Similarly, AMMS may be subjected to washing during their use, which might affect the performance. The effect of washing on heated glove liners with five heater elements was reported in chapter 5, pages 128-136. Therefore, the effect of washing on heater elements of AMMS had to be investigated, particularly due the moisture absorbent nature of the knitted spacer structure of AMMS. Any distortion of the stitches of the heater elements due to washing may influence their performance. Therefore, in order to understand the effect of washing the heating of the heater elements were compared before and after wash runs. The thermal images of the heater elements of 11.5 x 11.5 cm and 5.0 x 5.0 cm AMMS samples were captured with the FLiR i7 camera before and after washing. The samples were powered at 3.0V. The results and summarised below;

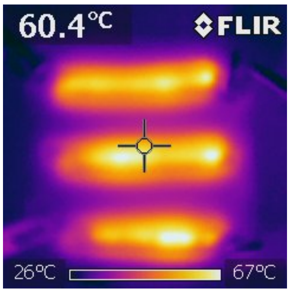
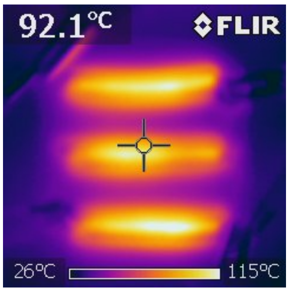
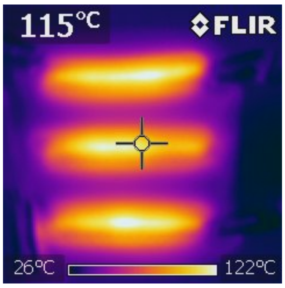
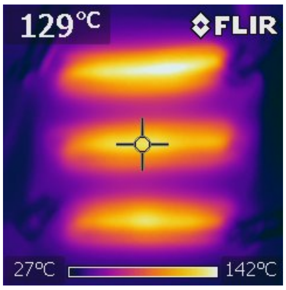
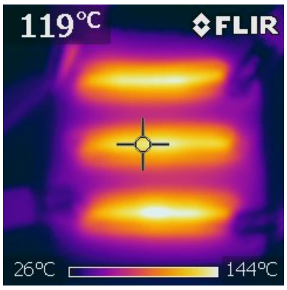
	Voltage [V]	Current [A]	Thermal Image
Before washing	3.0	0.52	
After washing [30°C,800rpm,2.35hrs]	3.0	1.09	
After washing run2 [30°C,800rpm,2.35hrs]	3.0	1.28	
After washing run3 [30°C,800rpm,2.35hrs]	3.0	1.35	
After washing run4 [30°C,800rpm,2.35hrs]	3.0	1.35	

Figure 6.4.4.1: Washing effect on 5.0 x 5.0 cm AMMS sample

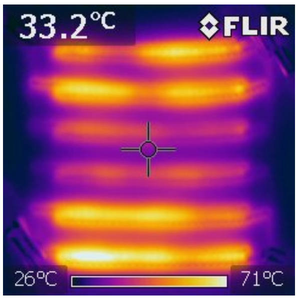
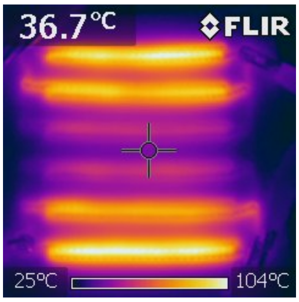
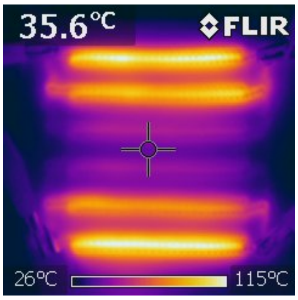
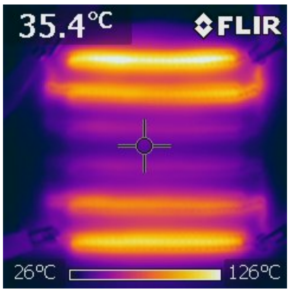
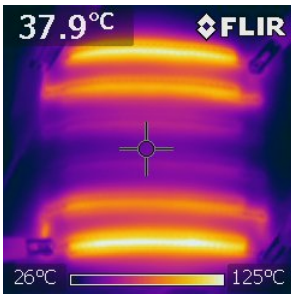
	Voltage [V]	Current [A]	Thermal Image
Before washing	3.0	1.17	
After washing [30^{o}C,800rpm,2.35hrs]	3.0	2.18	
After washing run2 [30^{o}C,800rpm,2.35hrs]	3.0	2.55	
After washing run3 [30^{o}C,800rpm,2.35hrs]	3.0	2.61	
After washing run4 [30^{o}C,800rpm,2.35hrs]	3.0	2.52	

Figure 6.4.4.2: Washing effect on 11.5 x 11.5 cm AMMS sample

Maximum temperature from the thermal images displayed in figure 6.4.4.2 above are further illustrated on figure 6.4.4.3 below; this was performed to understand the temperature trend as the AMMS sample was under wash cycles.

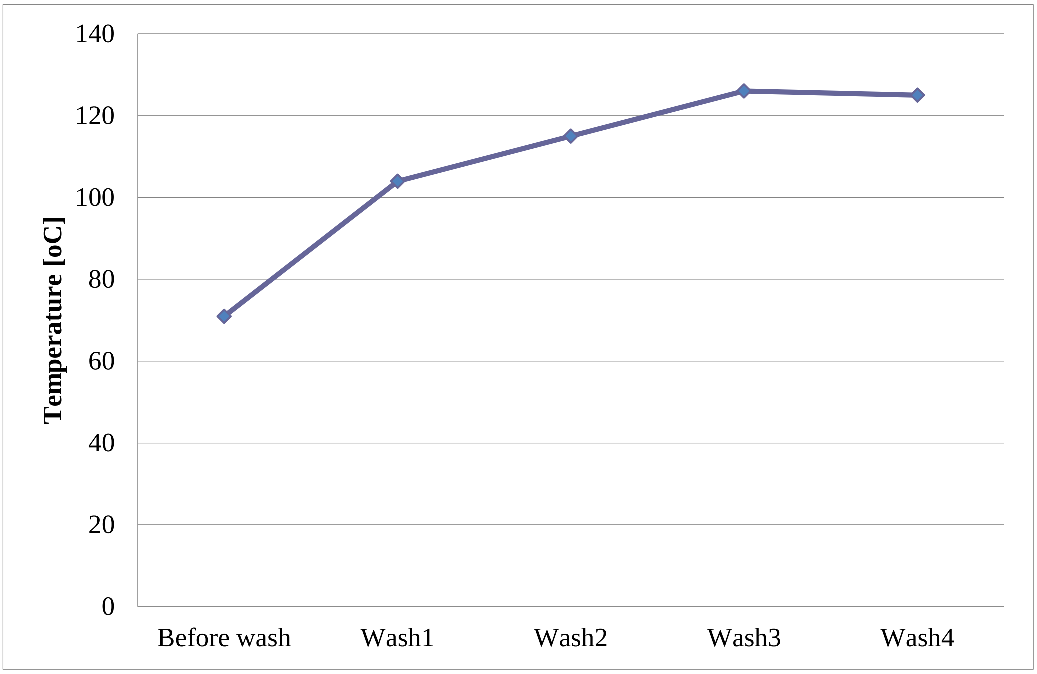


Figure 6.4.4.3: The influence of washing on maximum temperature of heater elements when powered at 3.0V

To investigate the AMMS further after wash test cycles, electrical resistance and current flow through the AMMS was also checked. As from above results, temperature changes across the AMMS sample would result into changes in electrical properties of AMMS too. Thus it was important to check electrical resistance and current before and after the wash cycles. An Agilent 34410A precision multimeter was used to measure and record the resistance of AMMS sample during and after wash cycle while current draw of heater element was recorded from TTi power supply. As applied in chapter 5 section 5.6.5; the similar procedure to measure and record electrical resistance of heater elements was applied in this section and results are displayed in figures 6.4.4.4 and 6.4.4.5 below;

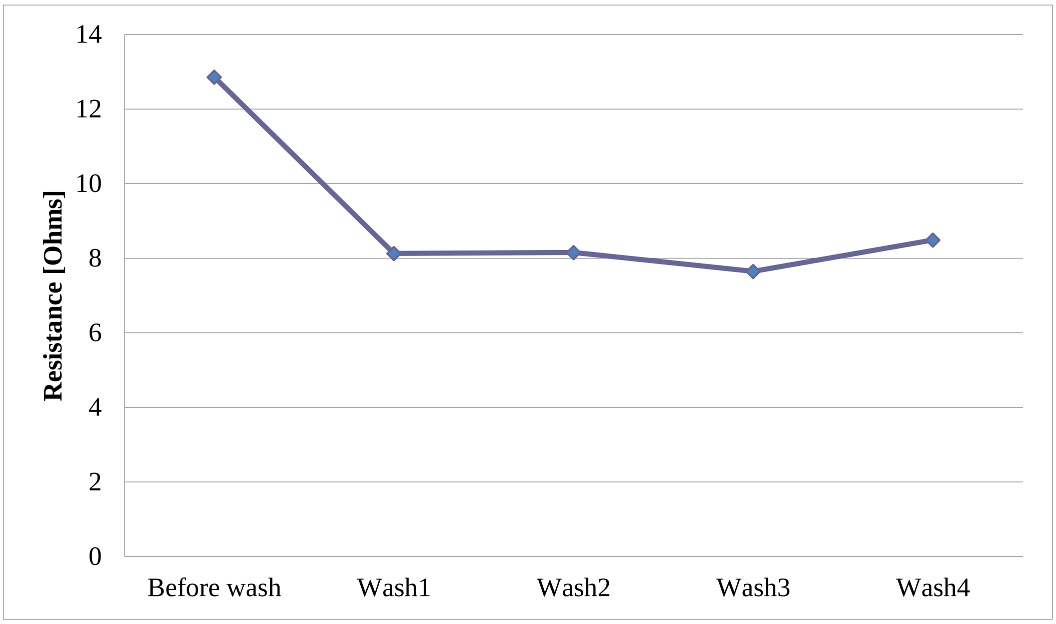


Figure 6.4.4.4: The change in electrical resistance of heater elements in 11.5 x 11.5 cm AMMS samples due to washing

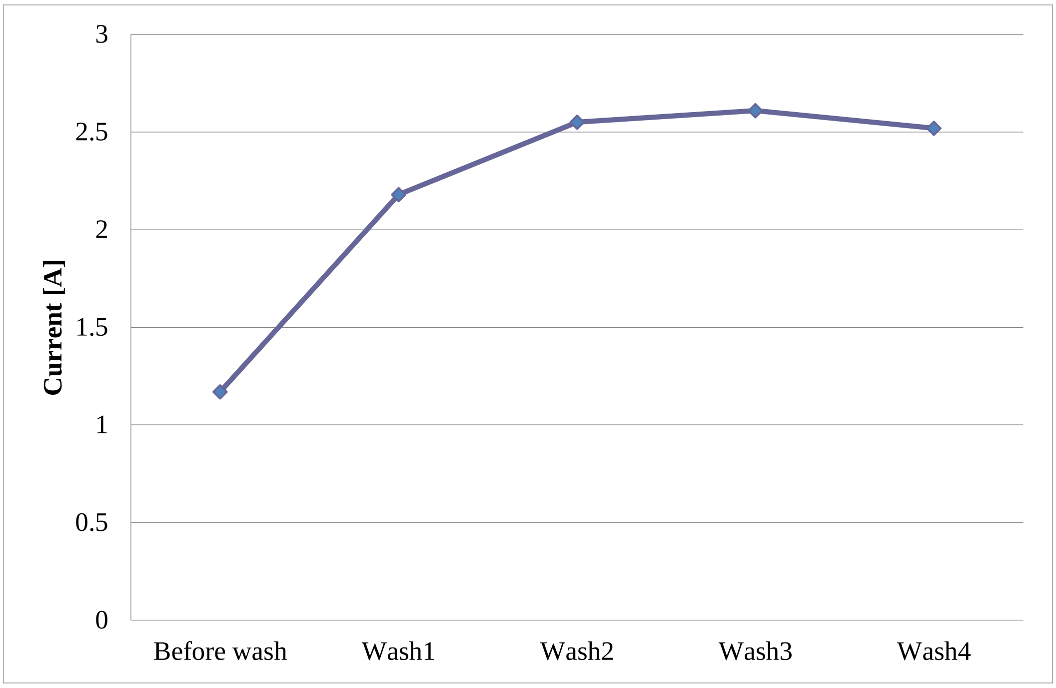


Figure 6.4.4.5: The influence of washing on current draw of heater elements when powered at 3.0V

For both smaller and larger AMMS samples test results (figures 6.4.4.1 and 6.4.4.2 respectively) it was observed that performance of heater elements was improved after the first wash and then stabilized on the next washes. This could be explained as the knit structure on the heater elements is relaxed after the first wash due to stresses formed during knitting(Ray, 2012). This relaxation could cause the knit contact points on the structure to improve and hence improve conductivity and heat rates. During the next washes, because of less stresses, the knit structure is not affected in terms of dimensional arrangement so it remains unchanged and hence after several washes it still performed literally the same. Figures 6.4.4.4 and 6.4.4.5 show the electrical properties of the heater elements after 4 washes. As before, after first wash, resistance is dropped and current increased due to improved knit contact points and remain constant on the next washes. This shows that the heating elements could be used to provide the necessary heat for improving moisture transfer on the fabric and still be processed like a normal day to day textile.

6.4.5 Moisture transmission test

The moisture transmission is one of the key attributes of the AMMS and this was investigated by using the test rig developed within the programme of research (chapter 4, pages 76-79). This would demonstrate the effectiveness of AMMS in different environments. The 11.5 x 11.5 AMMS samples knitted with 6 heater elements as shown in figure 6.3.3 were sprayed with 4.5 grams amount of distilled water and then placed between the two mini chambers of the test rig. The temperature and relative humidity in the mini chambers were set to simulate different test conditions.

6.4.5.1 Mathematical model simulation

Prior to testing the mathematical model described in chapter 4 was used to simulate the moisture transmission in AMMS under passive and active mode of operation; the active being when the heater elements in the structure are supplied with four watts of energy. This quantity of energy is believed to produce the required temperature responsible for gradient between the inner and outer part of the AMMS. The relation between temperature and energy supplied is formulated in chapter 3 represented by equation

4.3.2.4. The Matlab software developed to solve the mathematical equations is given in appendix 5 (pages 218-222). Similar conditions to those described in chapter 4 (pages 66-67) were used for the simulation and the results are illustrated in figures 6.4.5.1.1 and 6.4.5.1.2.

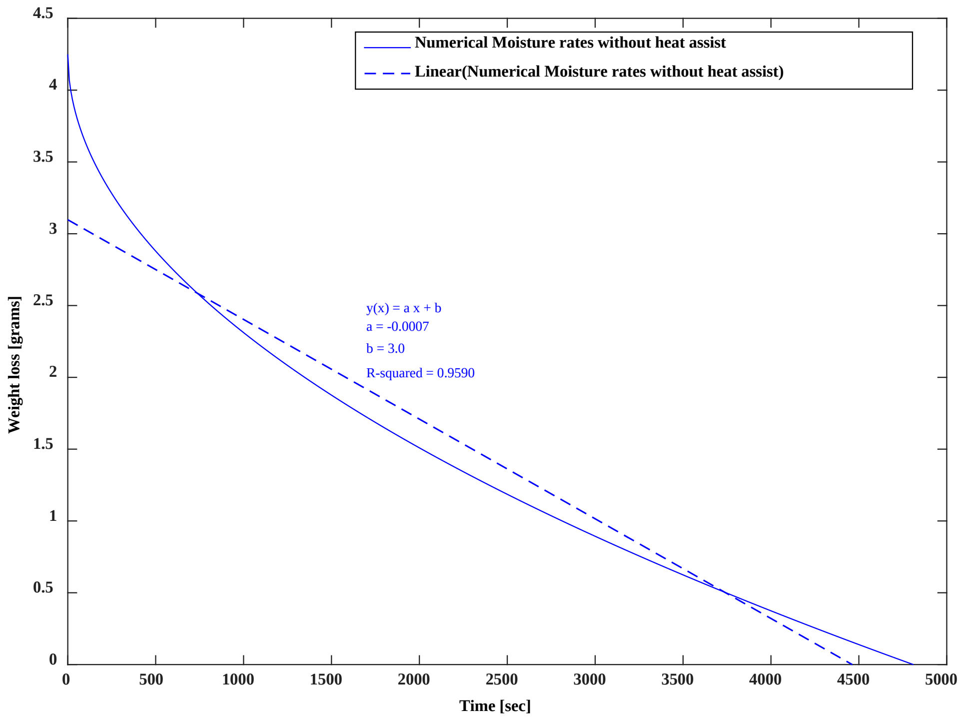


Figure 6.4.5.1.1: The results of moisture transfer and its evaporation in spacer structure knitted with 2 yarn ends and 2 tucks calculated by using the mathematical model

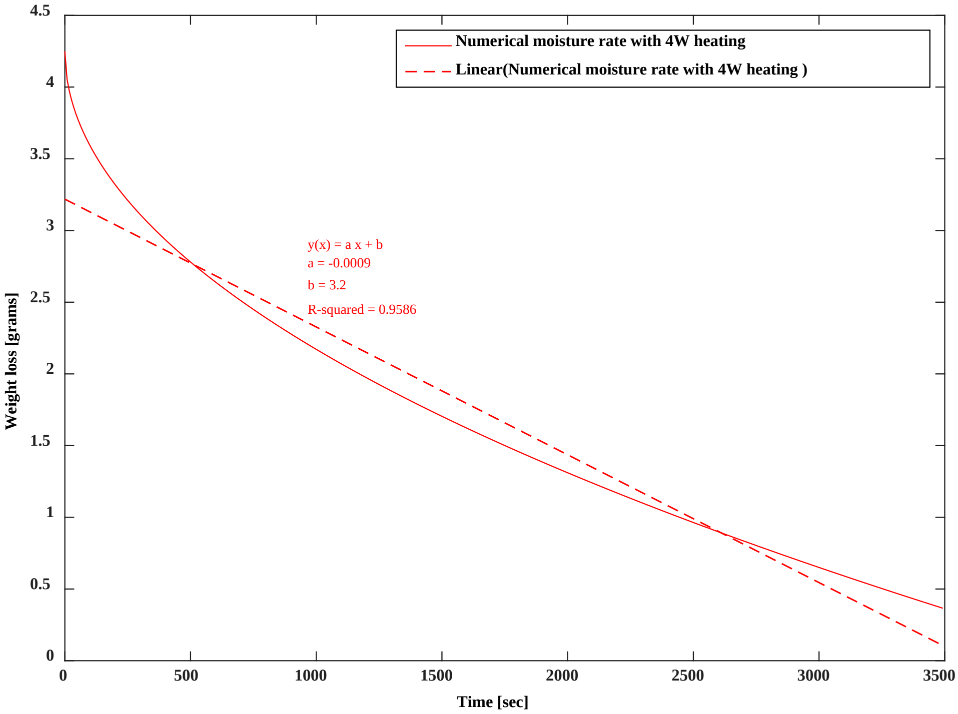


Figure 6.4.5.1.2: The results of moisture transfer and its evaporation in AMMS with six heater elements generating four watts of heat energy calculated by using the mathematical model

6.4.5.2 Experimentation on the test rig

In this section, procedure utilized in chapter 3 was used to test the larger AMMS sample on the test rig. Fabric and other parameters used in this test are the same as ones used for numerical modelling in section 6.2 above. The results are displayed below;

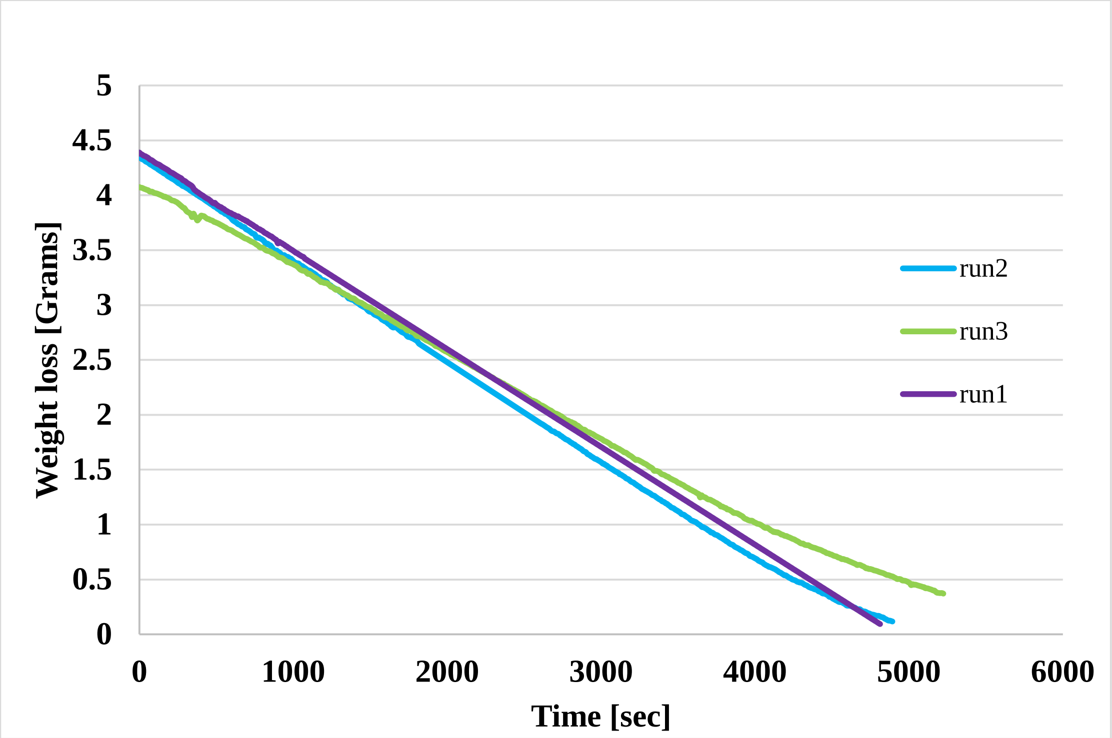


Figure 6.4.5.2.1: The results of moisture transfer and its evaporation in spacer structure knitted with 2 yarn ends and 2 tucks tested by using the test rig

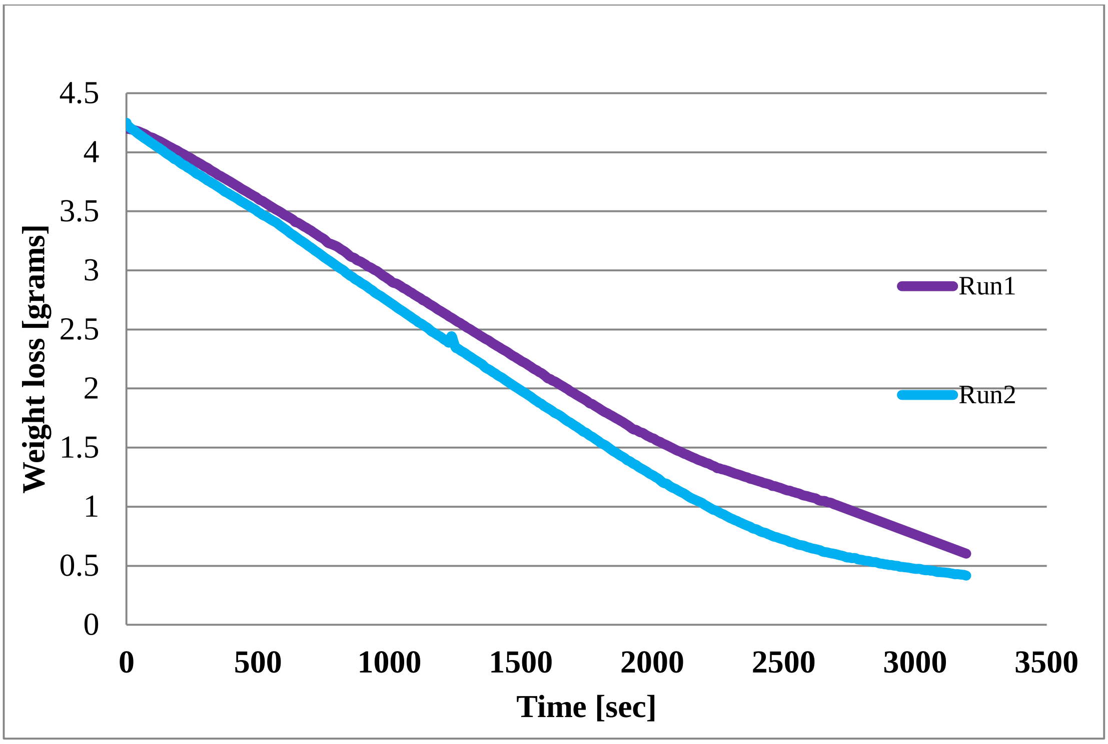


Figure 6.4.5.2.2: The results of moisture transfer and its evaporation in AMMS with six heater elements generating four watts of heat energy tested by using the test rig

6.4.5.3 Comparison of model and experimental results

This section compares results produced from both numerical and experimental investigation of the larger technical fabric. This is important to see the effectiveness of the model and test rig as well.

