Design and manufacture of heated textiles

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6.1 Introduction

Flexible textile-heating systems are one of the major important developments in heating technology. They have a huge advantage due to their ability to bend and flex and hence could provide heating effects for irregular geometries such as tubular and spherical structures. From Formula One tyre heating systems to heating blankets, textile-based heating systems play a huge role in our day-to-day activities today (see Figure 6.1a and b).

The major applications of heating systems can be categorized into two main systems: warmth and performance.

For heating purposes, heating systems are applied to provide necessary warmth to the user/system in cooler outer environment. In this situation, a warm environment is provided, which will protect the user/system from the cooler environment. This is important, as warm conditions are required for keeping the system running or the human body warm. The user requires his body to be kept warm for vital body systems to function without damage (Sampath et al., 2012). The human body must be maintained at a constant temperature of 37 °C; anything below can cause organ dysfunction, and the user can experience hypothermia (Au, 2011; Kar et al., 2007; Kissa, 1996). Because the users/system structures are mostly irregular shaped, flexible heating systems are an added advantage because efficient heat delivery can be achieved. Heating with non-flexible systems could cause heat huge losses due to fewer contact areas between the heating systems and the area requiring heat. Heat delivery is by conduction and convection (Xu et al., 2011; Hsieh, 1995; Sousa et al., 2004), so a flexible system will create more contact between the heat source and user/system and, hence, little heat loss.

Likewise, in performance-driven functionality, heating systems play a major role in maintaining human body at vital required heat levels. Many physical systems require heat to perform efficiently at different areas. For instance, in a chemical reaction, applied heat could accelerate rates of reactions and, hence, products are obtained much more quickly. Chemically, heat creates an excitation of atoms (Durrant and Durrant, 1970; Cotton and Wilkinson, 1980), which results in more interactions and, hence, higher rates of desired products. As in the heating systems category; conduction and convection are the major methods of heat transfer, sometimes with the addition of radiation.

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Figure 6.1 (a) Tyre warmers and (b) heating blankets.

6.2 Types of textile heaters and development

Textile-heating systems can be subdivided into two major categories: polymer-based and metal-based textile heaters. As the names suggest, they are categorized according to their heating element constructions. Metal-based heating textiles are the ones that consist of metals as heating elements (Altmann et al., 1990). In this design, metal wires and sometimes sheets are used to produce a heating effect (Figure 6.2).

Polymer-based textile heating uses polymer materials to produce heating yarn that, when direct current (DC) power is applied, will produce heat. Polymer systems are the new technology that was developed after the introduction of synthetic yarns. Synthetic yarns are produced by spinning molten polymers. They are made from monomers of known properties and characteristics. Figure 6.3 illustrates an example of polymer-based technology in which a flexible heating fabric is produced (EXO2theheatinside, 2014).

These systems enable the production of conductive yarns and sheets that could be made into textiles and still retain their conductivity. Conductive yarns can be produced by spinning polymers with different properties. For instance, polymers could be blended before spinning at predefined percentages so that output yarns would have

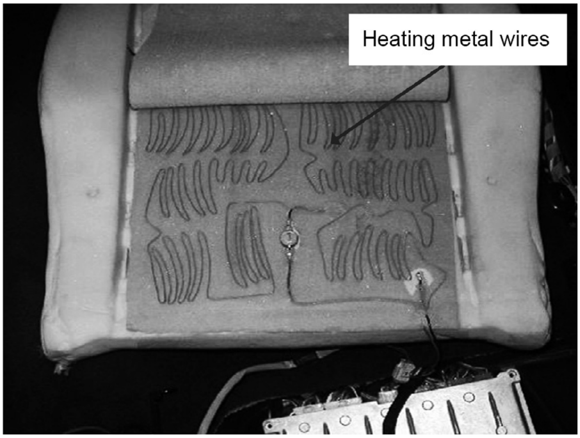

Figure 6.2 Metal-based textile heaters in car seats.

Figure 6.3 Flexible polymer-based heated fabric by EXO2.

specific properties. It is this development that has allowed polymer yarns with different levels of conductivity and heating effects to be successfully produced.