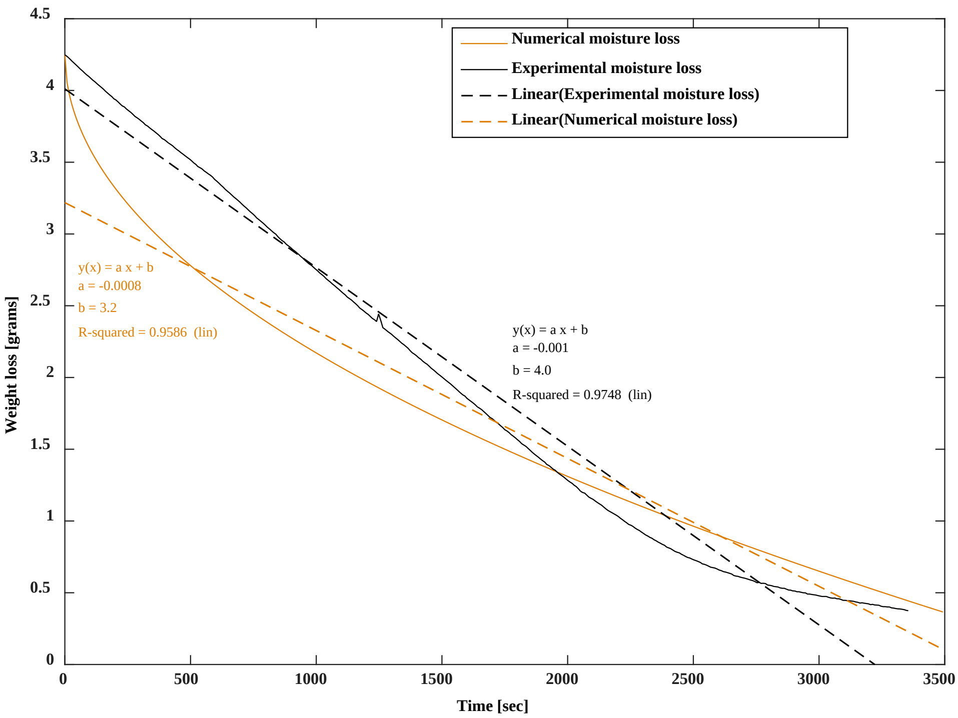


Figure 6.4.5.3.1: Comparison of model and experimental results with heating at 4W

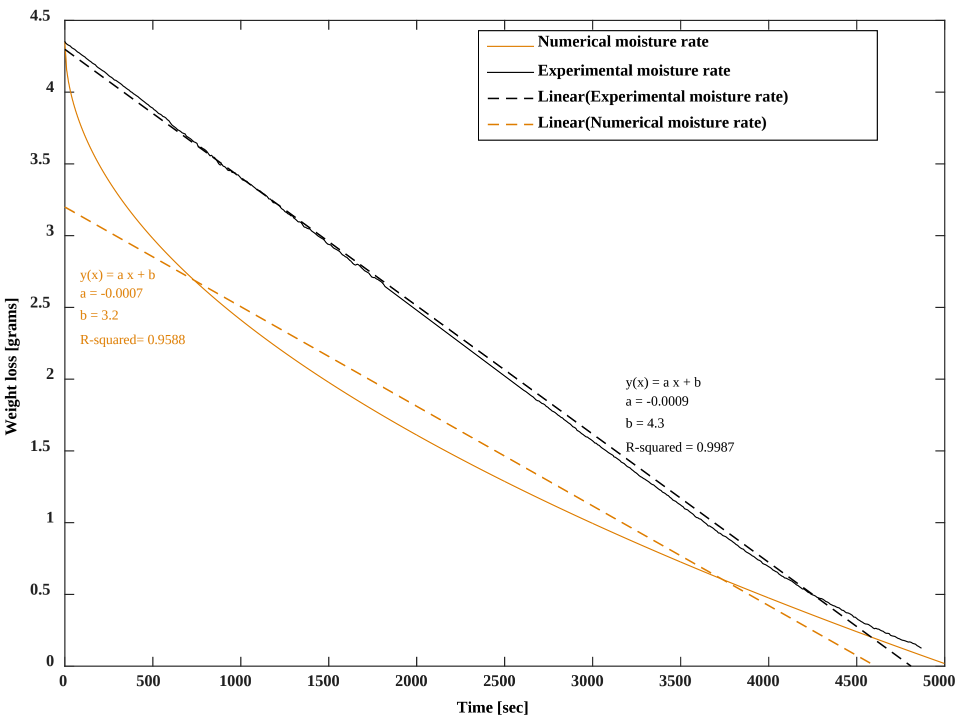


Figure 6.4.5.3.2: Comparison of model and experimental results without heating

Moisture transmission of AMMS with embedded heaters was conducted to study its properties. Figures 6.4.5.1.1 and 6.4.5.1.2 shows simulated results of the fabric with and without 4W heating effect respectively. Results showed that heating effect improved the moisture transmission up to 30% per area of sample. This improvement was also observed in chapter 4 where similar test was conducted on different type of spacer fabrics. This shows that heating has substantial effect on the pressure difference between the two sides of the fabric and improves the moisture drive across by enhancing the capillary action in the fabric. Another test was conducted by using the designed test rig (also used on chapter 3) to determine the moisture transmission rate with and without heating effect of 4W. Results are illustrated on figures 6.4.5.2.1 and 6.4.5.2.2. They are in correlation with simulated results above as this can be seen on figure 6.4.5.3.2 where model results were compared with experimental results.

6.5 Chapter summary

This chapter discussed in detail the design rules for the AMMS fabric and its manufacturing process. This included the merge of KSS and heating effect. The mathematical model created in chapter 3 was used to examine the number of heater elements to be used together with the amount of heating to be generated. It was found that 4W of input power was sufficient to operate 6 heater elements of 11.5 x 11.5cm AMMS fabric. Experimentation on the AMMS was performed and it showed reliable results. Among the tests conducted were moisture absorption, temperature rise, moisture wettability and wash tests. Mathematical model simulation of the fabric was performed and was found to be in line with experimental results. After determining the core areas of the AMMS, next step was to upscale and develop a full size garment integrated with heater elements. This is discussed in the next chapter.

Chapter 7

7.0 Development of Active Moisture Management Garment

7.1 Introduction

The purpose of the chapter is to elucidate the design and manufacture of an active moisture management garment with the Advanced Moisture Management Structure (AMMS). The new scientific knowledge created within the research detailed in previous chapters, led to the development of AMMS, which is the main structure of the garment.

7.2 Design and manufacture

The focus was to design an outdoor garment, and the factors that needs to be considered are concise below. Generally, outdoor garments should keep the wearer warm and dry. At high levels of activity, the human body removes excess heat by sweating and the sweat has to travel through the textile of the garment before it could evaporate to the atmosphere. The knitted spacer structure, which is the basic structure of AMMS can transfer the sweat through the knitted structure due to wicking. In a spacer structure this is due to capillary action of the fibre filling between the two fabric layers, which is influenced by the hydrostatic pressure difference between the two outer fabric layers. The research reported in the previous chapter of the thesis has demonstrated that the above hydrostatic pressure in a knitted spacer structure can be enhanced by creating a temperature gradient between its two fabric layers. The transfer of the sweat away from the skin will keep the wearer dry and the use of heater elements to create a temperature gradient in AMMS would keep the wearer warm, thus providing a dual function.

The human body releases sweat, which is produced by sweat glands, through the skin to be evaporated into the atmosphere. The sweat evaporates by absorbing heat energy from the human body resulting in the cooling of the body in order to maintain the core body temperature. Smith and Havenith(Caroline J. Smith, 2011) report the dynamics of sweat production in the human body and its distribution across the body during sport activities. Their research has demonstrated that the sweating in human body is mostly concentrated on to the front and rear of the upper body. However, the posterior and anterior sweat distribution is different. Further it showed that, in both anterior and posterior sweat rates differ at various body training intensity levels. Some parts produces more sweat than others and body mapping to illustrate this was created based on male athletes. From this research(Weiner, 1944, Caroline J. Smith, 2011), an outdoor garment design is based on and this represents upper part of the human body as this area has more sweat producing region.

Reflecting on the above an active jacket was designed with AMMS by using computerised flat-bed knitting technology.

The temperature gradient required for the proper functioning of AMMS is created with heater elements and these were placed on high sweat production areas of the body according to findings of Smith and Havenith research, which is shown in figure 7.2.1 below.

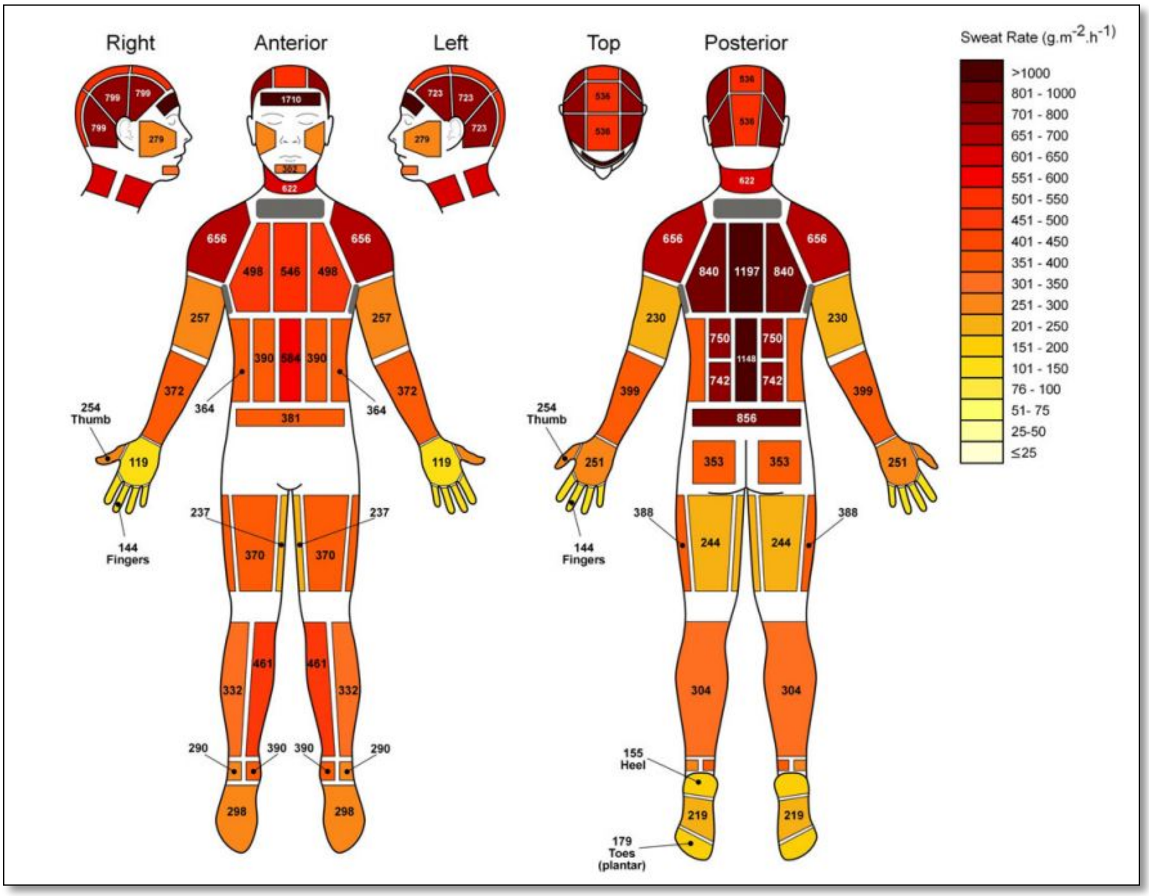


Figure 7.2.1: Distribution of sweat of the upper body in male athletes(Caroline J. Smith, 2011)

The active garment was designed in two parts, i.e. the front and rear panels, see figure 7.2.2 and figure 7.2.3. The two panels were then joined together by using conventional knitwear make-up techniques. The sizing of the active outdoor jacket was based on international standard clothing size small, i.e. chest size: 91-96cm.

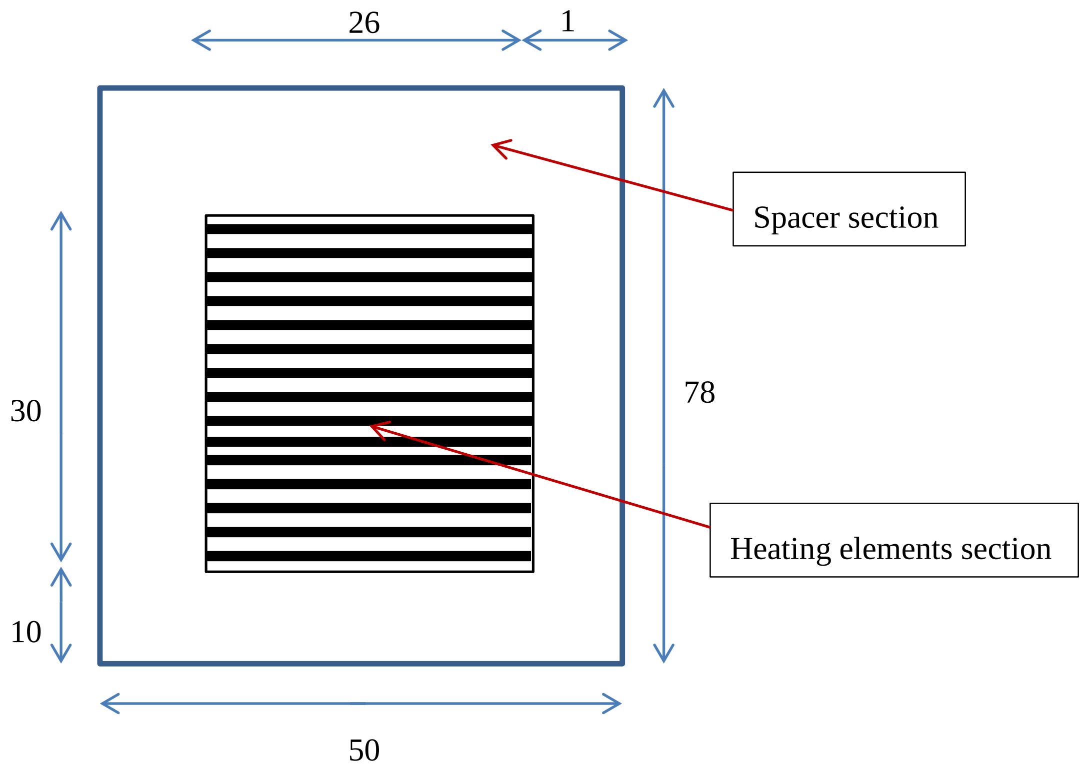


Figure 7.2.2: Design details of the knitted front panel of the active outdoor jacket, size small; all dimensions are in centimetres

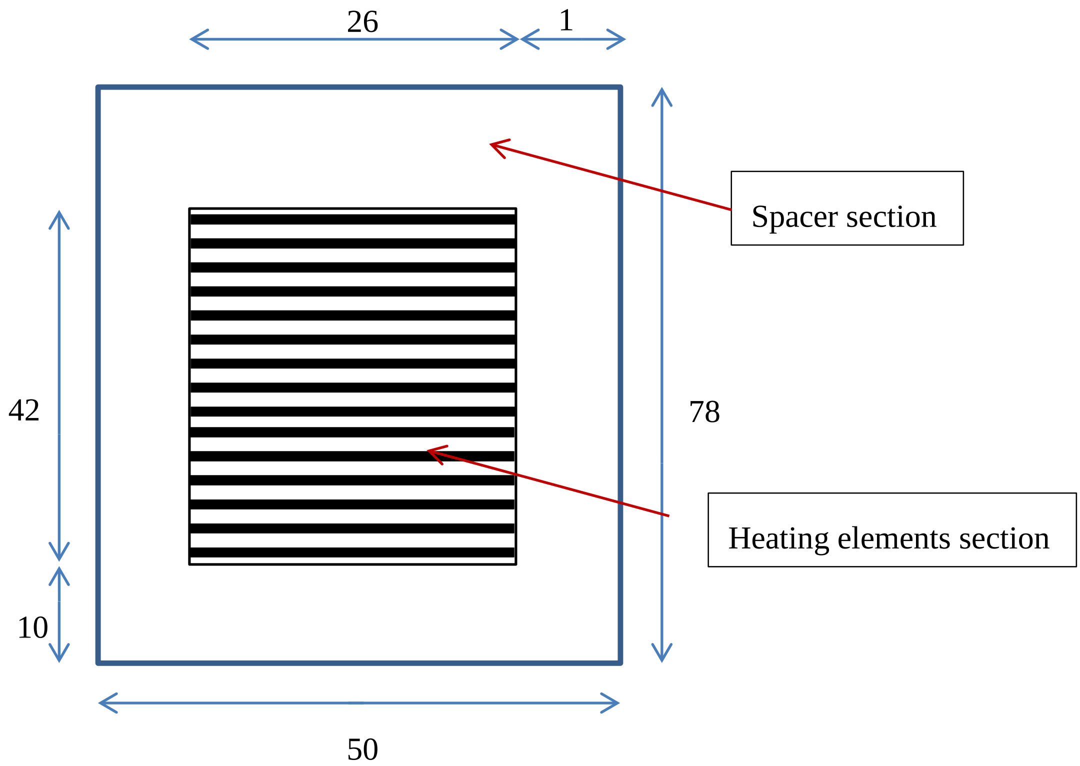


Figure 7.2.3: Design details of the knitted back panel of the active outdoor jacket, size small; all dimensions are in centimetres

The heating elements section of the above figures incorporates narrow size type (26.0 x 0.5 cm) with each space 1.0 cm apart. The connecting bus bars were made from thin filament copper yarns as described in chapter 4.