6.2.1 Heating theory

The technology behind heating systems stretches from the basic principle of Ohm's law in which the current flowing through a resistor, when a voltage source is applied, will causes the resistor to heat up and dissipate power as heat (Paynter and Boydell, 2011; see Figure 6.4).

As such a heating system would require three major components: a power source, a resistor and a connecting mechanism for the power source and the resistor. The power source would force an electric current to pass through the resistor, which in turn would genearate an amount of heat depending on the current flowing through the resistance; the current flow is limited by its resistance. Both the resistor and the connection mechanism have to be made from conducting materials. The efficient connecting mechanisms are made from metals. Copper is the best material due to its availability and

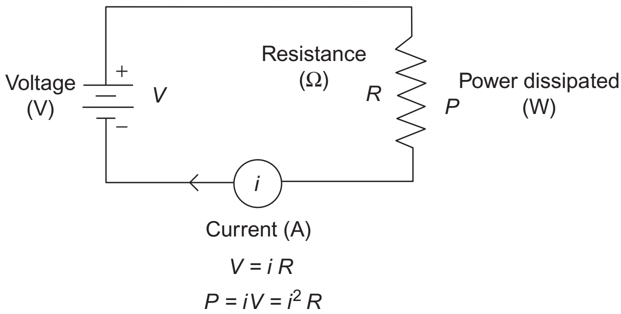

Figure 6.4 Ohm's law illustration.

good conductivity (Copper, 2015). In the case of wearable systems the resistors and connecting materials have to be thin enough to allow flexibility, and at the same time strong enough to prevent breakage and provide an efficient heating. To provide a system, which is comfortable to wear, the power supply for the heating system has to be small enough to reduce weight but provide a long-lasting current for heating. Most efficient wearable heating systems use a detachable power supply so that recharging can be done easily when required.

On a textile material, installing this heating system is a challenge. Most systems attach the heating unit onto a textile material; others sandwich it between two or more textile layers. Attaching these together is a challenging task, as it might prevent textile aesthetic and draping properties, and the resulting fabric might also be heavy. However, in other applications like in car seats, these limitations are not important because the combination of the heating system and textile material does not require much flexibility, nor is weight an issue.

6.2.2 Applications of metal-based heaters

Major applications of metal-based heating systems can be categorized into automotive, construction, sports and recreation.

Heating systems have been used in the automotive industry for quite a while now, mostly in the northern hemisphere. Vehicles developed for this market required improvements to provide a premium luxury environment for the customers due to cold environments and societal levels. Getting into the car on a cold morning for work or school would be much comfortable with heated seats, and in more high-end cars, a heated steering wheel as well, as shown in Figure 6.5.

To provide this heating effect, flexible, reliable and controllable heating systems have been developed using textiles. The common design is the insertion of heating elements into a woven fabric (Weiss, 2013). The combination provides the necessary heating effect from the elements and flexibility from the fabric. The heating elements used are made from thin copper wire. Sometimes they are protected from damage by an outer layer when the seat is in use. Performance of these heating systems is important, and appropriate controls have been introduced depending on the system

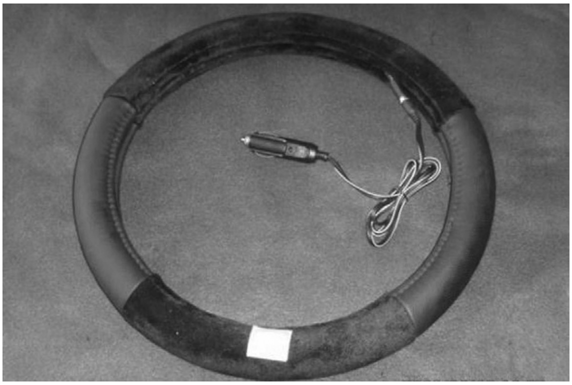

Figure 6.5 Heated steering wheel cover.

(Buie and Buie, 1997). Most heated seats are equipped with different heating levels, from high to low, and sometimes even more levels. This provides different heating effects, controlled by the user. Sometimes just a small amount of heating is required, while at other times a maximum amount is necessary, such as in extreme cold conditions. Having all these heating levels for the seats also requires an effective control system to regulate the amount of heat and the duration of heating. Heating elements will always provide substantial heating that is effective as long as the power is available. They are not self-regulatory. The problem comes when the user feels an accumulation of heat, which could cause discomfort (Crow, 1998; Fangueiro et al., 2010; Sweeney and Branson, 1990). Therefore, today the automotive heating systems are engineered so that the heating effect could be controlled with on and off times. The theory does apply in sports, recreation activities and in buildings and similar constructions, heating elements are included on a much bigger scale due to the size of the area.

The combination of heating systems with textiles is a niche sector, as the outcome could be very important. It is important to develop textile-based heating systems without compromising the flexibility and the drapability of a textile. Therefore the investigation of how to create a comfortable wearable heating system is a very important area of research.

6.3 Design rules for polymer-based textile heaters

This section describes the major considerations required in the design and manufacture of heated textiles.

6.3.1 Types of yarns

An important aspect in designing textile heating systems is the type of yarns to be used. Therefore it was decided to investigate the carbon loaded silicone yarn (FabRoc®) which is made by mixing together silicone and carbon polymers, and then extruded in a patented process to produce FabRoc® yarn (see Figure 6.6).

Figure 6.6 FabRoc yarn packages.

FabRoc® yarn is currently available as an elastic monofilament, thus allowing textile structures with good recovery properties to be produced. The mixing ratios of carbon and silicone are important, as they determine the overall electrical resistance of the filament yarn. They can be modified to produce varieties from low to high conductivity and resistance. Another crucial property of FabRoc® yarn is its ability to produce a better heating effect than the corresponding metal-based heating yarn. It has more heating power, radiating far-infrared energy, which can be used to provide therapeutic treatment of human skin (EXO2theheatinside, 2014; McAndrew, 2006). Generally, heating textiles consist of yarns for heating, and electrical conduction. In some designs, multiple heating elements are required, which means the designs must use different types of yarns between the elements. Type of yarns and designs to be used in these areas are important. Polyester yarns, as shown in Figure 6.7, are popular due to low cost and high strength.

Sometimes black polyester yarns are used, because the colour black is known for its ability to retain heat, which is needed for heating fabrics. The heating elements would produce heat at certain areas in the fabric, and in non-heating areas, the heat is retained by the black polyester yarns. This translates to fewer heating elements and less power consumption of the fabric. In other cases, a combination of colours can be used in

Figure 6.7 Polyester yarn packages.

heating elements and non-heating elements to create an aesthetic design depending on the end product.

6.3.2 Production process

The computerized flat-bed knitting process was utilised to produce a textile heating system. However, other knitting technologies such as circular weft knitting and warp knitting could also be used. Different types of designs ranging from 2D to 3D designs were produced (see Figure 6.8).

The use of the knitting process enabled the knitted loops and stitches to be cross-linked in order to reduce resistance for heating elements made from FabRoc® yarn.

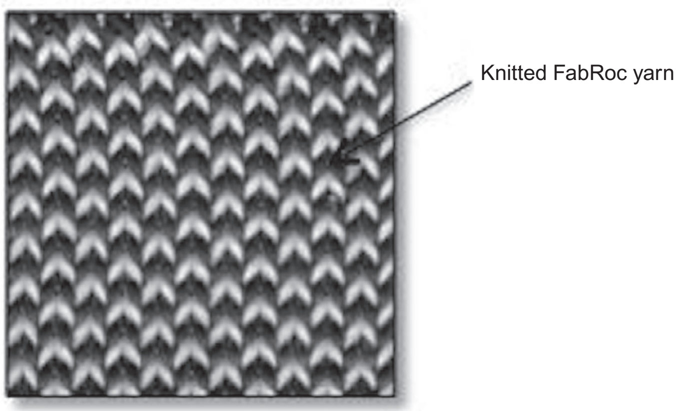

Figure 6.8 The structure of a knitted heater element.