An example of the rear knitted panel of the active outdoor garment is shown in Figure 7.2.4 below;

Figure 7.2.4: Knitted rear panel of the active outdoor garment

The next step after knitting both panels was to design how to connect the bus-bars of the heating elements to the power supply. Both the knitted panels consist of heating areas and have been designed with their bus-bars terminating at the left and right hand side of each panel; this is illustrated in figure 7.2.5;

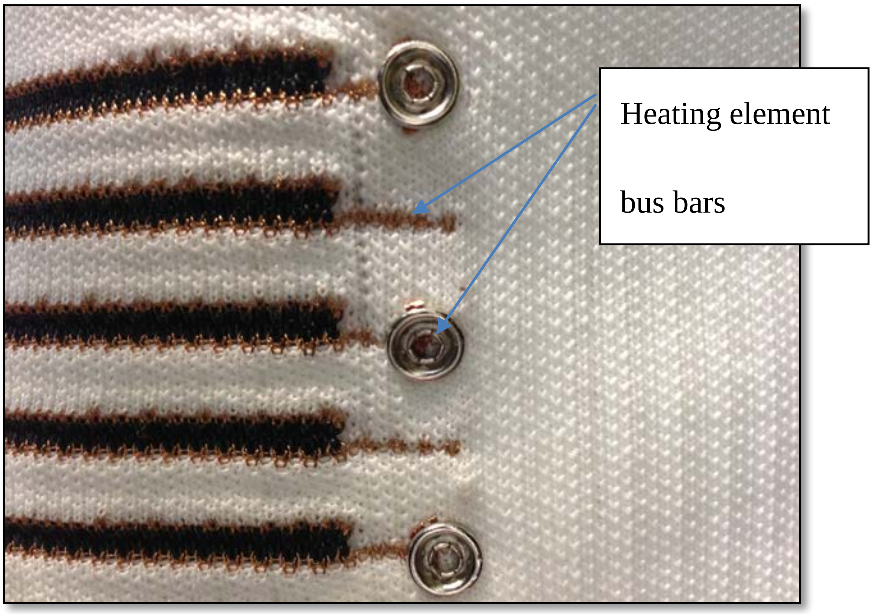


Figure 7.2.5: Image showing heater elements connecting bus bars

The active outdoor garment has to be designed so that all heating elements could be powered from a single power source. Two different methods were investigated; firstly, standard wire of gauge 2.0mm used in electronic industry was stripped of its insulation to expose 50mm length of nickel plated copper conductors at equal distance of 35mm. The exposed conductors was then attached to the bus-bars of the heating elements by using press studs, see figure 7.2.6. These stud connections were sufficient to power the heating elements and also provided robust mechanical connection with the knitted panel.

Figure 7.2.6: An image of an AMMS panel with the bus-bars of heater elements connected with an electrical wire

The second method was to use a wire made of 48 strands of 0.2mm fine copper conductors. The copper conductors were then covered with a circular warp knitted structure made of four 167dtex polyester yarns. The 48 copper strands were sufficient to power all 56 (26 front and 30 back) heating elements of an AMMS panel. Combining 48 strands of copper would have 2 significant advantages; first to provide less current resistance and allow efficient heat on the heater elements. 48 copper filaments had equivalent resistance to allow max of 3A as standard wire used in industry. Secondly, was the amount of yarns inside the polyester covering to allow press studs to establish a reliable connection more copper was required. As figure 7.2.8 shows due to more number of copper filaments, some are exposed and this kept the press studs connected to the inner copper filaments. The covering of the 48 strands copper wire achieved with a RIUS machine, model MC. RIUS is a knit braider machine consisting of 4 knitting needles and revolving disc to implement braiding movement. The copper conductors were delivered to the needles of the machine in a manner that it is positioned in the middle of the circular warp knitted structure (figure 7.2.7).

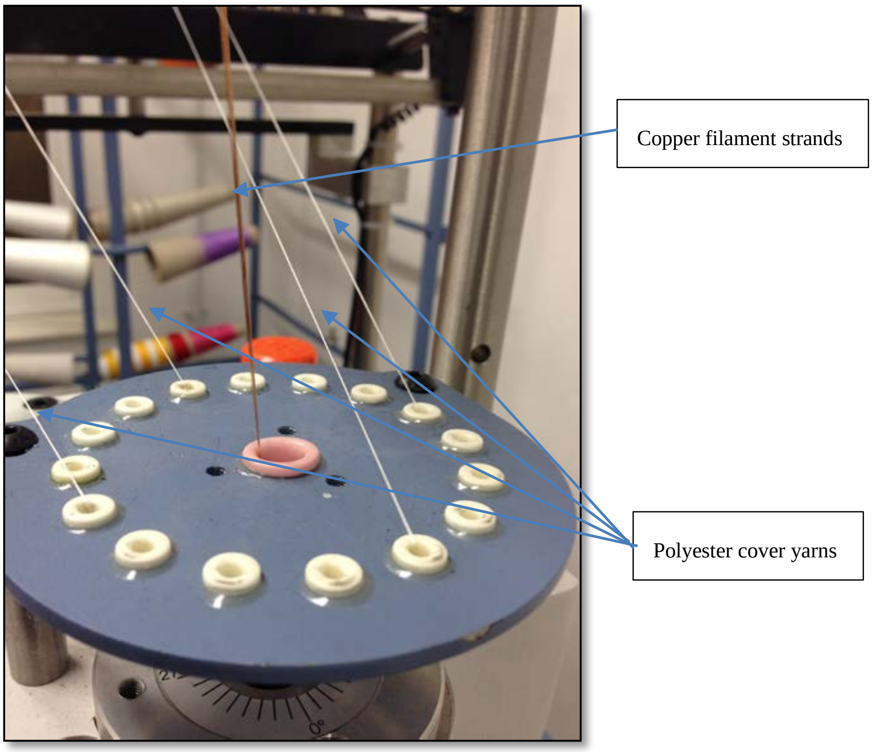


Figure 7.2.7: The delivery of copper conductors and polyester yarn in RIUS machine, MC

An image of the resultant conductive yarn is shown in figure 7.2.8. This conductive yarn was more flexible compared to the wire used in electrical industry, and was wound on to a package for easy handling.

Figure 7.2.8: Conductive yarn made from 48 copper conductors and polyester yarn

The new conductive yarn was attached with press studs to the bus-bars adopting the same procedure described earlier to connect the bus-bars with a standard electrical wire see figure 7.2.9. The main advantage of the second method is that it provided more flexible way of connecting the bus-bars of the heating elements in a manner that they can be powered with two central power lines.

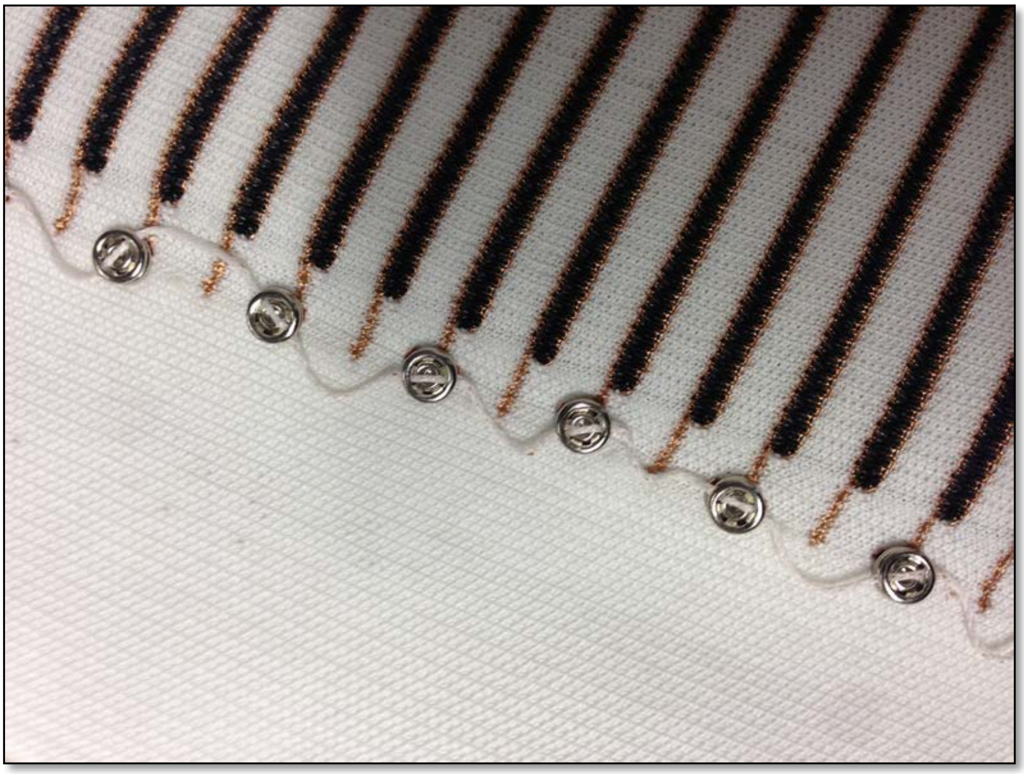
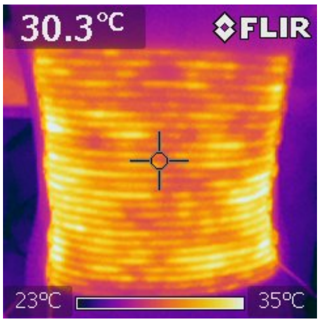
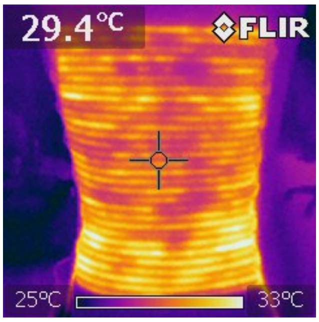


Figure 7.2.9: An image of an AMMS panel with the bus-bars of heater elements connected with the new conductive yarn

After connecting the bus-bars of the heater elements the panels were tested for their heating performance by using a laboratory bench power supply. The results are summarised in Table 7.2.1 below

Table 7.2.1: Heating performance of AMMS panels

Sample	Resistance [Ohms]	Voltage [V]	Current [A]	Thermal image

Front panel	0.89	5.1	5	
Rear panel	0.92	5.1	5	

The AMMS panels were then shaped by cutting them according to the standards, defined for a small size garment, to create the front and the back panel of the active outdoor garment. The shaped panels were then joined to produce the final jacket. The figures 7.2.11, 7.2.10 and 7.2.12 demonstrate the front, rear and side views of the active outdoor jacket.

Figure 7.2.10: Rear view of AMMS garment

Figure 7.2.11: Front view of AMMS garment

Figure 7.2.12: Side view of AMMS garment

7.3 AMMS garment user trial

Etienne Stot, Team GB's Canoeist Gold medallist at London 2012 Olympics, tested the AMMS garment technology during his training in cold conditions. Comfortable, reliable heat and fit for purpose was among the feedback received from Etienne. He recommended that, the technology have a substantial future in providing active fabrics for application in sports activities. Figure 6.3.1 below shows Etienne wearing the AMMS garment during his visit to NTU-ATRG with Dr. Brian Cunniffe of the English Institute of Sport.

Figure 7.3.1: AMMS garment as tested by Olympic Gold Medallist, Etienne Stot(NTU-ATRG, 2015)

7.4 Chapter summary

This chapter was concerned with the design and manufacture of AMMS garment with integrated heater elements. This together would be essential to provide quick moisture absorption and drying capabilities of the fabric. Different techniques were used in the design including the heater elements size and numbers together with their specific location. It was found according to literature; areas that showed high moisture generation were the front and back top parts of the human body. Heating efficiency of the fabric was also tested and showed predicted temperature on the heating elements. Electrical system on the fabric was the challenging part but different ways and connection were discussed and flexible power connection was obtained and using press-studs; provided the connection to the heater elements.

Chapter 8

8.0 Summary and Conclusions

8.1 Exclusive summary

The motivation of the research informed in the thesis the development of an advanced outdoor garment which is capable of rapid transfer of sweat generated by the human body to the outer surface of the garment and its quick evaporation. An in depth survey of the literature was carried out, in order to identify the existing knowledge base and the current gaps in knowledge on moisture transfer in textiles as moisture management fabrics are widely used to enhance wearer's comfortability and protection in outdoor garments. This study demonstrated, clearly, that the focus of all research in the area of moisture transfer and management in textiles has been to enhance the hydrostatic pressure difference in a textile structure by modifying the surface characteristics of fibres, the use of multiple layers of fabrics and using fabric finishing processes. This led to focus the research into the study of creating a temperature gradient across a knitted spacer structure in order to enhance the moisture transfer in the structure.

As the first step a preliminary investigation of applying heat on to a knitted spacer structure was carried out to test the new concept. As the results were very encouraging a mathematical model was formulated to study how the creation of a temperature gradient in a knitted spacer structure would improve moisture transfer in the spacer structure. The mathematical equations were solved using Matlab software to simulate the moisture transfer in knitted spacer structures. The results of the simulations indicated that the use of heating could improve the moisture rate on an 11.5 x 11.5 cm^2 knitted spacer structure up to 30%.

A new experimental test equipment was designed and built to validate the mathematical models, and later to analyse the knitted spacer structures developed later in the research, the new test rig can be used to test samples under different environmental conditions.

The results of the simulations led to the development of an active moisture management structure (AMMS) consisting of a knitted spacer structure and heating elements. . The MK GAT system was used to determine the moisture absorption rate, and the new test rig was utilised to measure the moisture transmission across different knitted spacer structures. The knitted spacer structure constructed with 2 spacer yarn ends and 2 tucks of yarns between the two fabric layers of the structure was found to be the most effective.

Knitted heating elements were also studied and integrated into the knitted spacer structures to create AMMS. The heating elements were designed based on the patented Thermoknit technology in which carbon loaded silicon yarn (FabRoc) is used as heating material, and copper yarn made of multiple copper wires of 0.2 mm were used to form the bus-bars of the heating elements. It was found that narrow heating elements of 0.5 mm height provided an effective and reliable heating effect. This design has an advantage of having reliable heating effect and has less effect the moisture absorbency of the knitted spacer structure. Integration of heating elements onto the spacer structure was studied and optimised.

Integration of heating elements onto the spacer fabric was studied and was found that, placing them at the inner side of the cover which will be closest to the skin will provide necessary hydrostatic pressure gradient required to influence moisture transfers process across the garment.

8.2 Conclusions

Moisture management textiles development have been at the forefront of science and engineering research. Better ways to improve moisture handling by textiles have been introduced in recent years. These include studies in fibre science; fabric membranes with controlled pore-size-distribution; and fabric layering techniques involving separate layer moisture-handling characteristics. This PhD project takes this improvement to a higher level with the following key contributions to knowledge;

- The introduction of heat into one of the fabric layers becomes an important addition as active control of moisture flow between layers of the fabric is introduced. Active control of moisture transfer enables textiles to perform actively and not passively. Passive technology in textiles is reported to have limits, as variation of external conditions occurs, and this imparts a feel of discomfort to the textile wearer. Thus active systems developed in the project could be useful in this context, as these mean that textiles can be designed to be intelligent. This stretches the limits of performance even at extreme and changing conditions.
- The project provided a key knowledge of the way in which moisture transmission across the spacer structure could be enhanced by addition of heater elements onto one layer of the knitted, spacer structure. Heater elements placed on the inner side of the spacer structure would help improve hydrostatic pressure difference between the two sides of the spacer structure. The knitted, spacer structure forms micro channels in the middle layer which act as capillaries with two different pressures created on the two, outer fabric layers. This new knowledge also introduces a new way for studying and understanding knitted spacer structures both numerically and experimentally. The mathematical model developed in the

project provides a platform to study and understand knitted spacer structure moisture transmission whilst performing at two contrasting environmental conditions. This is useful as performance of the knitted structure can be studied and understood prior to production. Experimentally, the project introduced a test system following the principle adopted in the mathematical model to study moisture transmission of knitted, spacer structures. This is a cost-effective test system, which would enable textile structures, not only spacer structures, to be studied under the influence of the two environmental conditions.

- The development of this new knowledge opened new ways to manufacture and develop textile structures. The project's key technology of using computerised, flat-bed knitting to integrate heater elements into spacer structures led to development of design rules for combining both heater elements and spacer structures into one. This process opened up new techniques and designs of heater elements, spacer structures and their manufacturing techniques. The development of flat-bed knitting technology was helpful. This versatile fabric manufacturing system enabled different heater-element structures and spacer structures to be produced.

The research created an extensive understanding of moisture transfer in knitted spacer structures by using heat to control the hydrostatic pressure difference. This extends textile research further, making textiles more useful and dependable in our day-to-day lives.

8.3 Future progress for the research

The main principle of the research was the application of capillary mechanism for heat assisted moisture transfer in knitted spacer fabric by application of heat on the inside layer of the KSS. Heat was applied to maintain the hydrostatic pressure difference across the two sides of the KSS. By this, moisture transfer would be improved even at varying outside environment conditions which previously would hinder moisture movement from the inner layer due to less driving force.

The next major progress for the research could be the introduction of inbuilt sensors which would be useful in monitoring the state of inner and outside conditions and for this, would determine the extent of heating required to support moisture movement across the KSS. This eventually would also allow heating rate to be applied intermittently and only during application. This would help to reduce heat build-up in the inner layer which might cause discomfort to the wearer. A novel technology is been carried out to try and include micro sensing into the yarns and this would provide easy integration into the KSS with heating capabilities. NTU-ATRG are on the for front on this technology (NTU-ATRG, 2015) and could be applied to provide the necessary inclusion into the KSS.

Another improvement on the project would be the study of heating system location on the KSS. In the project, mathematical modelling and experimental test were carried out with heat system located on the inner layer of KSS with the principle mechanism to increase inner capillary pressure to drive moisture to the outer side (which is having lower capillary pressure). This could be studied further by placing the heating system on the outer layer of the KSS. This would create a moisture pulling effect apart from pushing effect used in the project. It will be interesting to see how the two processes coalesce and improve moisture transfer rate. This could provide moisture transfer by increasing the evaporation rate on the outer layer of the KSS and would encourage more moisture from the inner layer to migrate to the outer layer of the KSS.

The scope of the project was limited to the way into which heat is used to enhance the hydrostatic pressure difference between the sides of the knitted spacer fabric in order to improve moisture transmission. The heat applied to one part of the KSS was assumed to influence only the hydrostatic pressure difference. The major future investigation could be the study this heating effect might impact to the human body during its operation. Because heating is applied during high sweat activities, this stage would comprise high skin temperatures due to high muscle actions so the study could be used to investigate if heating on one side of the KSS might affect the skin temperature. Also connected to this is the study, of heat released by the body if could be used to improve the hydrostatic pressure difference between the sides of the KSS. This will enable the process to be self-sufficient as no external heating would be required and just the heat released by the body due to sweating could be used to improve sweat removal to the outer environment.

8.4 Problems encountered during the research

In any research sometimes difficulties may arise during the process and in the project there are some problems that require to be addressed;

The heating elements used in the fabric constituted of FabRoc yarn. This was made by mixing together silicone and carbon materials. Manufacturing process would determine the overall resistance of the yarn and any variations in the manufacturing process would affect the electrical properties of the yarn. This variation was experienced in the variation of resistance of yarn at various length points and this would affect electrical conductivity and eventually heating effect. More refined yarn is needed in this so as to sharpen and reduce irregularities in resistances of yarns and improve heating effect.

The bus bars of heating elements used copper as the conductive medium. Copper is more efficient and comprises of lower electrical conductivity. However, as the fabric is designed to handle liquid moisture it means copper could get contaminated. Chemically, copper would react with moisture which is believed to possess similar properties as water, and copper (ii) ions would be generated indicated by bluish deposits on the fabric. This would eventually be washed off but more work should be done to prevent this bluish formation on the fabric. Similar effects of copper is oxidation. This is the reaction with atmospheric oxygen. Oxidation would cause copper to reduce its electrical conductivity and affect heating in a long run.

Manufacturing of the AMMS has to be improved as well. Different kind of yarns are required depending on the design of the garment. The main ones are FabRoc, copper and elastomeric. FabRoc yarn is elastic in nature and would require extremely care during manufacture to prevent breakage. During the project process FabRoc yarn breakage was experienced. This would be because of high tension induced during knitting process. Improvement to avoid this has been done by using special yarn delivery systems which tries to distribute tension between the yarn package and feeder, but more needs to be done. Breakages were encountered with copper yarn during knitting. Three strands of copper yarns was used in the manufacture of garment due to the effectiveness of electrical conductivity. Problems ware encountered when only one strand was used to knit on the machine.

In testing of fabrics some problems were encountered. Moisture absorption of fabric was one of the key tests conducted by using a MK Gats system. This equipment required the fabric samples to be placed on top of the porous plate for absorption to occur. The issue was the contact between the fabric sample and the porous plate as reported by Saeed(Saeed, 2006). The fabric had less contact to the plate and this affected absorption rate as it took longer due to less contact area. This problem was improved by using a counterbalance force on top of the sample. A wire mesh placed on top of the sample would ensure maximum contact of the sample to plate and this would provide true absorption effect. More improvement has to be focused to produce effective counterbalance weight/force to further produce reliable and true results of the test samples.

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Appendix 1: Matlab code for KSS6T2E

```
Clear
%Hot chamber air properties
TempIN=310;                    %Inside temperature [K]
RHin=0.25;                     %Inside humidity
PressAirIN=101350;             %Inside air pressure [Pa]

%Cold chamber air properties
TempOUT=280;                   %Outside temperature [K]
RHout=0.75;                    %Outside humidity
PressAirOUT=101350;            %Outside air pressure  [Pa]

%Fabric properties
b=0.420;          %Fabric thickness  [cm]
L=10;             %Fabric length   [cm]
w=8;              %Wales per cm
c=11;             %Courses per cm
s=6;              %Number of needle spaces between two tuck needles
rows=6;           %Number of spacer yarns within one repeat
DenF=1.4;         %Density of fibre  [g/cm3]
Crimp=0.291;      %Yarn crimp
Tex=33.4;         %Count of spacer yarn
NF=96;            %Number of filaments
```

```
A=100;                 %Fabric area 10 X 10  [cm2]
Por=0.55;              %Porosity of fabric
MassWet=8.685;   %Initial weight of Moisture  [g]

%Water properties
Theta=75;              %Contact angle   [degrees]
SurfT=0.072;           %surface tension   [N/m]
ViscW=8.9e-4;          %Viscocity of water [Pa.s]

DenW=1000;                     %Density of water   [kg/m3]
SG=(DenF*1000)/DenW;       %Specific gravity

%Heating effect
QIN=0;
QOUT=0;
h=200;                 %Heat transfer coefficient [W/m2K]

TempINsf=TempIN+(QIN/(h*((A/4)/10000)));
TempOUTsf=TempOUT+(QOUT/(h*((A/4)/10000)));

%Capillary radius calculation
AA=(b*s)/w;
BB=(b^2)+((s^2)/(w^2));
CC=rows*c;
EE=1/(1-Crimp);
```

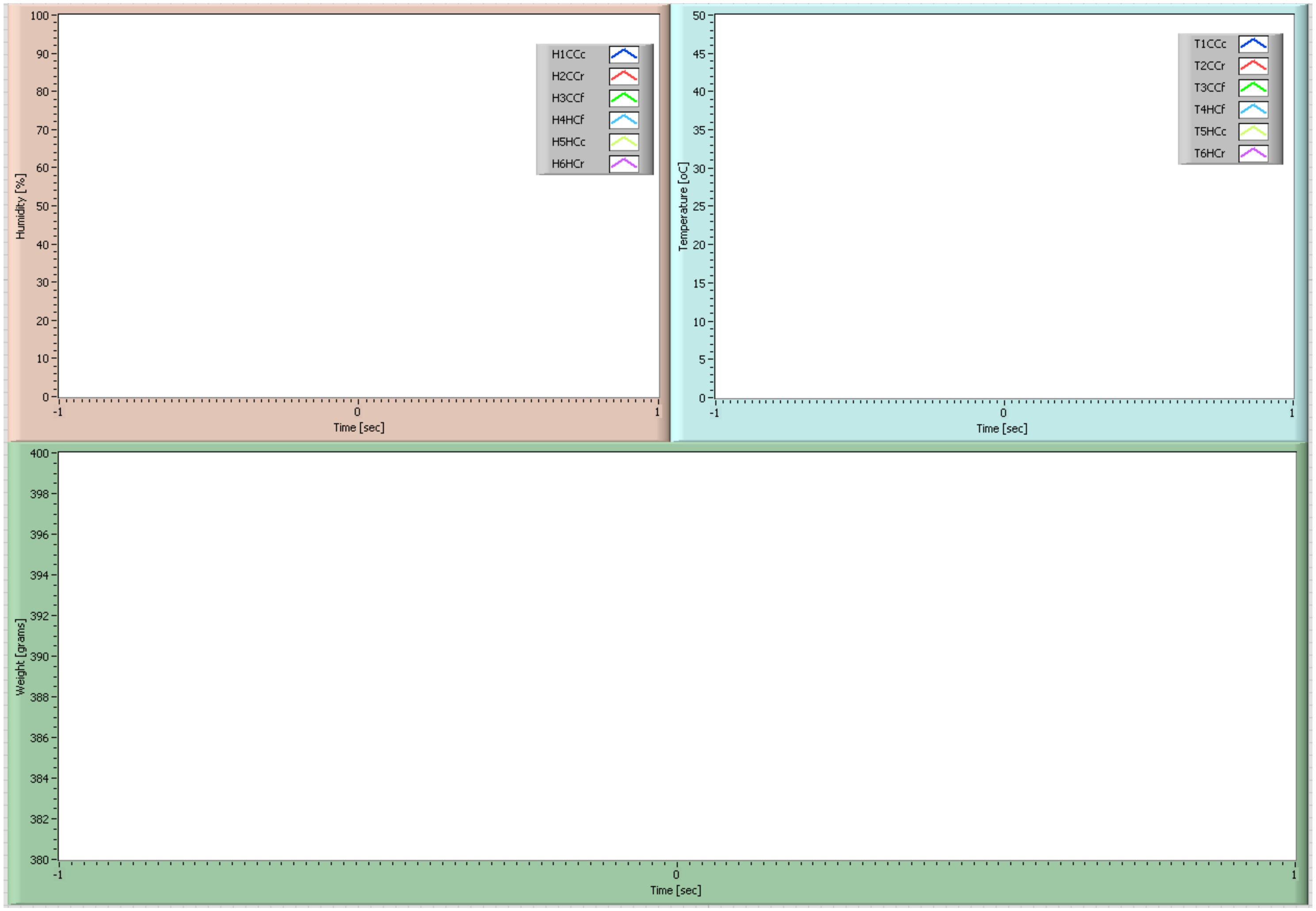
```
PP=(CC*sqrt(BB*EE))/(10^5);

QQ=NF*CC*3.14*sqrt(BB);

r=(sqrt((AA-((PP*Tex)/DenF))/QQ))/100;


%Capillary pressure

PressCAP=(2*SurfT*cosd(Theta))/r;


%Saturation pressure: Arden Buck equation

 %surrounding environment

    PsatINsurr=(6.1121*exp((18.678-(TempIN-273)/234.5)*(TempIN-273)/(257.14+(TempIN-273))))*100;

    PsatOUTsurr=(6.1121*exp((18.678-(TempOUT-273)/234.5)*(TempOUT-273)/(257.14+(TempOUT-273))))*100;


%Surface environment

 if TempINsf==TempIN

       PsatINsurf=0;

   else

    PsatINsurf=(6.1121*exp((18.678-(TempINsf-273)/234.5)*(TempINsf-273)/(257.14+(TempINsf-273))))*100;

   End

if TempOUTsf==TempOUT

       PsatOUTsurf=0;

   else

    PsatOUTsurf=(6.1121*exp((18.678-(TempOUTsf-273)/234.5)*(TempOUTsf-273)/(257.14+(TempOUTsf-273))))*100;
```

```
    end

%Vapor pressure
      %Surrounding environment
     PressVAPinSurr=RHin*PsatINsurr;
     PressVAPoutSurr=RHout*PsatOUTsurr;
  %Surface environment
     PressVAPinSurf=RHin*PsatINsurf;
     PressVAPoutSurf=RHout*PsatOUTsurf;
 %Total pressure
PressTin=PressVAPinSurr+PressVAPinSurf+PressAirIN+PressCAP;
PressTout=PressVAPoutSurr+PressVAPoutSurf+PressAirOUT;

%Change in pressure
 DeltaPress=PressTin-PressTout;

%Calculation of liquid rise
phi=atand((b*w)/s);            %Cappilary angle of inclination
K=((r^2)*DeltaPress*sind(phi)/(8*ViscW));
Time=0:4:9000;
H=(sqrt(K*Time));

%Total mass of liquid take up by capillary
%L in cm as assumption in the mathematical modelling
 Mw=3.14*NF*(r^2)*DenW*H*1000*L;
```

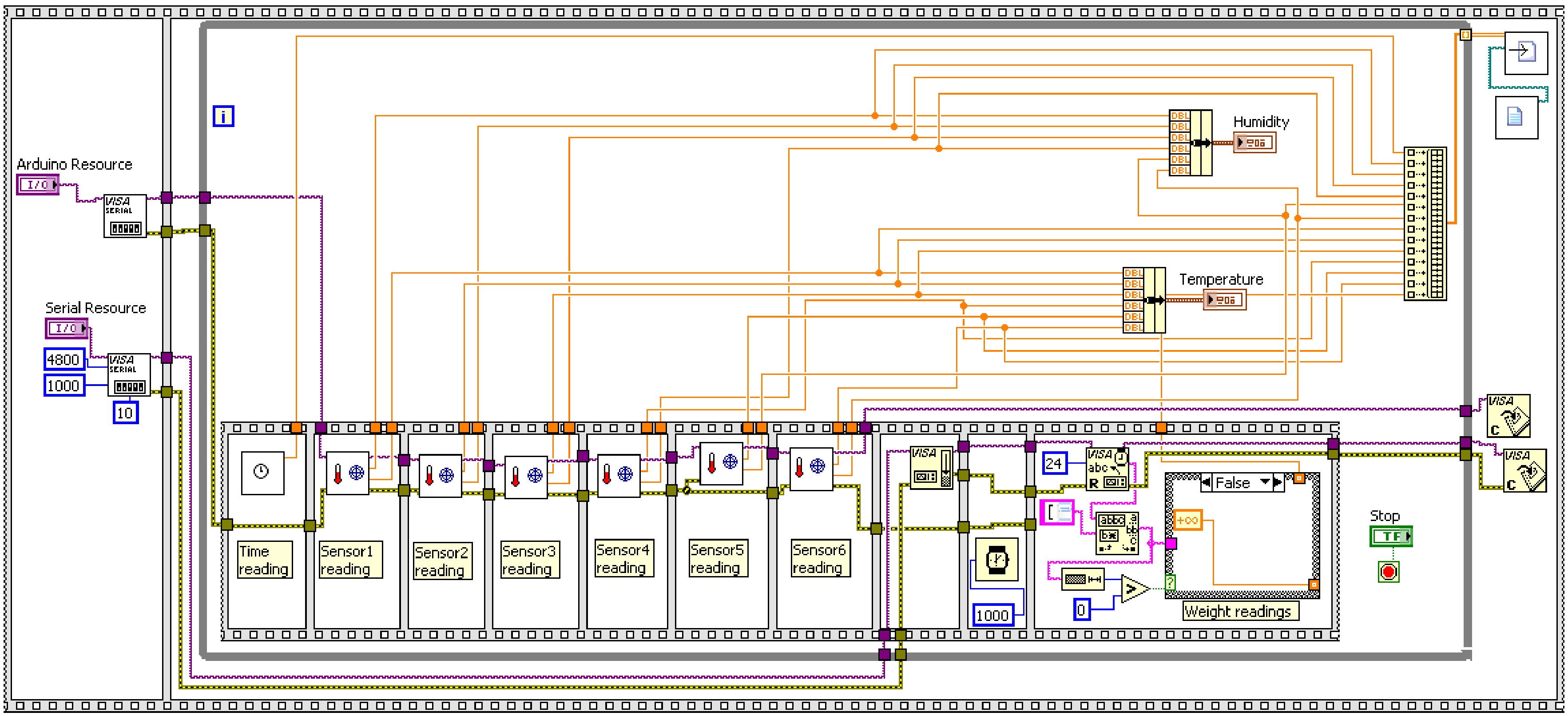
```
%Total mass transmitted
massMOD=MassWet-Mw;
```

Appendix 2: LabVIEW Data acquisition program

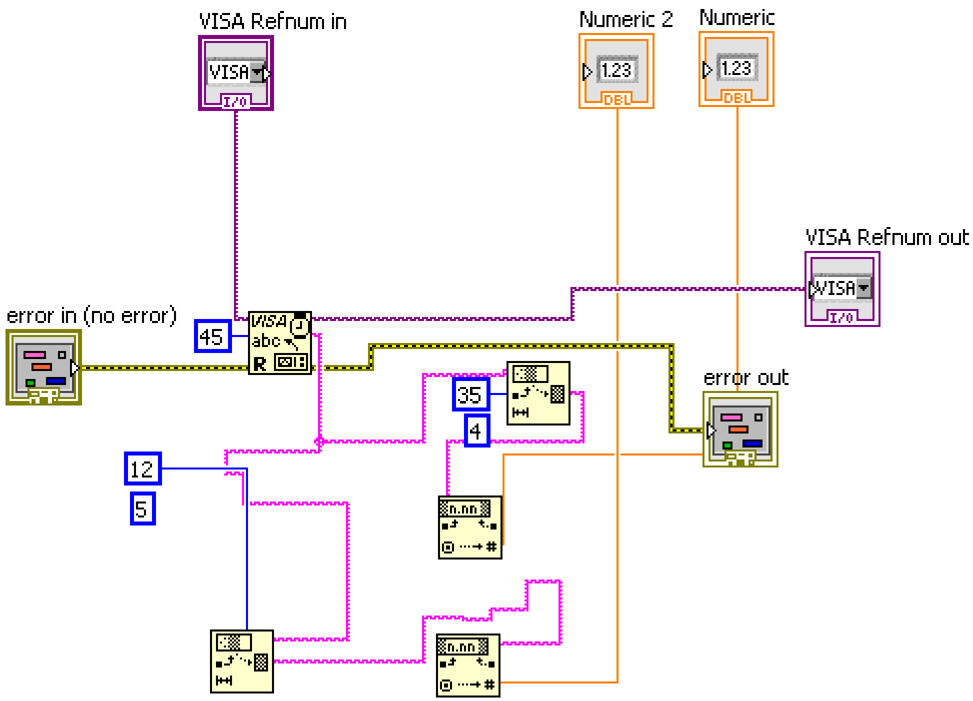
Part A: Front panel



Part B: Block Diagram



Part C: Humidity and Temperature sensor sub VI



Appendix 3: Arduino nanoV3 code

```
//Start

#include "DHT.h"

// Pin connections assignment

#define DHTPIN1 2

#define DHTPIN2 3

#define DHTPIN3 4

#define DHTPIN4 5

#define DHTPIN5 6

#define DHTPIN6 7

// Sensor type definition

#define DHTTYPE DHT22   // DHT 22  (AM2302)

// Connect pin 1 (on the left) of the sensor to +5V

// Connect pin 2 of the sensor to whatever your DHTPIN is

// Connect pin 4 (on the right) of the sensor to GROUND

// Connect a 10K resistor from pin 2 (data) to pin 1 (power) of the sensor

DHT dht1(DHTPIN1, DHTTYPE);

DHT dht2(DHTPIN2, DHTTYPE);

DHT dht3(DHTPIN3, DHTTYPE);

DHT dht4(DHTPIN4, DHTTYPE);

DHT dht5(DHTPIN5, DHTTYPE);

DHT dht6(DHTPIN6, DHTTYPE);

void setup() {

  Serial.begin(9600);
```

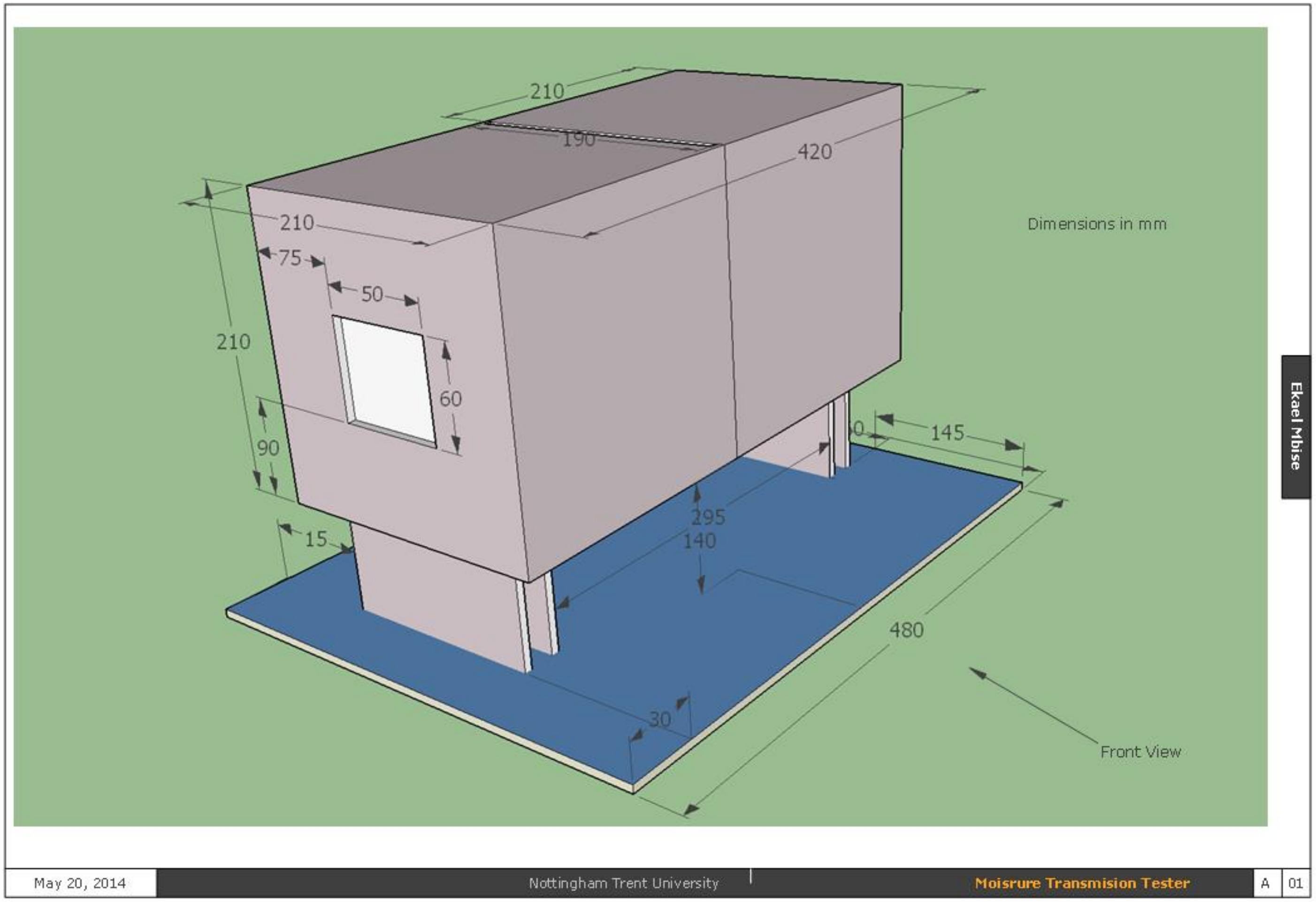
```
  //Serial.println("DHTxx test!");
  dht1.begin();
  dht2.begin();
  dht3.begin();
  dht4.begin();
  dht5.begin();
  dht6.begin();
}
void loop() {
  // Temperature and Humidity readings
  // Reading temperature or humidity takes about 250 milliseconds!
  delay(5000);                          // Initial time delay
  float h = dht1.readHumidity();
  float t = dht1.readTemperature();

  float h2 = dht2.readHumidity();
  float t2 = dht2.readTemperature();

  float h3 = dht3.readHumidity();
  float t3 = dht3.readTemperature();

  float h4 = dht4.readHumidity();
  float t4 = dht4.readTemperature();

  float h5 = dht5.readHumidity();
```

```
  float t5 = dht5.readTemperature();


  float h6 = dht6.readHumidity();
  float t6 = dht6.readTemperature();
 // Temperature and Humidity display
// check if returns are valid, if they are NaN (not a number) then something went wrong!
  if (isnan(t) || isnan(h)) {
    Serial.println("Failed to read from DHT");
  }
  else {
    Serial.print("Humidity 1: ");
    Serial.print(h);
    Serial.print(" %\t");
    Serial.print("Temperature 1: ");
    Serial.print(t);
    Serial.println("*C");
    Serial.print("Humidity 2: ");
    Serial.print(h2);
    Serial.print(" %\t");
    Serial.print("Temperature 2: ");
    Serial.print(t2);
    Serial.println("*C");
    Serial.print("Humidity 3: ");
    Serial.print(h3);
    Serial.print(" %\t");
```

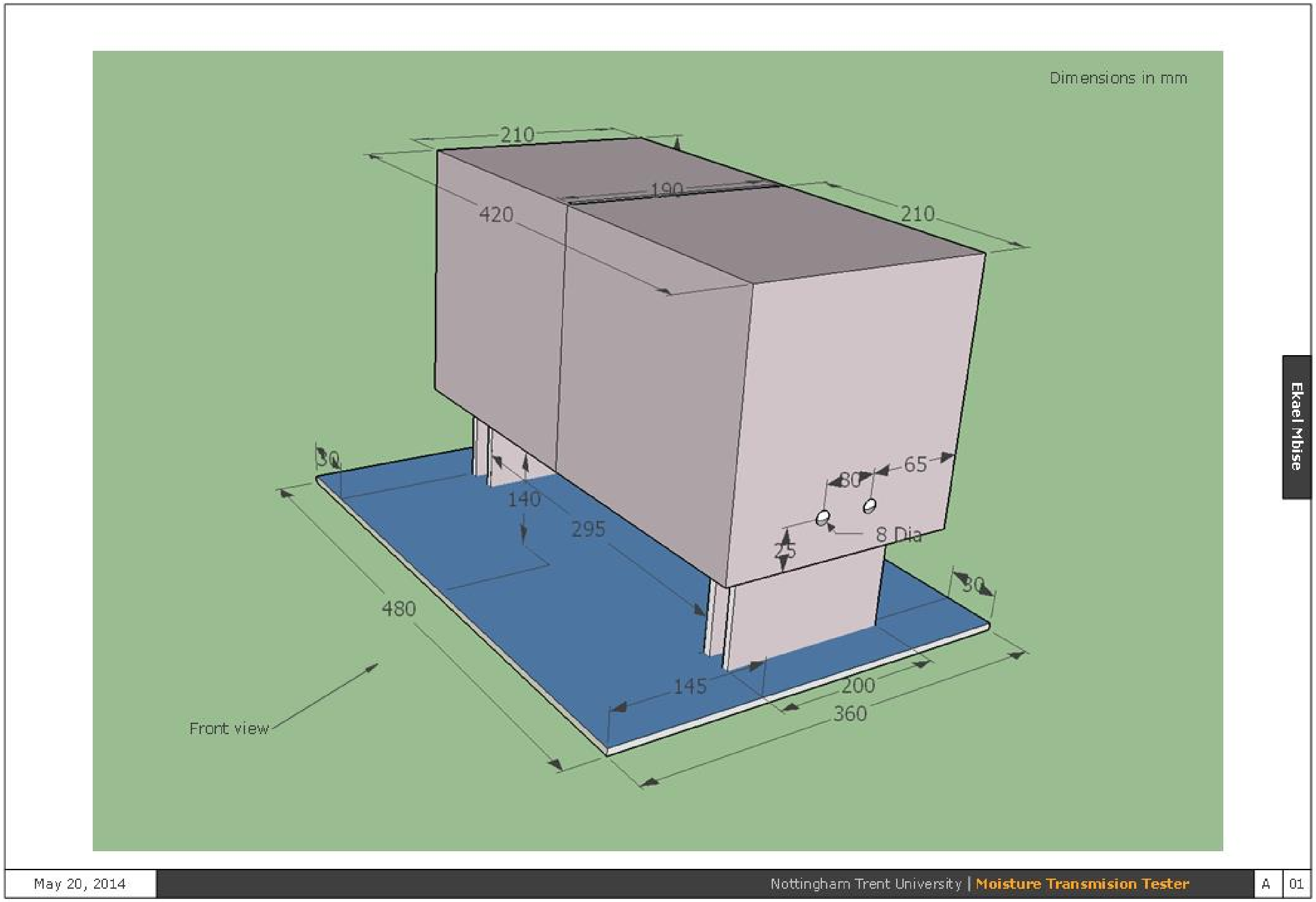
```
    Serial.print("Temperature 3: ");
    Serial.print(t3);
    Serial.println("*C");
    Serial.print("Humidity 4: ");
    Serial.print(h4);
    Serial.print(" %\t");
    Serial.print("Temperature 4: ");
    Serial.print(t4);
    Serial.println("*C");
    Serial.print("Humidity 5: ");
    Serial.print(h5);
    Serial.print(" %\t");
    Serial.print("Temperature 5: ");
    Serial.print(t5);
    Serial.println("*C");
    Serial.print("Humidity 6: ");
    Serial.print(h6);
    Serial.print(" %\t");
    Serial.print("Temperature 6: ");
    Serial.print(t6);
    Serial.println("*C");
  }
}
// Finish
```