Figure 6.9 Stoll computerised flatbed knitting machine.

Computerised flatbed knitting machines (Figure 6.9) are suitable to produce these heating systems.

Computerized flatbed knitting machines incorporate CAD (Computer-aided design) systems, as shown in Figure 6.10, which allow designs to be made on a computer and then transferred to the machine for knitting. They are versatile, as different kinds of designs can be made on them, ranging from 2D to 3D and whole garments in which a complete seamless garment is produced directly on the machine.

This makes the manufacture of heated textiles more cost effective and reduces the waste of yarn. As stated earlier, FabRoc® yarn is elastic by nature, which challenges knitting process, as FabRoc® yarns tend to stretch during knitting and could break due

Figure 6.10 Stoll CAD system.

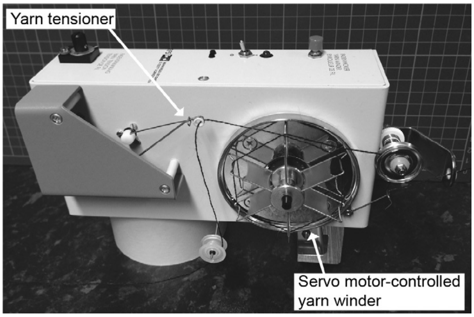

Figure 6.11 Yarn positive delivery system from Memminger GmbH.

to their low breaking strength. In order to avoid yarn breakages and knitting difficulties, a special yarn delivery system from Memminger GmbH was used (Kennon et al., 2000) to deliver FabRoc® yarn at reduced yarn tension. The Memminger system (see Figure 6.11) would deliver yarn at a predetermined yarn tension by using a motor. This technology allowed FabRoc® yarn to be knitted without breakage.

6.3.3 Dimensions of the heaters

In the design and production of knitted polymer-based heaters, size and design influence the heating efficiency. The design of the polymer-based heater in terms of size is crucial. It affects the way electrical connections are made and, as pointed out earlier, knitting polymer-based yarns would reduce the overall resistance and provide high current conductivity for heating to occur. So an optimum size must be found to produce efficient and reliable heaters. The research in the Advanced Textiles Research Group (ATRG) at Nottingham Trent University has shown that narrower sized heaters had significant heating effects compared to wider sized ones (see Figure 6.12).

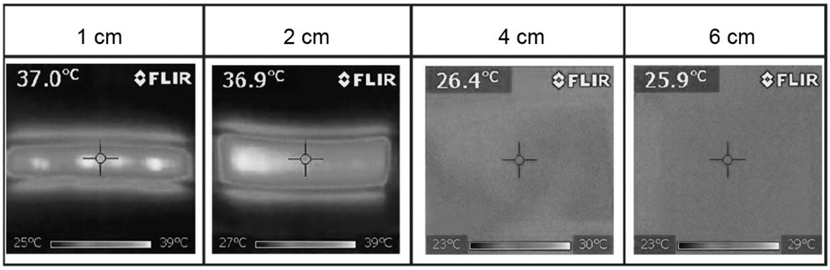

Figure 6.12 Width comparison of thermal images at 3.0 V power supply.

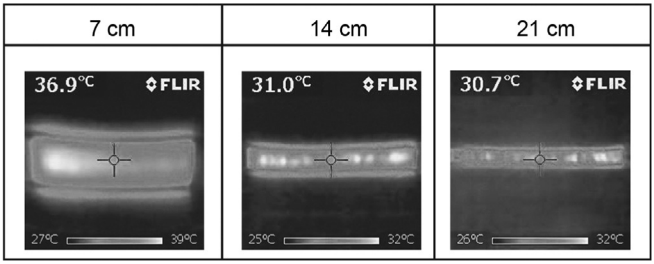

Figure 6.13 Length comparison of thermal images at 3.0 V power supply.

However, the length of the heater elements (Figure 6.13) had no significant change in heating effects. Therefore, when designing knitted heaters one should consider their dimensions carefully.