Appendix 4: Moisture Transmission Tester Technical Drawings

A: View 1



B: View 2



Dimensions in mm
210
190
420
210
30
140
295
80
65
8 Dia
25
480
30
145
200
360
Front view
Ekael Mbise
May 20, 2014
Nottingham Trent University | Moisture Transmision Tester
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01

Appendix 5: Matlab code for AMMS fabric

```
clear

%Hot chamber air properties

TempIN=310;                    %Inside temperature [K]

RHin=0.25;                     %Inside humidity

PressAirIN=101350;             %Inside air pressure [Pa]


%Cold chamber air properties

TempOUT=280;                   %Outside temperature [K]

RHout=0.75;                    %Outside humidity

PressAirOUT=101350;            %Outside air pressure  [Pa]

%Fabric properties

b=0.15;                        %fabric thickness       [cm]
beff=50*b/100;                 %Effective Fabric thickness  [cm]
L=10;                          %Fabric length   [cm]
FW=10;                         %Fabric width    [cm]
HEw=0.5;                       %Heater elements width [cm]
Nh=6;                          %Number of heater elements
w=9;                           %Wales per cm
c=11;                          %Courses per cm
s=2;            %Number of needle spaces between two tuck needles
rows=2;         %Number of spacer yarns within one repeat
DenF=1.4;                      %Density of fibre  [g/cm3]
```

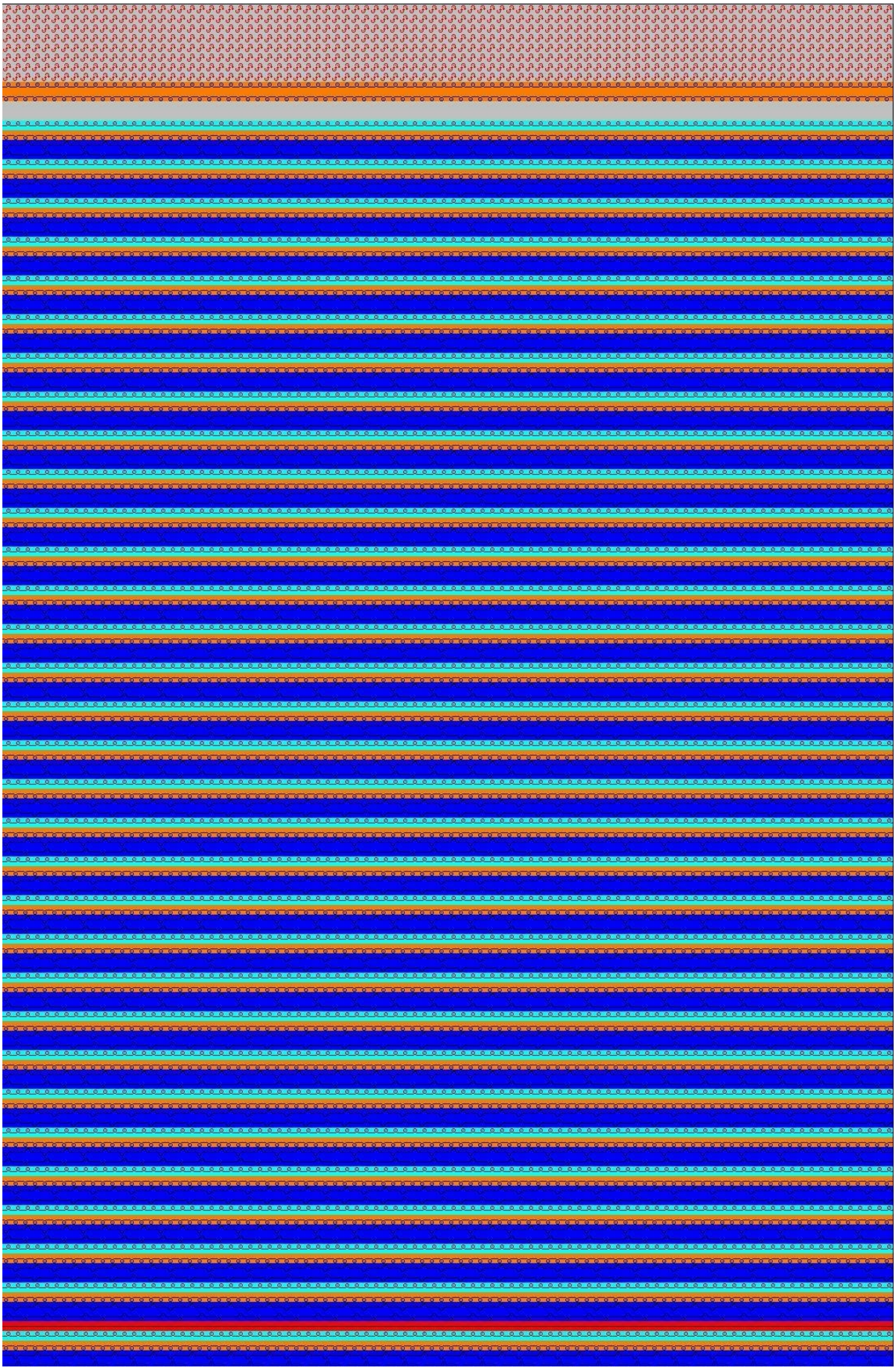
```
Crimp=0.291;                    %Fabric crimp
Tex=33.4;                       %Count of spacer yarn
NF=48;                          %Number of filaments
Por=0.55;                       %Porosity of fabric
MassWet=4.249;                  %Initial weight of Moisture  [g]

%Effective dimensions

if Nh==0
   Leff=L;
else
Leff=L-(HEw*Nh);
end

Aeff=Leff*FW;

%Water properties

Theta=75;                       %Contact angle   [degrees]
SurfT=0.072;                    %surface tension   [N/m]
ViscW=8.9e-4;                   %Viscosity of water [Pa.s]
DenW=1000;                      %Density of water   [kg/m3]
SG=(DenF*1000)/DenW;            %Specific gravity



%Heating effect

QIN=0;
QOUT=0;
 h=200;                         %Heat transfer coefficient [W/m2K]

if QIN==0 && QOUT==0;           %Effective heating area [cm2]
   Aht=1;             %Division by one to overcome zero divide by zero
```

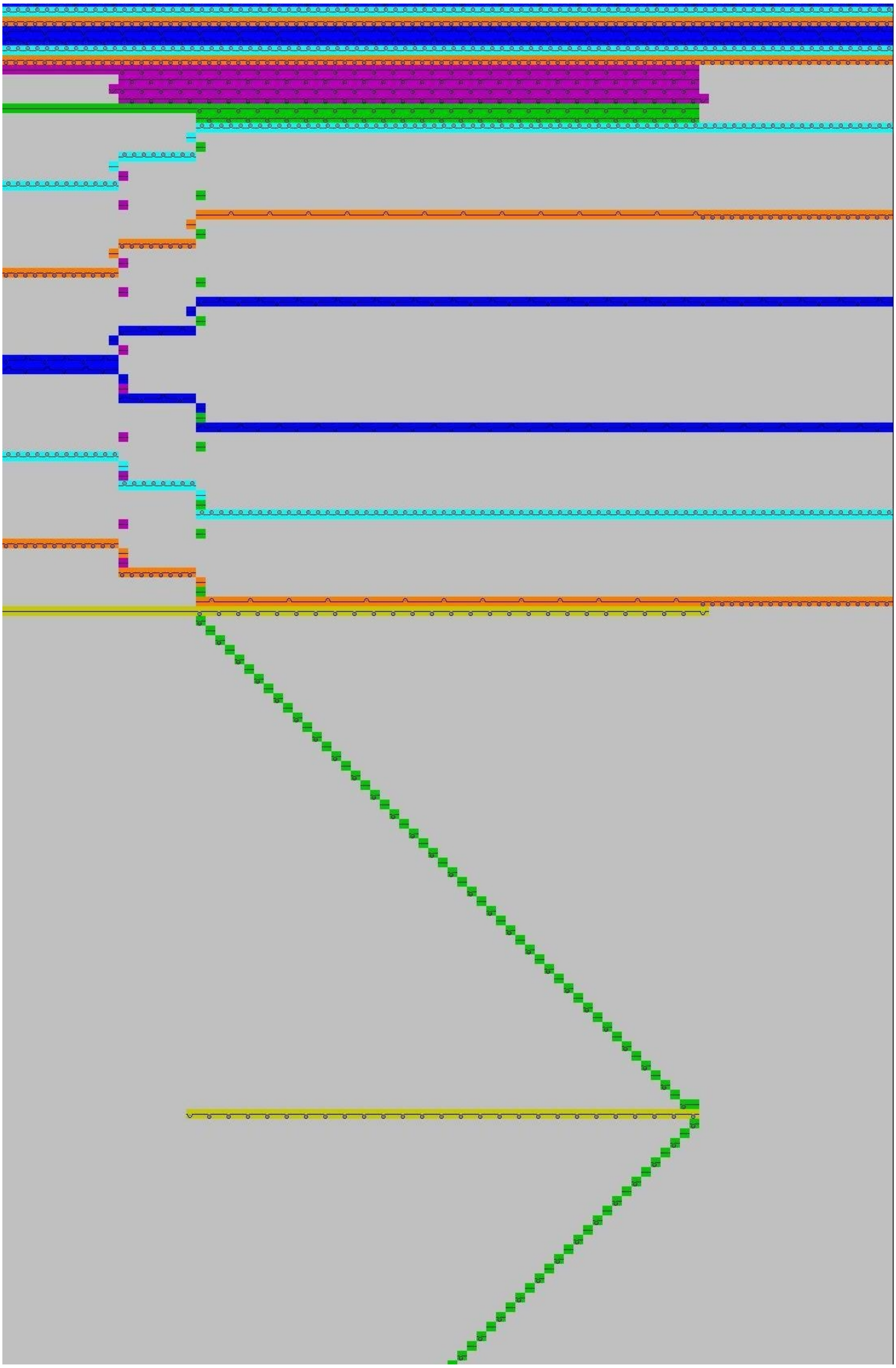
```
  else Aht=(L*FW)-Aeff;

end

TempINsf=TempIN+(QIN/((h*Aht)/10000));

TempOUTsf=TempOUT+(QOUT/((h*Aht)/10000));

 %Capillary radius calculation

AA=(beff*s)/w;

BB=(beff^2)+((s^2)/(w^2));
CC=rows*c;
EE=1/(1-Crimp);
PP=(CC*sqrt(BB*EE))/(10^5);
QQ=NF*CC*3.14*sqrt(BB);

r=(sqrt((AA-((PP*Tex)/DenF))/QQ))/100;


%Capillary pressure

PressCAP=(2*SurfT*cosd(Theta))/r;

%Saturation pressure: Arden Buck equation
   %Surrounding environment

     PsatINsurr=(6.1121*exp((18.678-(TempIN-273)/234.5)*(TempIN-
273)/(257.14+(TempIN-273))))*100;


     PsatOUTsurr=(6.1121*exp((18.678-(TempOUT-273)/234.5)*(TempOUT-
273)/(257.14+(TempOUT-273))))*100;
```

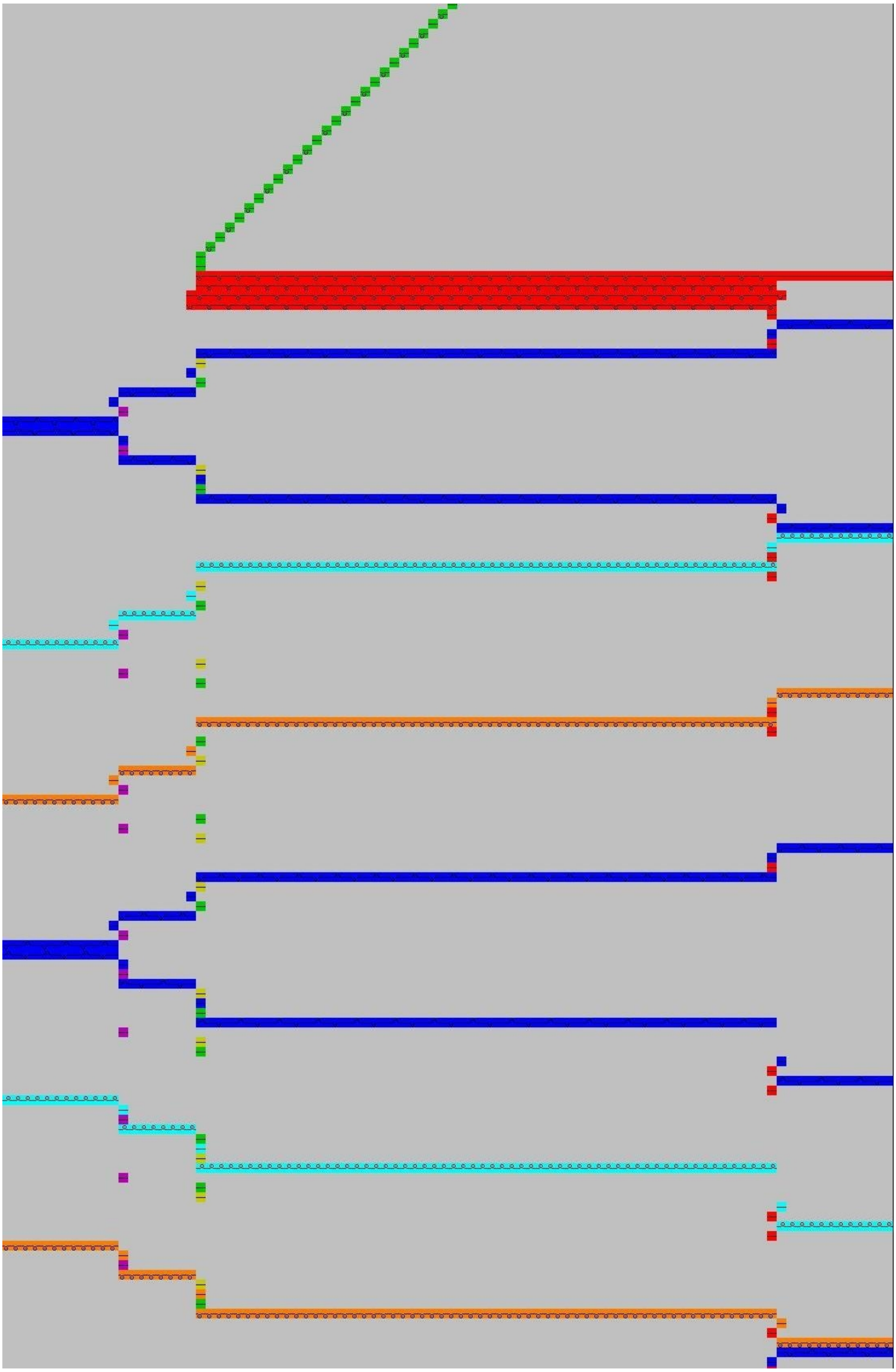
```
  %Surface environment

   if TempINsf==TempIN
      PsatINsurf=0;
   else
    PsatINsurf=(6.1121*exp((18.678-(TempINsf-273)/234.5)*(TempINsf-
273)/(257.14+(TempINsf-273))))*100;
   end

   if TempOUTsf==TempOUT
      PsatOUTsurf=0;
   else
    PsatOUTsurf=(6.1121*exp((18.678-(TempOUTsf-273)/234.5)*(TempOUTsf-
273)/(257.14+(TempOUTsf-273))))*100;
   end

%Vapour pressure
  %Surrounding environment

    PressVAPinSurr=RHin*PsatINsurr;

    PressVAPoutSurr=RHout*PsatOUTsurr;

  %Surface environment

    PressVAPinSurf=RHin*PsatINsurf;

    PressVAPoutSurf=RHout*PsatOUTsurf;

%Total pressure

PressTin=PressVAPinSurr+PressVAPinSurf+PressAirIN+PressCAP;
```

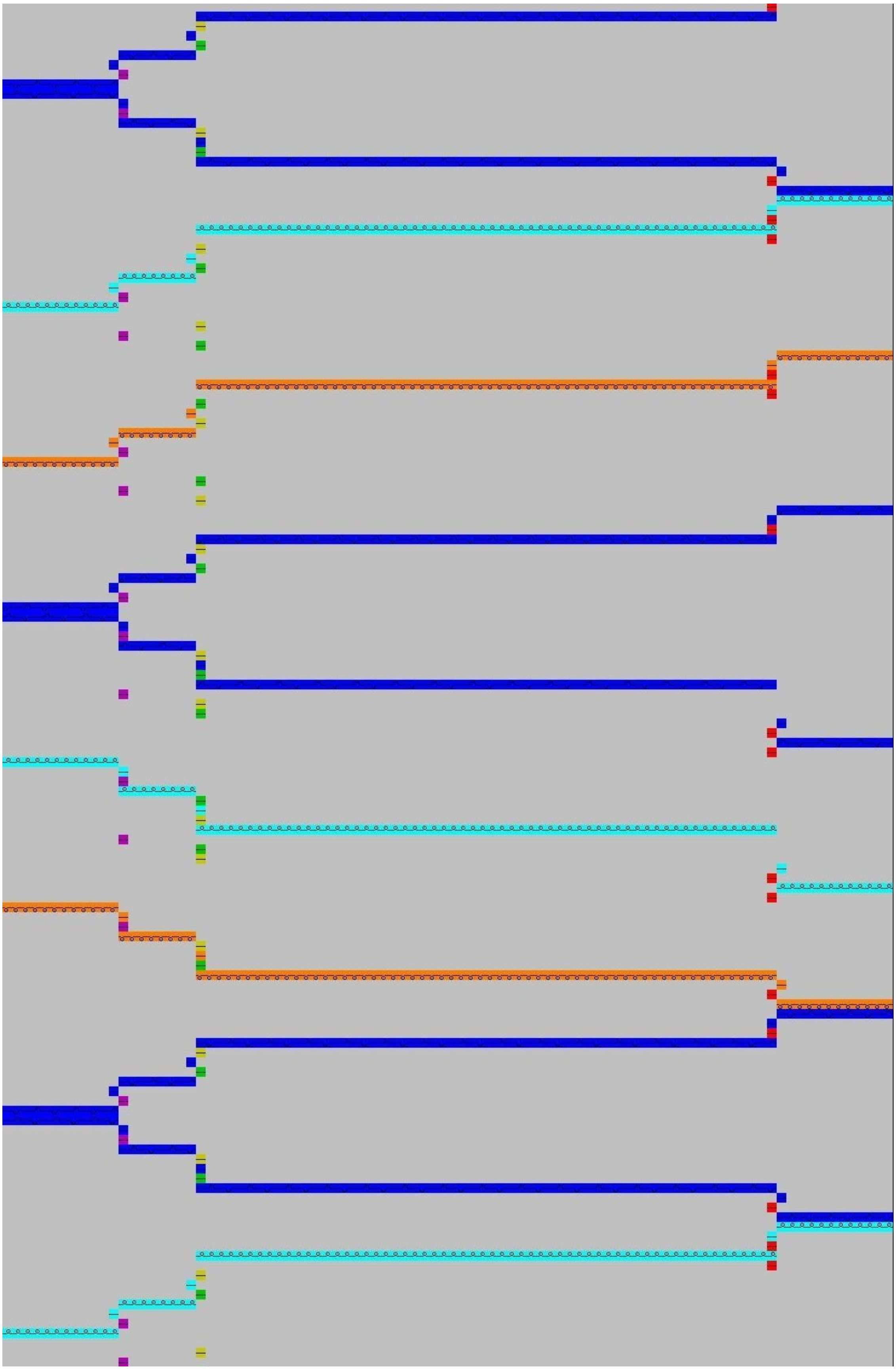
```
PressTout=PressVAPoutSurr+PressVAPoutSurf+PressAirOUT;


%Change in pressure

DeltaPress=PressTin-PressTout;

%Calculation of liquid rise

phi=atand((beff*w)/s);              %Capillary angle of inclination

 K=((r^2)*DeltaPress*cosd(phi)/(8*ViscW));

Time=0:8.71:5000;
 H=(sqrt(K*Time));

%Total mass of liquid take up by capillary

Mw=3.14*NF*(r^2)*DenW*H*1000*Leff;

%Total mass transmitted

massMOD=MassWet-Mw;
```

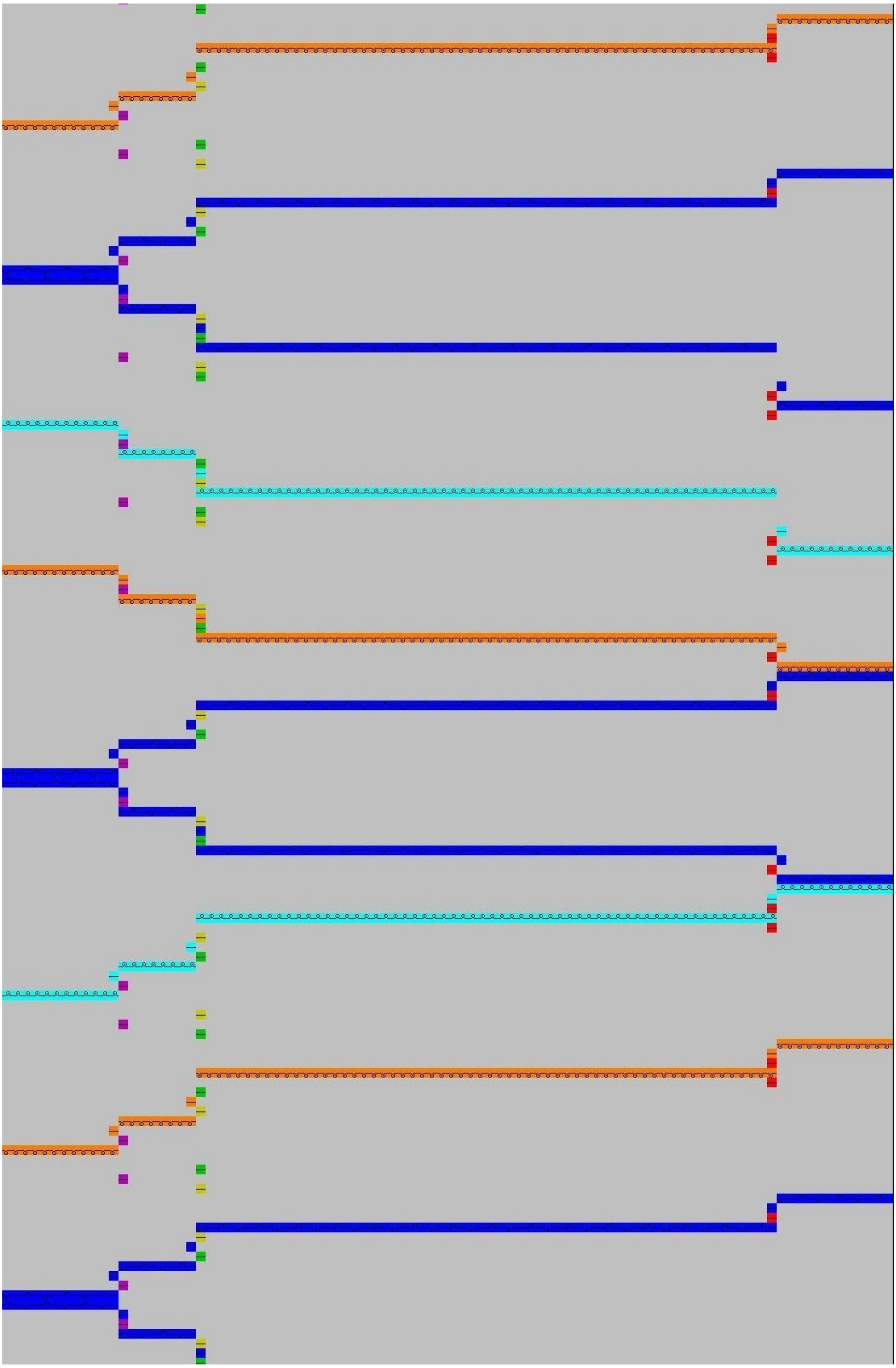
Appendix 6: AMMS fabric CAD program

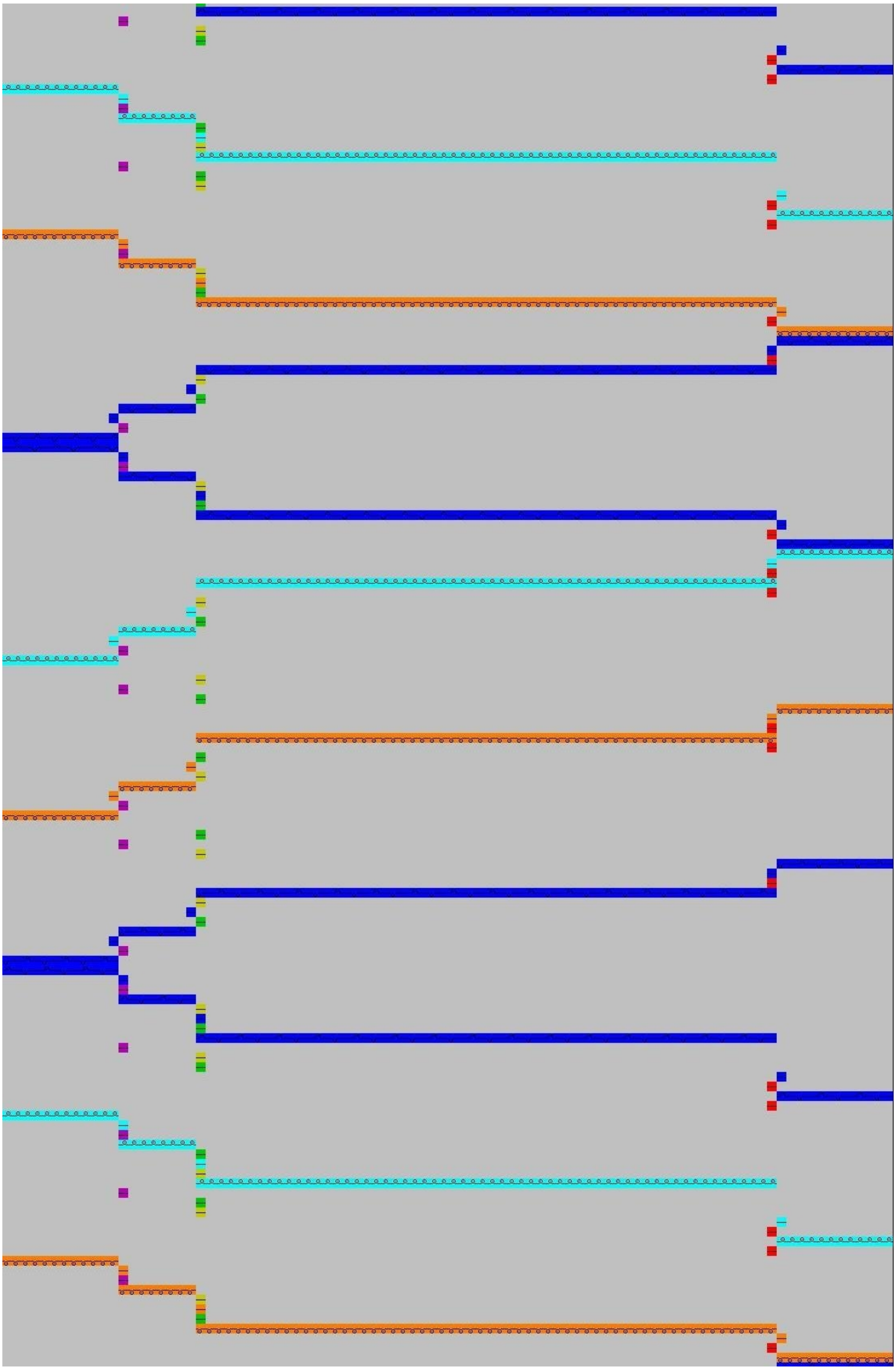


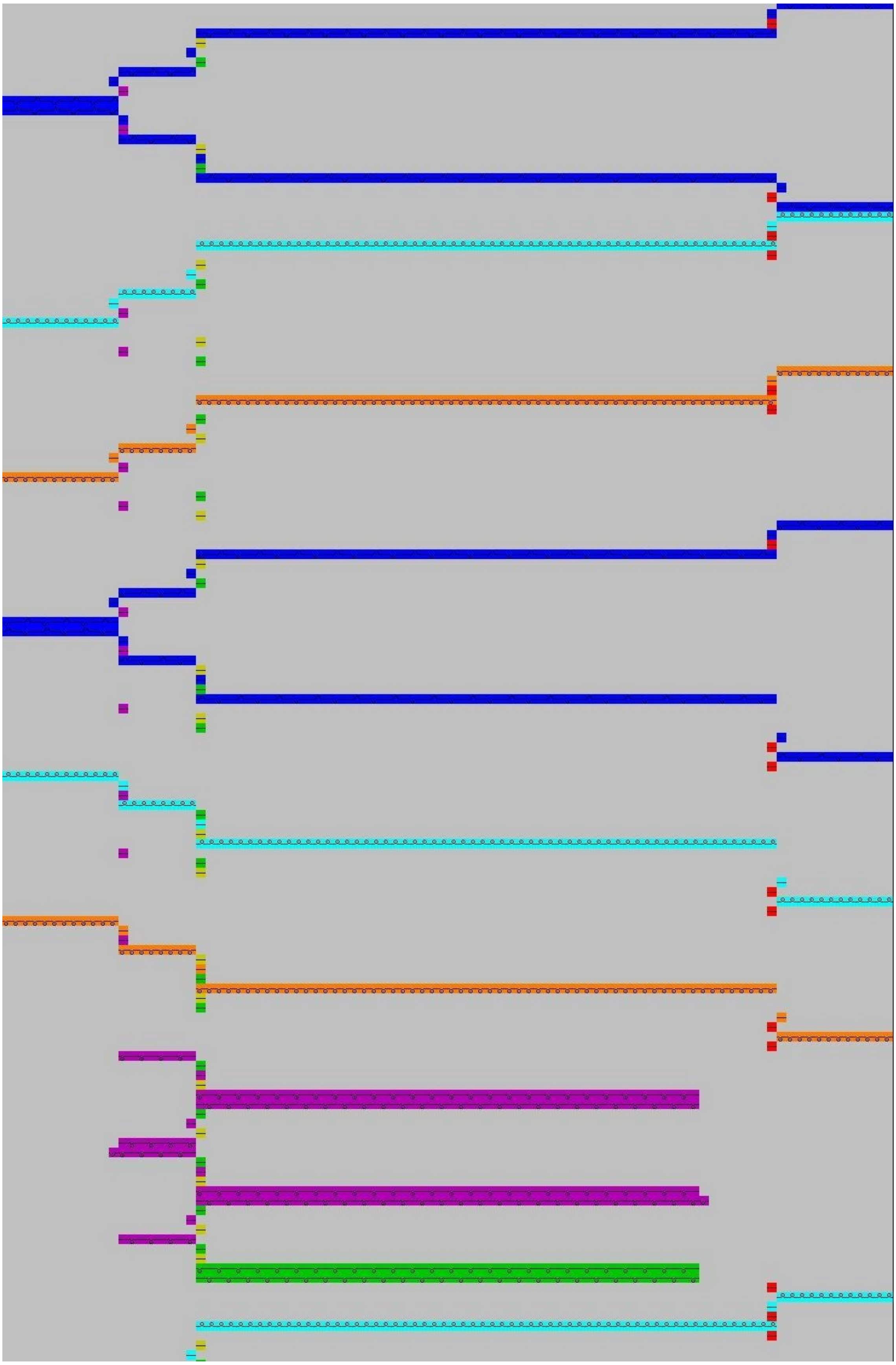


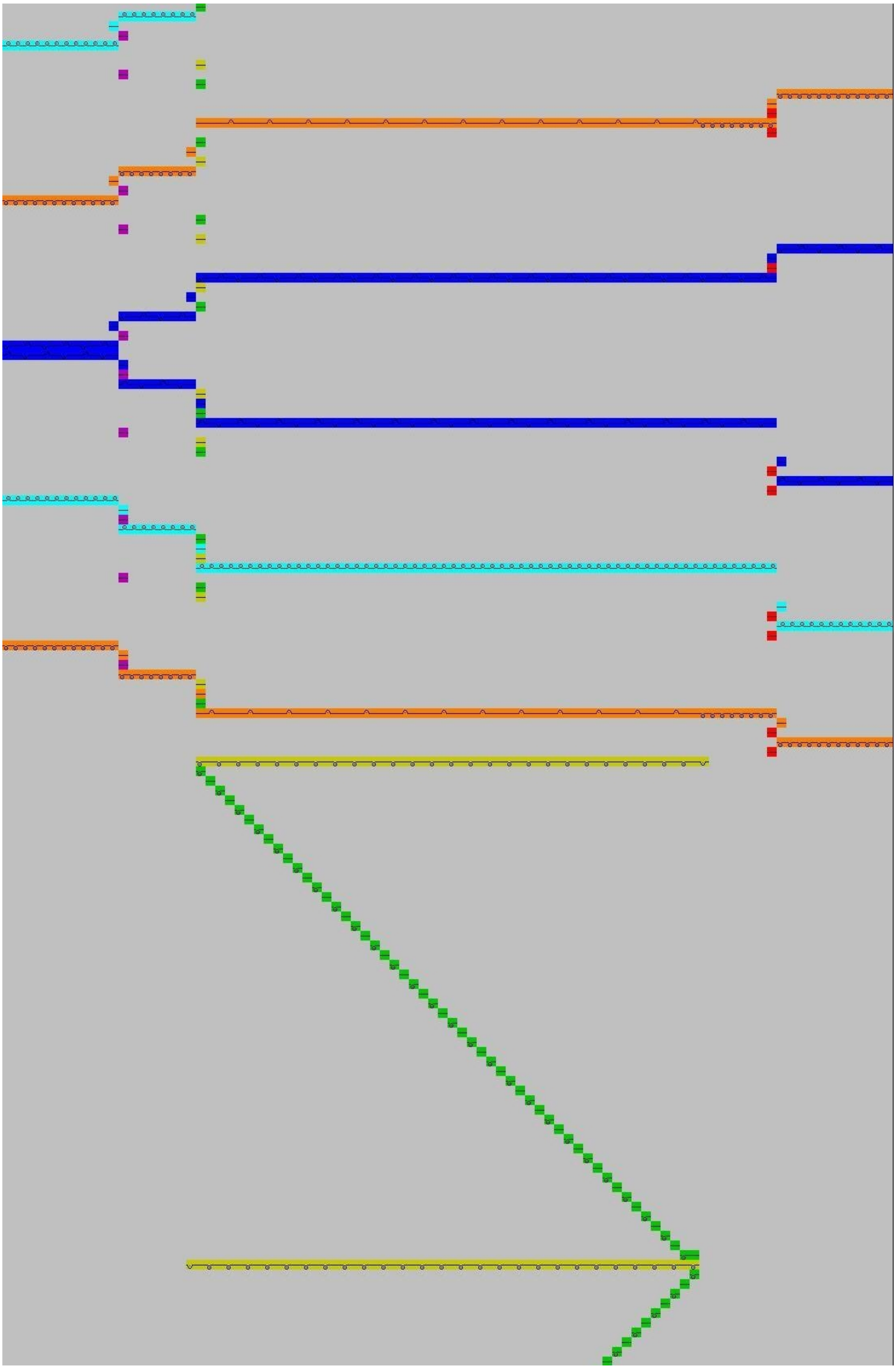


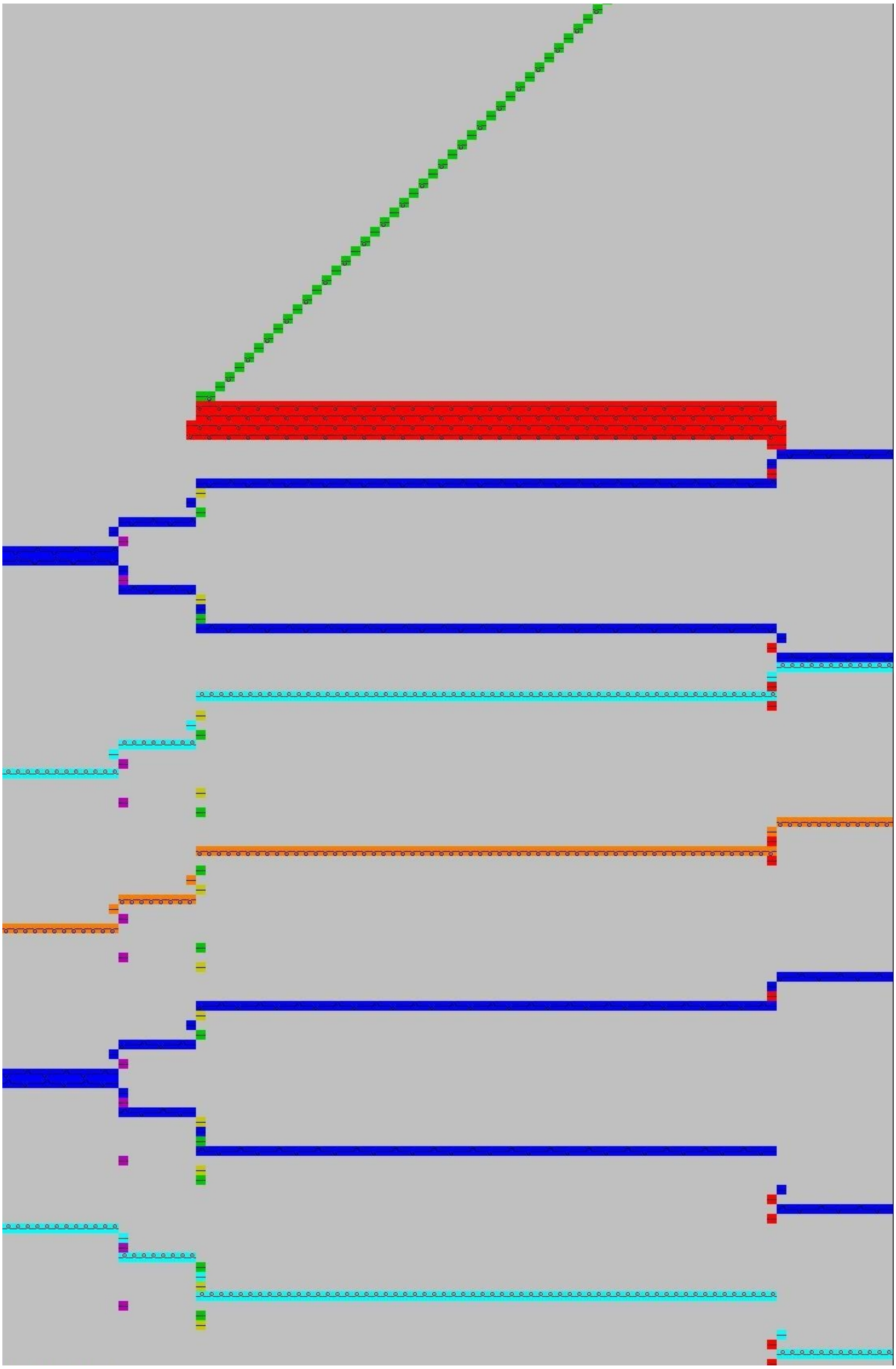


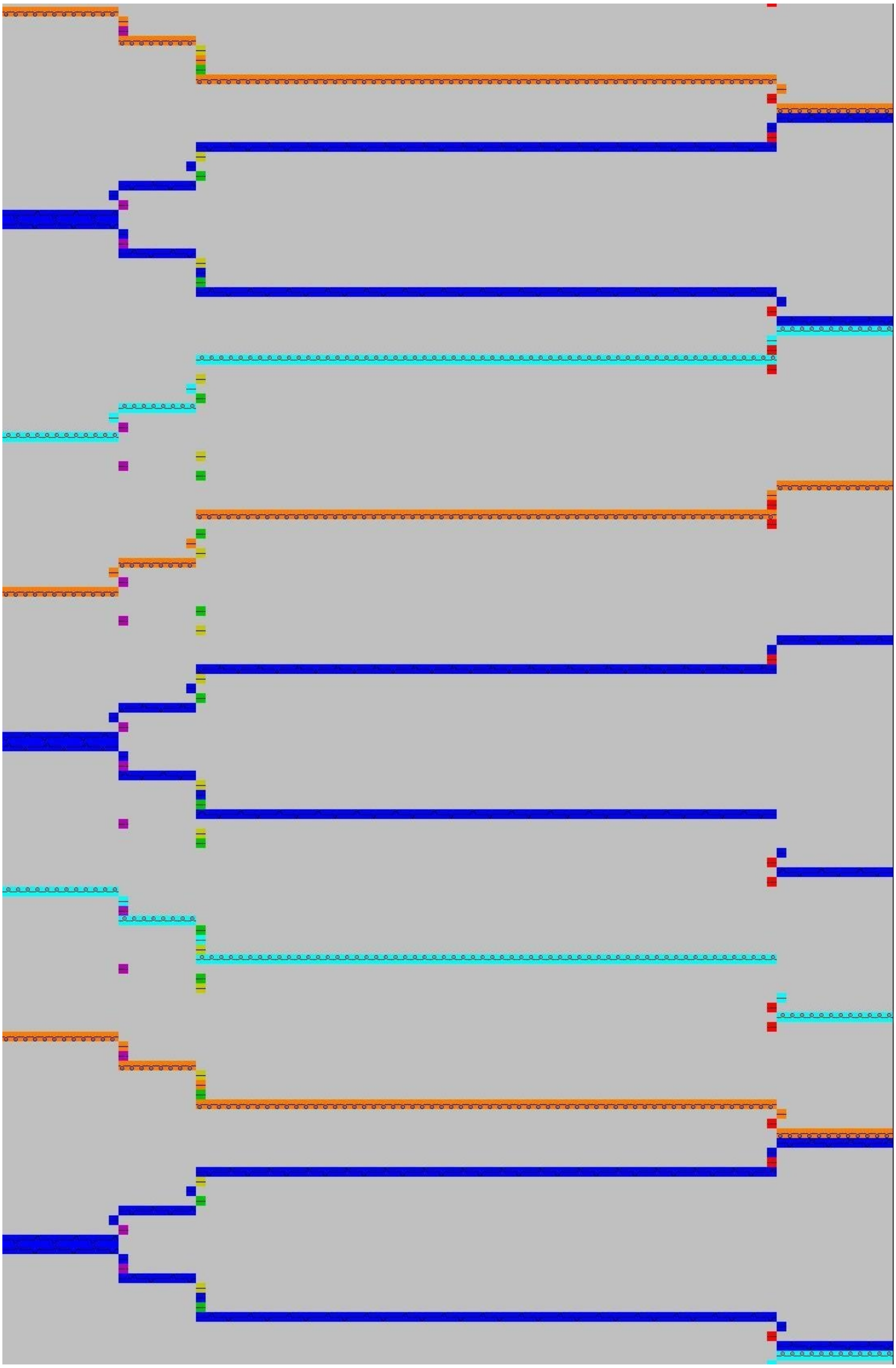


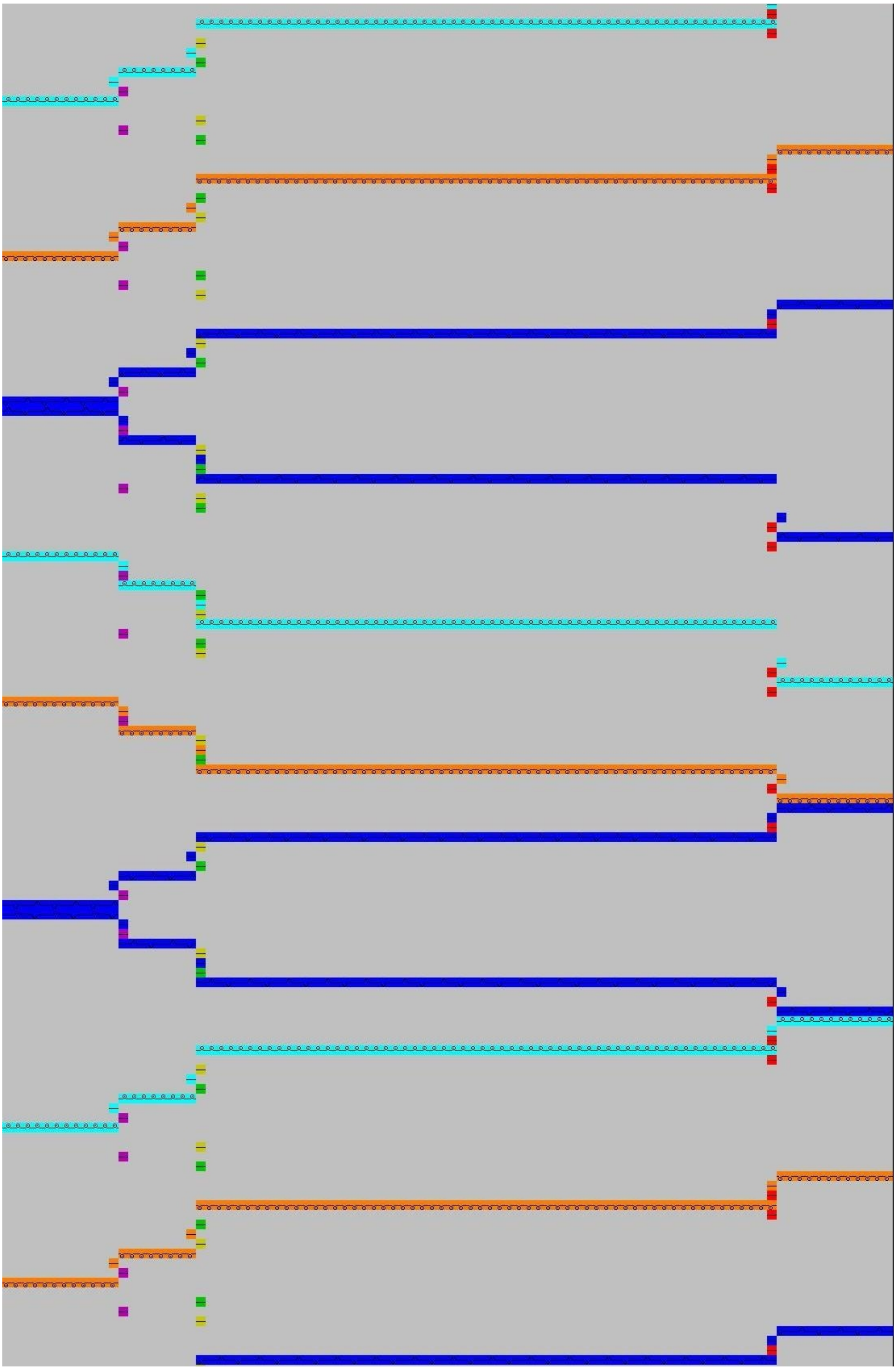


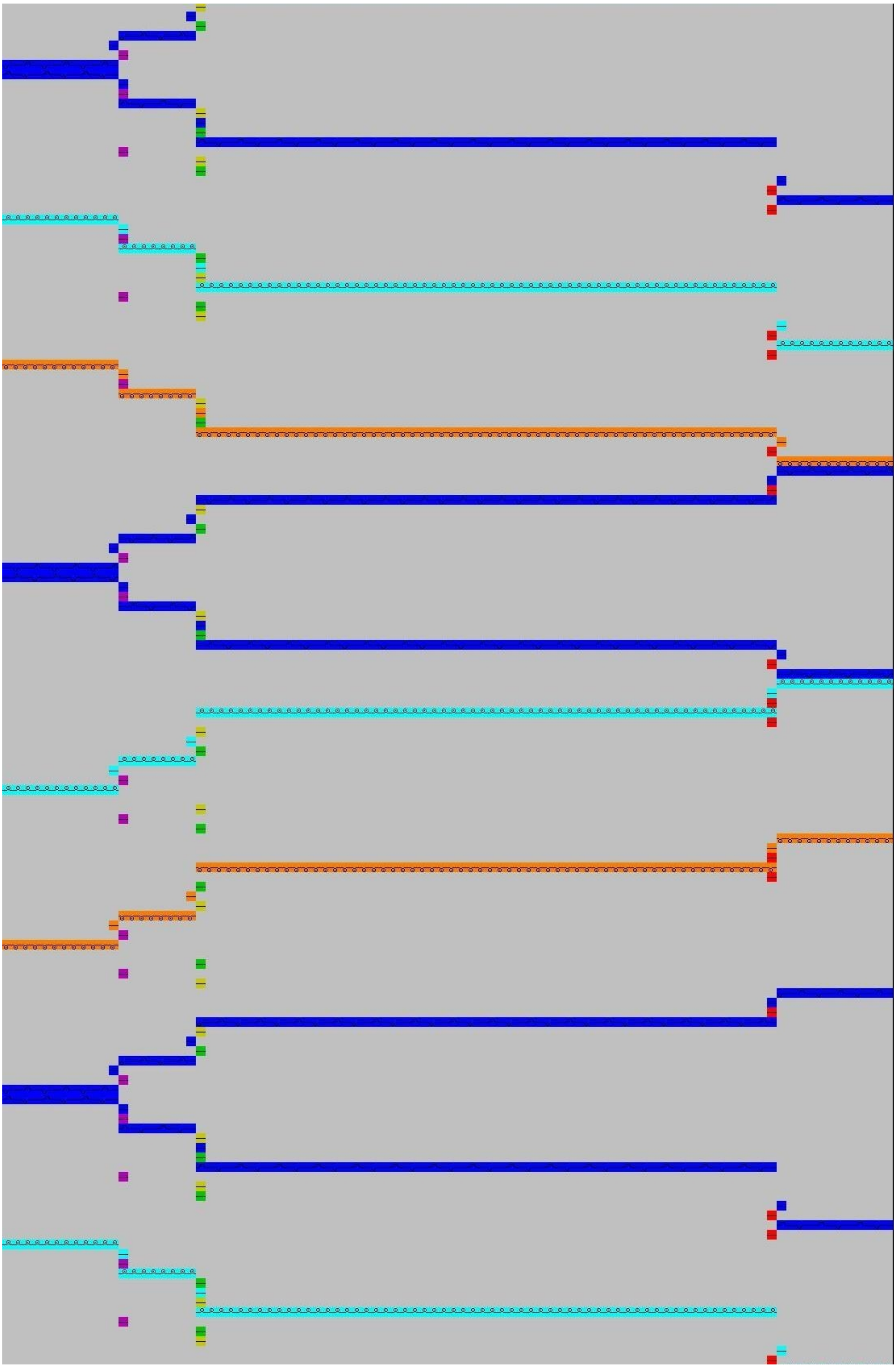


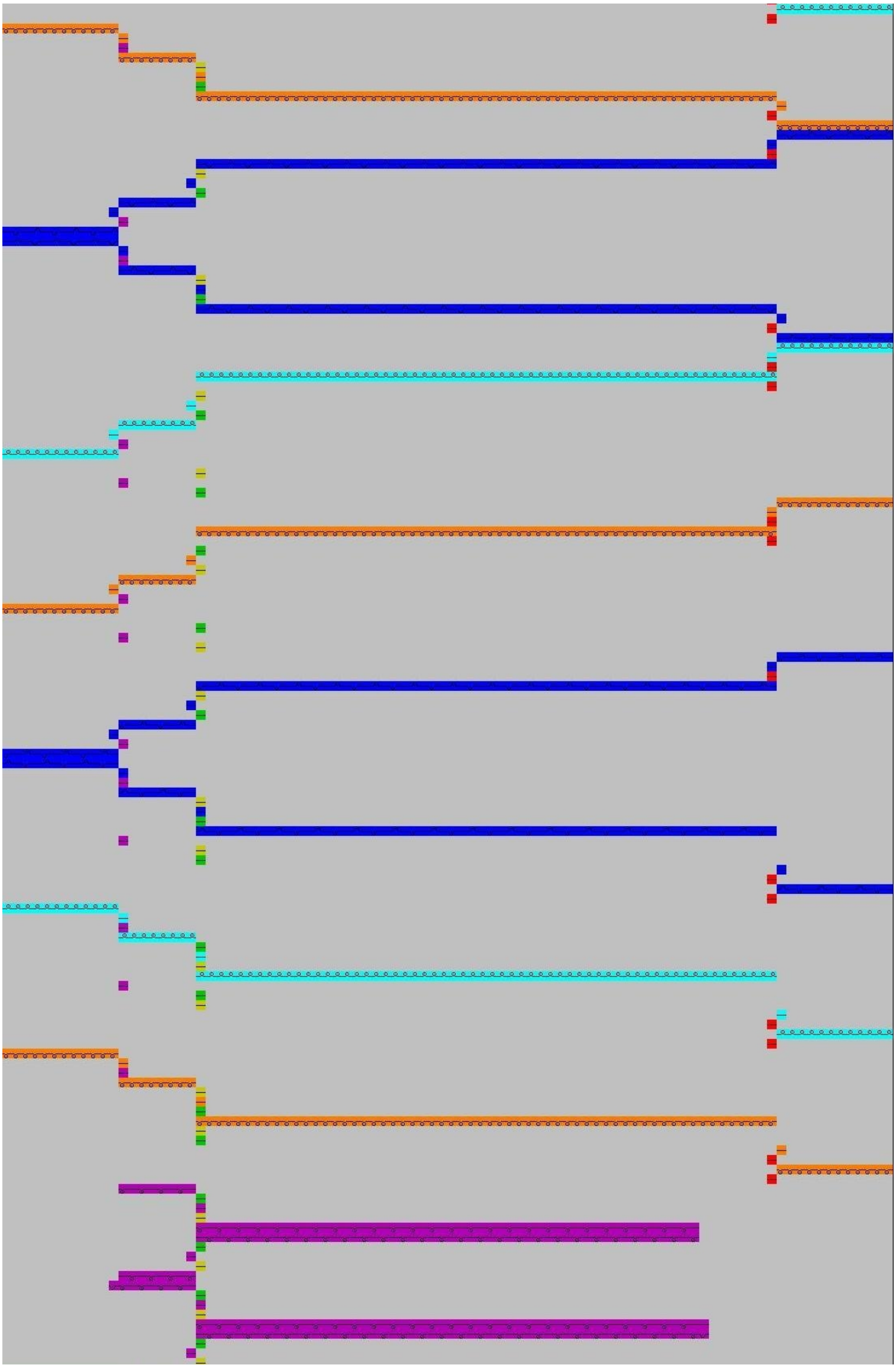


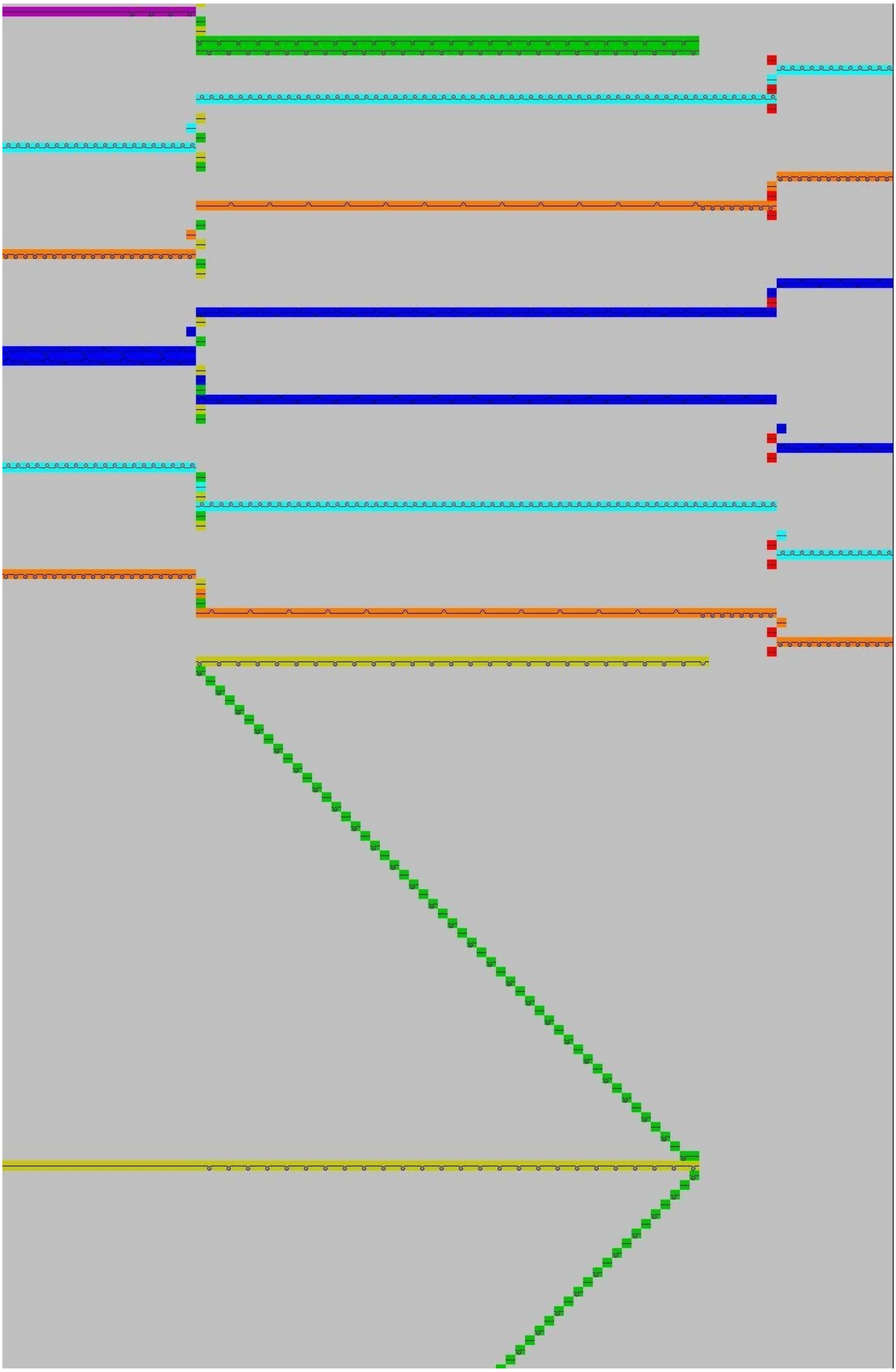


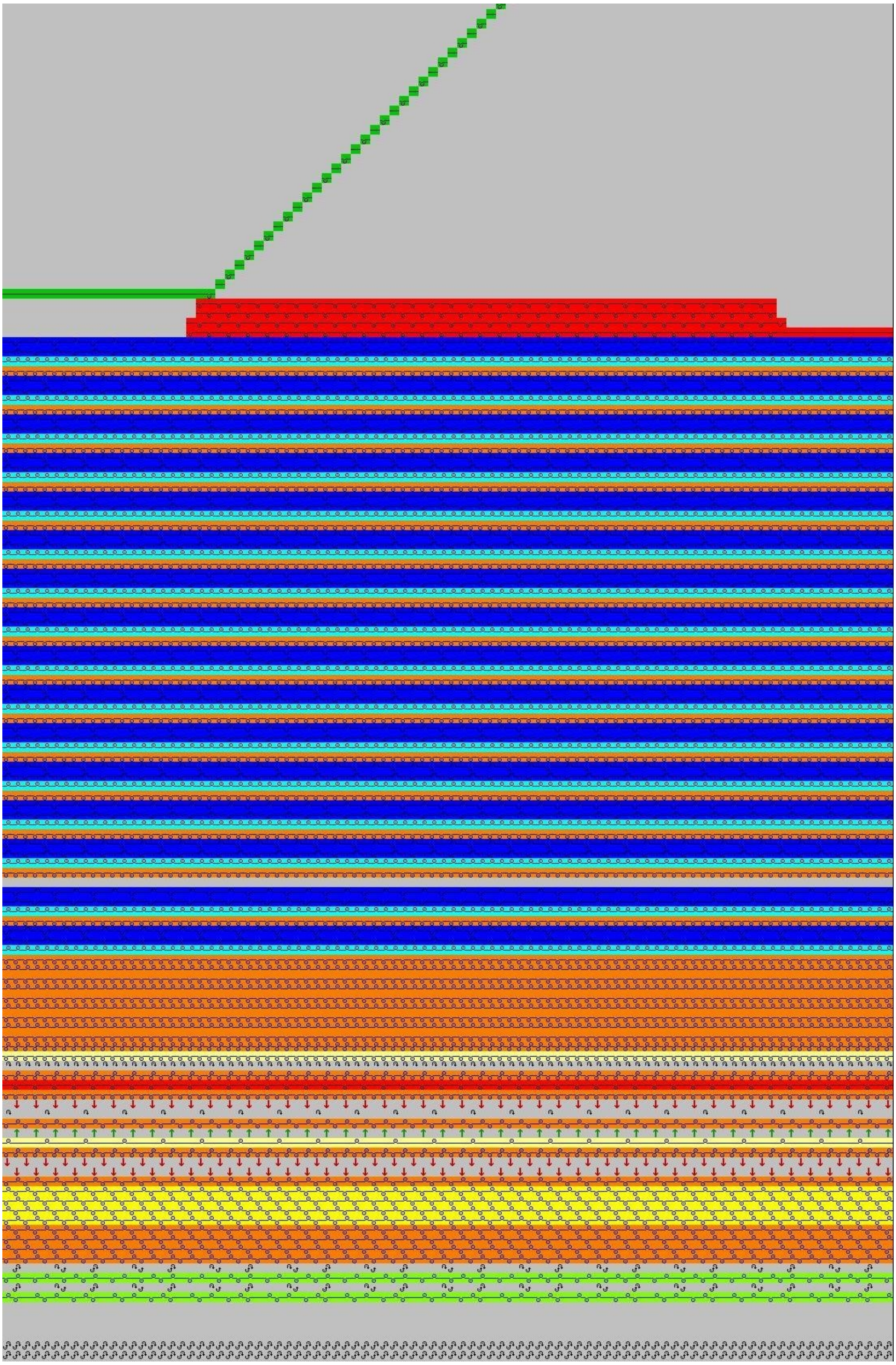












Appendix 7: Research activity

During the course of the research I have been fortunate to participate in interesting activities which helped me to further understand the project and mostly; able to reach more people so that the project could be beneficial to the society and could be used to change lives and improve living standards. Below is the summary of the research activities;

I. Conference attended

1. Third annual research practise course conference, Nottingham, June 2012
2. Materio Future factory conference, Nottingham, November 2012
3. Dr. Philip Breedon's Inaugural lecture: Materials intelligence: Informing smart design, Nottingham, April 2013
4. Advances in functional Textiles, International conference, Manchester, July 2013
5. Organizer: Breaking Boundaries 2014: First Annual Professional Research Practice Conference, Nottingham Trent University, Nottingham, May 2014
6. From Invention to consumption: E-Textiles. Workshop 3: summary and planning. Nottingham, August 2014
7. Sixth international conference on Future Technical Textile, Istanbul, Turkey, October 2014