6.3.4 Electrical connection network

Generally polymer-based heaters are powered by DC power supplies such as batteries. When applied the power supply will facilitate a current to flow through the heating elements, resulting in the generation of heat. This is based on Ohm's law, explained earlier, and in the case of a heating element knitted FabRoc® yarn a current would flow through the knitted loops and stitches of the heating element generating heat. The electrical power to the heating elements is provided by using knitted bus bars, and these are knitted by using a conductive yarn, however, it is essential to use a conductive yarn with a very low resistance to produce the bus bars in order to ensure sufficient current flow from the power supply to the knitted heater. The selection and design of conductive yarns in the knitted structure is important. Different kinds of conductive yarns can be used; one of the popular types is a yarn consisting of fine nylon filaments with a micro layer of silver (Figure 6.14).

The resulting yarn is flexible and has very good conductive properties. Due to its flexibility this yarn can easily be knitted and still conduct a current. It is that the bus bars created with this yarn have a low electrical resistance so that efficient heating can

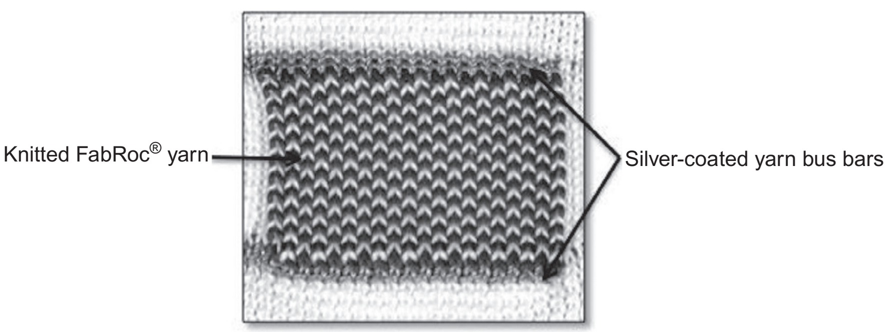

Figure 6.14 Knitted heating element.

be achieved at low voltages. The connections between the bus bars knitted from silver clad nylon yarn and the heater element, which is knitted with FabRoc® are shown in Figure 6.14. All the three important parts, i.e. the bus bars, heating element(s) and connections, of the heating textile structure are created during the knitting process, thus forming an integrally knitted structure. However, any contact between the two bus bars (positive and negative) must be avoided in order to prevent electrical short circuits. A short circuit between the bus bars would result in the development of hot spots in the heated structure and could also damage the power source. The design of the bus bar is important. The research of ATRG has demonstrated that knitting more courses in the bus bars will reduce the electrical resistance and, hence, improve the current flow (Figure 6.15). The research has shown that the electrical resistance dropped significantly when the courses in bus bars were increased to four, and further increase of courses did not have much significance. The research showed that the knitted loops formed a mini-electrical network, which in turn resulted in reduction of the overall resistance of the heater element(s) formed with FabRoc® yarn and bus bars knitted with silver conductive yarn.

6.3.5 Power supply system

Rechargeable batteries could be used to activate a wearable heating system. Battery power is suitable due to their availability and they can be recharged easily. Most rechargeable batteries are made of lithium-ion technology, and they are available in different sizes and shapes (Jha, 2012). This allows power packs to be seamlessly incorporated into the design of the wearable heating systems. For instance, the power source of an EXO2 glove (EXO2theheatinside, 2014) is integrated into the glove and its form has been designed with the shape of the glove in mind, as shown in Figure 6.16. Generally, power supply controllers are also integrated within the power packs to control the power going to the heaters.

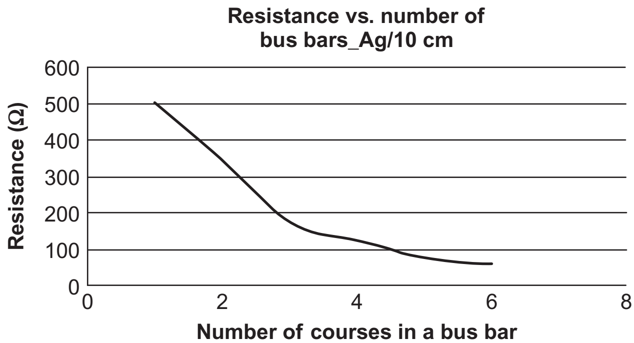

Figure 6.15 Resistance variation with number of courses in a bus bar.