8. Smart fabrics workshop 2, Nottingham, November 2014.
9. Wearable Technology Show, Excel London, March 2015
10. Seminar, Wearable tech, fashion and emancipation, Dr. Conor Farrington, University of Cambridge, Nottingham, May 2015.
11. Professor Amin Al-Habaibeh's Inaugural Lecture: Intelligent Engineering Systems: Innovations from Medical Design to Energy, Nottingham, June 2015

II. Presentations and exhibitions

1. Poster presentation; The development of a quick dry fabric for outdoors garments, Research practise course, Nottingham, May 2012

2. Paper presentation; Development of a quick dry fabric for outdoors garments, Fifth annual research practise course conference, Nottingham, May 2013
3. Heating fabrics Exhibition; Advanced Engineering Event, NEC Birmingham, November 2013
4. Heating fabrics Exhibition; MediCity Launch event, Boots HQ, Nottingham, November 2013
5. Brainstorming session for textiles in automotive; MediCity, Boots HQ, Nottingham, January 2014.
6. Heating fabrics Exhibition; NTU Commercial showcase event, Nottingham, May 2014
7. Design and manufacture of heated textiles. CADBE PhD Annual conference; Nottingham, June 2014
8. Masters Students project outline presentation, Nottingham, June 2014
9. Poster presentation: Design and manufacture of heated textiles, Sixth international conference on Future Technical Textile, Istanbul, Turkey, October 2014
10. Smart fabrics workshop delegates laboratory tour and products demonstration, NTU-ATRG, Bonington, Nottingham, and November 2014.

III. Publications

1. Development of a quick dry fabric for outdoors garments. Fifth annual research practise course conference, Nottingham, May 2013
2. The next generation of electronic textiles. Co-author, First international conference on digital technologies for the textiles industries, Manchester, September 2013
3. Book chapter: Electronic Textiles: Smart fabrics and wearable technology. Titled; design and manufacture of heated textiles, released May 2015. **ISBN 9780081002018**
4. Technical Report: Seamless knitted prosthetic sleeves for the management of perspiration-Phases 2a and 2b. Final Technical Report to MoD. MoD contract number DSTL/AGR/00410/01. March 2015

IV. Training

1. LabVIEW software package training, LabVIEW core 1 and Core 2, Newbury, February 2013
2. Professional research practise course, Nottingham, 2011-2014

V. Editorial

1. Panel editor: Breaking Boundaries 2014: First Annual Professional Research Practice Conference, Nottingham Trent University, Nottingham, May 2014

VI. Patent

1. Fabrics for garments. British application patents no. 1414138.6, August 2014

VII. Workshop facilitator

1. Narratives in An Internet of Soft Things, Workshop 3, LED, RFID & Sensor yarns, Nottingham Trent University, Nottingham, UK, February 23-27, 2015

ANNEX 1: RS INDUSTRIAL GRADE ADHESIVE

RS CLP/GHS revision date 01/12/14

CP1205 v1.4 RS 144-406

SAFETY DATA SHEET

According to 1907/2006/EC, Article 31

AB1 Cast Acrylic Bonder

Revision 1
Date 2014-12-17

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1. Product Identifier

Product name	AB1 Cast Acrylic Bonder
Product No.	RS 144-406

1.2. Relevant identified uses of the substance or mixture and uses advised against

Identified uses	For bonding of small lap and butt joints on cast acrylics.
Uses advised against	At this moment in time we do not have information on use restrictions. They will be included in this safety data sheet when available

1.3. Details of the supplier of the safety data sheet

Supplier

RS Components Ltd
Birchington Road
Corby
Northants NN17 9RS
+44 (0) 1536 402888
+44(0) 1536 401588
technical.help@rs-components.com

1.4. Emergency telephone number

+44 (0) 01536 402888 (8am - 8pm)

SECTION 2: Hazards Identification

2.1. Classification of the substance or mixture

2.1.1. Classification – 67/548/EEC	F; R11 Xn: R40 Xi: R37/38-43 Symbols: F: Highly flammable. Xn: Harmful.
Main Hazards	Highly flammable. Irritating to respiratory system and skin. Limited evidence of a carcinogenic effect. May cause sensitisation by skin contact.
2.1.2. Classification – EC 1272/2008	Flam. Liq. 2: H225; Skin Irrit. 2: H315; Skin Sens. 1: H317; STOT SE 3: H335; Carc. 2: H351;

2.2. Label elements

Hazard pictograms

Signal Word	Danger
Hazard Statement	Flam. Liq. 2: H225 – Highly flammable liquid and vapour.
	Skin Irrit. 2: H315 – Causes skin irritation.
	Skin Sens. 1: H317 – May cause an allergic skin reaction.
	STOT SE 3: H335 – May cause respiratory irritation.
	Carc. 2: H351 – Suspected of causing cancer.
Precaution Statement:	P210 – Keep away from heat/sparks/open flames/hot surfaces. – No smoking
Prevention	P233 – Keep container tightly closed
	P242 – Use only non-sparking tools
	P243 – Take precautionary measures against static discharge
	P261 – Avoid breathing dust/fume/gas/mist/vapours/spray
	P272 – Contaminated work clothing should not be allowed out of the workplace
	P280 – Wear protective gloves/protective clothing/eye protection/face protection
	P281 – Use personal protective equipment as required
Precautionary Statement:	P261 – Avoid breathing dust/fume/gas/mist/vapours/spray
Response	P302+P352 – IF ON SKIN: Wash with plenty of soap and water
	P304+P340 – IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing
	P308+P313 – IF exposed or concerned: Get medical advice/attention
	P312 – Call a POISON CENTRE or doctor/physician if you feel unwell
	P332+P313 – If skin irritation occurs: Get medical advice/attention
	P363 – Wash contaminated clothing before reuse
Precaution Statement:	P403+P233 – Store in a well-ventilated place. Keep container tightly closed
Storage	P405 – Store locked up

SECTION 3: Composition/information on ingredients

3.2. Mixtures

67/548/EEC / 1999/45/EC

Chemical Name	Index No.	CAS No.	EC No.	Conc. (%w/w)	Classification
Methylene Chloride (Dichloromethane)	602-004-00-3	75-09-2	200-838-9	35 – 65%	Carc. Cat. 3: R40
Methyl Methacrylate	607-035-00-6	80-62-6	201-297-1	20 - 50%	F; R11 Xi: R37/38 R43
2-Phenoxyethanol	603-098-00-9	122-99-6	204-589-7	1 – 10%	Xn: R22 Xi; R36

SECTION 4: First aid measures

4.1. Description of first aid measures

Inhalation Irritation to respiratory system. Move the exposed person to fresh air. Seek medical attention.

Eye contact Rinse immediately with plenty of water for 15 minutes holding the eyelids open. Seek medical attention if irritation or symptoms persist.

Skin contact Irritating to skin. Wash off immediately with plenty of soap and water. Remove contaminated clothing. Seek medical attention if irritation or symptoms persist.

Ingestion DO NOT INDUCE VOMITING. Seek medical advice if irritation or symptoms persist.

SECTION 5: Firefighting measures

5.1. Extinguishing media

Carbon oxides.

5.2. Special hazards arising from the substance or mixture

Burning produces irritating, toxic and obnoxious fumes.

5.3. Advice for firefighters

Wear suitable respiratory equipment when necessary.

SECTION 6: Accidental release measures

6.1. Personal precautions, protective equipment and emergency procedures

Ensure adequate ventilation of the working area. Wear suitable protective equipment

6.2. Environmental precautions

Do not allow product to enter drains. Prevent further spillage if safe.

6.3. Methods and material for containment and cleaning up

Absorb with inert, absorbent material. Sweep up. Transfer to suitable, labelled containers for disposal. Clean spillage area thoroughly with plenty of water.

SECTION 7: Handling and storage

7.1. Precautions for safe handling

Avoid contact with eyes and skin. Ensure adequate ventilation of the working area. Adopt best Manual Handling considerations when handling, carrying and dispensing.

7.2. Conditions for safe storage, including any incompatibilities

Keep in a cool, dry, well-ventilated area. Keep containers tightly closed.

SECTION 8: Exposure controls/personal protection

8.1 Control parameters

Methyl Methacrylate	**WEL 8-hr limit ppm:** 50 **WEL 15 min limit ppm:** 100	**WEL 8-hr limit mg/m3:** 208 **WEL 15 min limit mg/m3:** 416
Methylene Chloride (Dichloromethane)	**WEL 8-hr limit ppm:** 100 **WEL 15 min limit ppm:** 300	**WEL 8-hr limit mg/m3:** 350 **WEL 15 min limit mg/m3:** 1060

8.2. Exposure controls

8.2.1. Appropriate engineering controls	Ensure adequate ventilation of the working area.
8.2.2. Individual protection measures	Wear chemical protective clothing
Eye / face protection	Approved safety goggles
Skin protection – Hand protection	Chemical resistant gloves (PVC).
Respiratory protection	Wear suitable respiratory equipment.

SECTION 9: Physical and chemical properties

9.1. Information on basic physical and chemical properties

State	Liquid
Colour	Clear
Odour	Pungent
Boiling point	37°C

Flash point	10°C
Autoignition temperature	420°C
Relative density	1.1
Solubility	Slightly miscible in water

SECTION 10: Stability and reactivity

10.2. Chemical stability

Stable under normal conditions

SECTION 11: Toxicological information

11.1. Information on toxicological effects

Skin corrosion/irritation	Irritating to respiratory system and skin.
Respiratory or skin Sensitisation	May cause sensitisation by skin contact
Carcinogenicity	Limited evidence of a carcinogenic effect.

SECTION 12: Ecological information

Further information	No known adverse environmental effects.

SECTION 13: Disposal considerations

General information	Dispose of in compliance with all local and national regulations.

SECTION 14: Transport information

Hazard pictograms

14.1. UN Number

UN1992

14.2. UN proper shipping name

FLAMMABLE LIQUID, TOXIC, N.O.S. (contains METHYL METHACRYLATE, STABILIZED and DICHLOROMETHANE)

14.3. Transport hazard class(es)

ADR/RID	3
Subsidiary risk	6.1
IMDG	3
Subsidiary risk	6.1

IATA	3
Subsidiary risk	6.1
<u>14.4. Packing group</u>	
Packing group	II
<u>14.5. Environmental hazards</u>	
Environmental hazards	No
Marine pollutant	No
ADR/RID	
Hazard ID	336
Tunnel category	(D/E)
IMDG	
EmS Code	F-E S-D
IATA	
Packing instruction (Cargo)	364
Maximum quantity	60 L
Packing Instruction (Passenger)	352
Maximum quantity	1 L

SECTION 15: Regulatory information

Labelling	
	The product is classified in accordance with 67/548/EEC
Symbols	F: Highly flammable. Xn: Harmful

Risk phrases	R11 – Highly flammable
	R37/38 – Irritating to respiratory system and skin
	R40 – Limited evidence of a carcinogenic effect
	R43 – May cause sensitisation by skin contact
Safety phrases	S16 – Keep away from sources of ignition – No smoking
	S24 – Avoid contact with skin
	S36/37 – Wear suitable protective clothing and gloves

SECTION 16: Other information

Other information

Text of risk phrases in Section 3	R11 – Highly flammable R22 – Harmful if swallowed R36 – Irritating to eyes R37/38 – Irritating to respiratory system and skin R40 – Limited evidence of a carcinogenic effect R43 – May cause sensitisation by skin contact

Further information

The information supplied in this Safety Data Sheet is designed only as guidance for the safe use, storage and handling of the product. This information is correct to the best of our knowledge and belief at the date of publication however no guarantee is made to its accuracy. This information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any other process.

ANNEX 2: TTI POWER SUPPLY DATA SHEET

EL-R Series - linear regulated precision laboratory power supplies

EL-R Series - Model Range					
Model	O/Ps	Voltage	Current	Power	Aux. O/P
EL301R	One	0 to 30V	0 to 1A	30W	
EL183R	One	0 to 18V	0 to 3.3A	60W	
EL302R	One	0 to 30V	0 to 2A	60W	
EL561R	One	0 to 56V	0 to 1.1A	60W	
EL155R	One	0 to 15V	0 to 5A	75W	
EL303R	One	0 to 30V	0 to 3A	90W	
EL302RD	Two	0 to 30V	0 to 2A	120W	
EL302RT	Three	0 to 30V	0 to 2A	130W	1.5 - 5V @2A
Related Models					
EL302P	30V/2A model with RS-232 interface				

Simplicity in use

EL-R series power supplies use classic analog controls for voltage and current.

The large and bright displays have a fixed resolution to avoid confusion.

Preset voltage and current levels are shown when the DC output switch is turned off.

Remote sense is available when needed but is disabled by setting the switch to Local.

EL-R Series

Simplicity with Precision

The new EL-R series has been developed from the top selling EL series. By adding four digit meters and switchable remote sensing, the EL-R series offers much higher precision whilst retaining the simplicity of operation which many bench-top power supply users prefer.

Eight models are offered including single, dual and triple outputs and covering a power range of 30 watts up to 130 watts.

Linear regulation

All EL-R series models* use true linear regulation for the best possible performance. Excellent line and load regulation is matched by very low output noise and good transient response.

Four digit meters

The EL-R series incorporates separate voltage and current meters on each main output with a resolution of 10mV and 1mA. The fixed resolution avoids the misinterpretation of readings that can occur with auto-ranging 3 or 3½ digit meters where the decimal point position moves as the reading changes.

Remote Sensing

Each main output incorporates remote sense terminals that can be enabled or disabled at the flick of a switch.

Remote sensing is essential for maintaining precise regulation at the load and true metering of the load voltage. Many other power supplies omit remote sense, and quote regulation figures that could never be achieved in practice.

N.B. A 2 metre length of a 24/0.2 wire pair has a resistance of around 0.1 Ω. For a 5V load drawing 3A the metering error without remote sense would be 0.3V and the effective full current load regulation would be around 6%, against a quoted figure of perhaps 0.01% for the power supply itself.

DC output switches

Each main output has a DC on-off switch. This enables voltage and current settings to be viewed before the load is connected and allows multiple outputs to be controlled individually. Surprisingly, many power supplies omit this essential feature.

Constant voltage or constant current

Each main output can operate in constant voltage or constant current mode with automatic crossover and mode indication. Coarse and fine voltage controls are provided. The current control is logarithmic enabling low current levels to be set accurately.

Silent cooling

All EL-R series models use convection cooling and are entirely free of fan noise.

Safety binding-post terminals

EL-R series power supplies are fitted with the new TTi designed output terminals. These can accept a 4mm safety plug with rigid insulating sleeve, a requirement specified by an increasing number of laboratories for safety reasons.

However, unlike the 4mm safety sockets used on some other products, the new TTi terminals can also accept fork connectors or bare wires, giving maximum connection flexibility.

ANNEX 3: RAYTEK TEMPERATURE SENSOR DATA SHEET

Specifications and Features	MX2	MX4+	MX4+NI
Temperature Range	-30°C to 900°C (-25°F to 1600°F)		
Temperature Range with SZ option	-50°C to 500°C (-58°F to 932°F)		—
Accuracy (Assumes ambient operating temperature of 23°C (73°F))	±0.75% of reading or ±1°C (±2°F) whichever is greater		
Repeatability	≤ ±0.5 of reading or ≤ ±1°C (±2°F), whichever is greater		
Response Time	250 mSec (95% of reading)		
Spectral Response	8 to 14μm, thermopile detector		
Adjustable Emissivity* (from 0.1 to 1.0 by 0.01)	✔	✔	✔
Ambient Operating Temp.	0°C to 50°C (32°F to 122°F)		
Relative Humidity	10-90% at 30°C (86°F) non-condensing		
Storage Temperature	-20°C to 50°C (-25°F to 122°F)		
Weight	480g (1 lb. 6 oz.)		
Power	2 AA Batteries	2 AA Batt./AC adapter	2 AA Batt./AC adapter
Power Supply (110 or 220V), PS232 Computer Cable, 1.5 m (60 in), K thermocouple probe	—	✔	✔
Laser Class II	3-dot laser sighting (Meets IEC Class 2 & FDA Class II requirements)		
Single Laser Class III	Option (U.S. only)	—	—
Distance to Spot (D:S)	60:1 (50:1 with Close Focus Option)		60:1
Minimum Measurement Diameter	19mm (0.76") (6mm (0.24") with Close Focus Option)		19mm (0.76")
Maximum and Minimum Temperature	✔	✔	✔
Audible/Visible High/Low Alarm	✔	✔	✔
Differential and Average Temperature	—	✔	✔
Bar Graph Display	✔	✔	✔
100 Points Data Logging	—	✔	✔
Display Hold	✔	✔	✔
LCD Backlit	✔	✔	✔
Temperature Display	°C or °F selectable		
Display Resolution	0.1°C of reading up to 900°C (0.2°F up to 999.8°F)		
Data Graphing Software (Windows compatible)	—	✔	✔
Data Output: RS232 or 1mV per degree (°C or °F)	—	✔	✔
Hard Carrying Case	✔	✔	✔
Tripod Mount	1/4-20 UNC		
Nonincendive (Factory Mutual Research Nonincendive Rated, Class I, Division 2, Groups A, B, C, D; Class I, Zone 2 IIC; T4 Ta=50°C when used with 1.5V alkaline batteries. WARNING: Battery changes non-hazardous locations only. Only Raytek temp probes part XXXMXTP or XXXMXTCK2 can be connected)	—	—	✔
Close Focus	Option	Option	—
Subzero	Option	Option	—
NIST DKD Calibration Certificate	Option	Option	Option
Warranty 1 Year**	✔	✔	✔

**For more details, visit www.raytek.com/emissivity.htm ** US only. Warranty duration may vary by country.*

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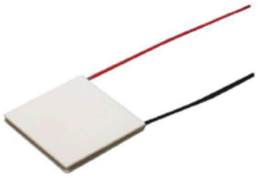
ANNEX 4: PELTIER DATA SHEET

Thermoelectric Module

multicomp



Scope:

This specification is applied to multicomp thermoelectric modules
Revision of these specifications is carried out after consent.

Specifications:

Parameters			Remarks
Internal resistance	1.4Ω ±10%		Note-1
I max.	13A		Note-2
V max.	24.1V		Note-3
-	Th = 27°C	Th = 50°C	-
Q max.	200W	224W	Note-4
ΔT max.	68°C	75°C	Note-5
Solder melting point	138°C		Note-6
Maximum compress	98.07N / cm² (10kgf / cm²)		Note-7

Note-1 : Measured by AC 4 - terminal method at 25°C
Note-2 : Maximum current at ΔT max.
Note-3 : Maximum voltage at ΔT max.
Note-4 : Maximum cooling capacity at I max. V max. and ΔT = 0°C
Note-5 : Maximum temperature difference at I max. V max. and Q = 0W
(Maximum parameters are measured in a vacuum 1.3 P)
Note-6 : The solder melting point of thermoelectric module
Note-7 : Recommended maximum compression (not destruction limit)

Recommendations:

- Operating range : -40°C to +90°C
- Dropping or exerting mechanical shock will cause breakage, take care in handling
- Thinly spread thermally conductive grease should be placed between module and heat exchanger
  Surface deviation from flatness should be kept under 0.02mm
- For optimum reliability and performance it is recommended that the module be utilised <0.7I max.
  Silicone sealed for moisture protection

Thermoelectric Module

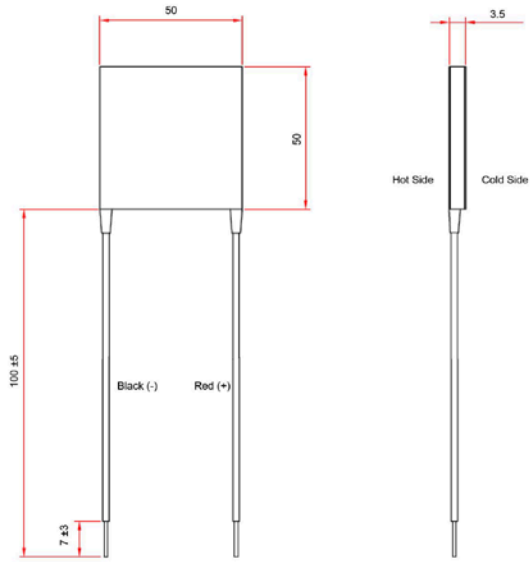
Specification Table

Thot = 27°C

I max. (A)	U max. (V)	Qc max. W	dT max. °C	A	B	H	Part Number
13	24.1	200	68	50	50	3.5	MCTE1-19913L-S

Dimensions : Millimetres

Outline Drawing:



Dimensions : Millimetres

ANNEX 5: TEMPERATURE AND HUMIDITY SENSOR DATA SHEET

Aosong Electronics Co.,Ltd

Your specialist in innovating humidity & temperature sensors

1. Feature & Application:

* Full range temperature compensated * Relative humidity and temperature measurement
* Calibrated digital signal *Outstanding long-term stability *Extra components not needed
* Long transmission distance * Low power consumption *4 pins packaged and fully interchangeable

2. Description:

DHT22 output calibrated digital signal. It utilizes exclusive digital-signal-collecting-technique and humidity sensing technology, assuring its reliability and stability.Its sensing elements is connected with 8-bit single-chip computer.

Every sensor of this model is temperature compensated and calibrated in accurate calibration chamber and the calibration-coefficient is saved in type of programme in OTP memory, when the sensor is detecting, it will cite coefficient from memory.

Small size & low consumption & long transmission distance(20m) enable DHT22 to be suited in all kinds of harsh application occasions.

Single-row packaged with four pins, making the connection very convenient.

3. Technical Specification:

Model	DHT22
Power supply	3.3-6V DC
Output signal	digital signal via single-bus
Sensing element	Polymer capacitor
Operating range	humidity 0-100%RH; temperature -40~80Celsius
Accuracy	humidity +-2%RH(Max +-5%RH); temperature <+-0.5Celsius
Resolution or sensitivity	humidity 0.1%RH; temperature 0.1Celsius
Repeatability	humidity +-1%RH; temperature +-0.2Celsius
Humidity hysteresis	+-0.3%RH
Long-term Stability	+-0.5%RH/year
Sensing period	Average: 2s
Interchangeability	fully interchangeable
Dimensions	small size 14*18*5.5mm; big size 22*28*5mm

4. Dimensions: (unit----mm)

1) Small size dimensions: (unit----mm)

2

Thomas Liu (Business Manager)

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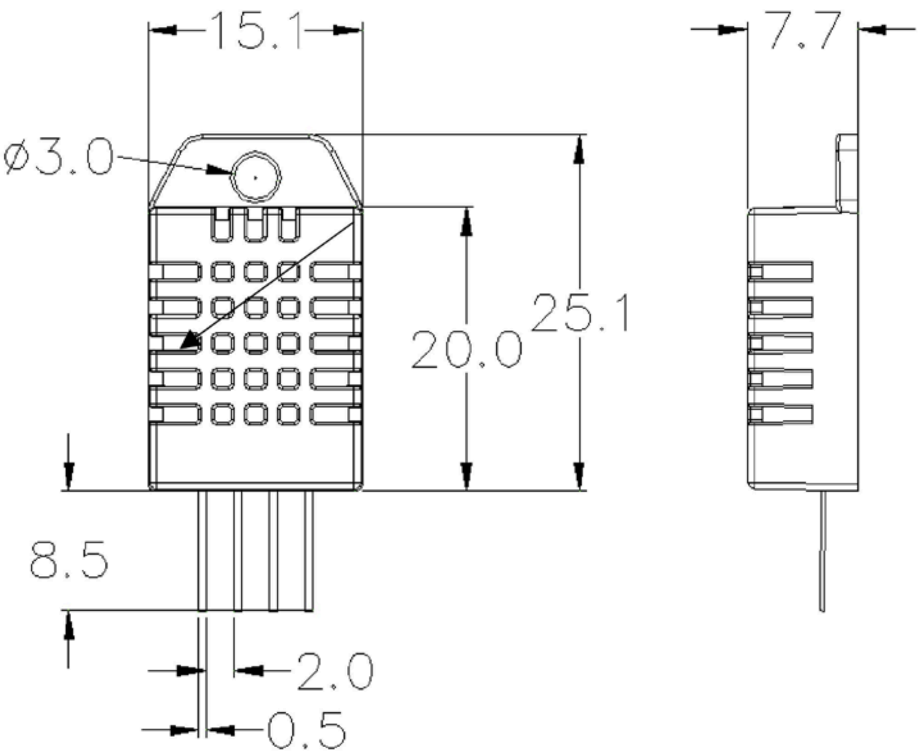

Pin sequence number: 1 2 3 4 (from left to right direction).

Pin	Function
1	VDD----power supply
2	DATA--signal
3	NULL
4	GND

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