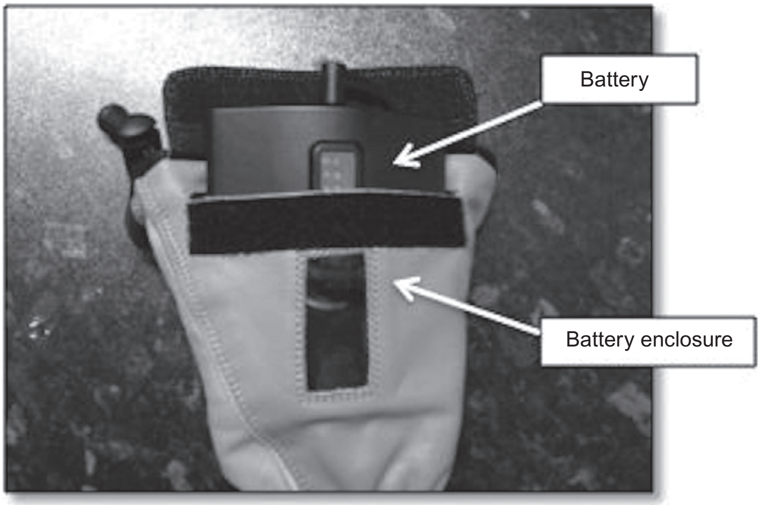

Figure 6.16 EXO2 power pack.

This would allow different heating effects to be achieved, as the controller will regulate the current flowing to heater elements. In some applications, a heating effect for a longer period of time could result in the temperature in certain areas of the heating textile to rise. The control system can be designed to prevent this from happening by switching off the current flow for predefined periods of time. Most of the power packs have integrated power control and management systems.

6.3.6 Post-processing of heating textile structures

During the knitting process yarns are subjected to mechanical stresses, and this has an impact on the size and shape of the stitches of the knitted heating structure. This would influence the dimensional stability of the structure and should be considered during manufacture. Most of these undesired stresses could be eliminated by using a post-processing technique such as steaming, which is very common in the manufacture of knitwear. The steaming process encourages the molecules of the fibres to attain a low energy state, thus causing the knitted structure to relax (Spencer, 2001). Normally, this would cause the knitted structure to shrink slightly; the amount by which the structure shrinks would depend on the type of fibres.

6.4 Applications of polymer-based heating systems

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

6.4.1 Heated gloves

Heated gloves are considered as an entry point for polymer-based heating textiles. In these the heating element could be produced with a carbon loaded silicone yarn such as FabRoc®. In heated gloves, extreme flexibility is required, and due to excessive bending of the arms and fingers, and heating gloves made by using metal wires may not have the required suppleness. The technique of knitting heating elements using FabRoc® yarn has been patented by EXO Technology Ltd as "Thermoknit Technology" (McAndrew, 2006). A heated glove liner has been developed using Thermoknit Technology (see Figure 6.17).

A glove for skiing has been developed by EXO Technology with the glove liner. A rechargeable battery is integrated into the glove to power the heating elements.

6.4.2 Heated fabrics

Heating fabrics have been developed with heating elements knitted with FabRoc® yarn for the number of different applications. In the example given in Figure 6.18 four heater elements are used for heating.

There are many potential applications for heated fabrics which could be used to improve the cabin environment of automotive with heated car seats, parcel shelves and steering wheels, and produce heating garments for sports and recreation outdoor activities. In car seats, polymer-based heating structures could be positioned behind upholstery layers for protection against abrasion. As the focus of car seat designers is more on the aesthetics of the upholstery layer, the polymer-based heating textile layer could be tailored for its performance. Polymer-based heaters are much more flexible than metal-based heaters, as such they could be used to provide heat even into confined places like glove compartments and central consoles of a car due to their superior draping. They would have less chance of fatigue failure in places where constant bending is apparent, for example on adjustable seats. Outdoor activities such as hiking and jogging require the user to have substantial body-covering clothing for warmth and

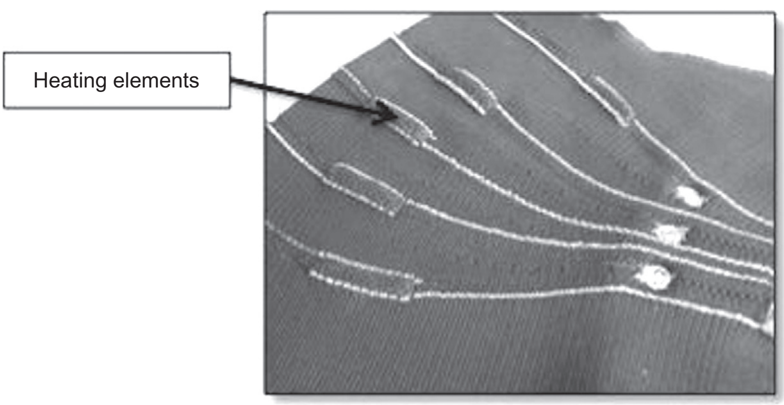

Figure 6.17 Thermoknit glove liner.

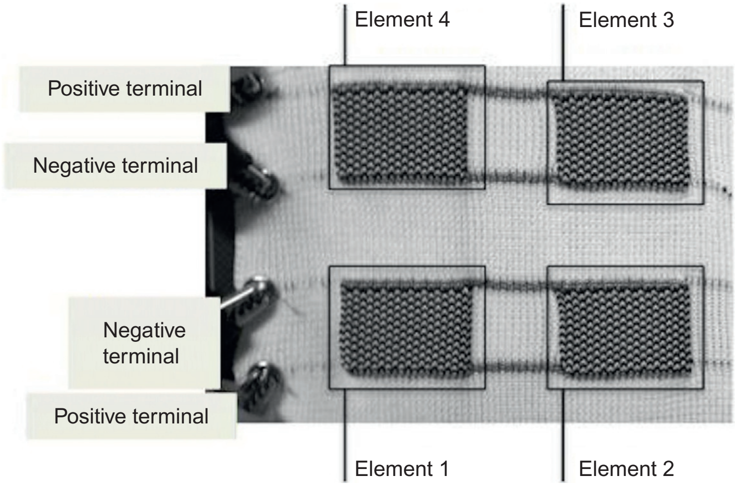

Figure 6.18 Heated fabric square-boxed design.

wind protection. Human body requires maintaining a constant body temperature, and textiles are being used to help maintain body temperature in colder outdoor temperatures. Special clothing has been developed for humans to survive in places of extreme cold weather condition such as the Arctic and Antarctic, where outside temperatures can reach −50 °C. Heated textiles,mostly polymer based, could be used to provide the necessary heating. They are mostly advantageous because they are more efficient and require less electrical power, so smaller, easier to carry, batteries could be used. Polymer-based heaters, as previously seen, are flexible in nature. They can be folded and compacted when not in use, without destroying their structure and performance. This makes them very easy to pack and carry, especially in remote areas such as the Arctic and Antarctic. Polymer-based heaters can be designed to produce efficient knitted vest liners that could be worn in between layers of clothing and provide a heating effect when required. There are heated vests in the market, but washing them seems difficult, as they may lose performance.

6.5 Future trends

Textile-heating systems have come a long way from metal-heating sheets attached to a textile garment, through to knitted heating elements incorporated into a textile material during the production process. This has been a success because textiles can retain their much-needed flexibility and still provide heating functionalities. In terms of performance, future trends could be concentrated on improving the heating efficiency, and power management. Better conducting yarns for connectivity between the power supply and heating elements can be developed to replace the current silver-clad yarns. Silver-clad yarns are expensive. Materials like very fine copper wire could be knitted to provide the connections and bus bars as copper is well known for its high electrical conductivity and excellent antimicrobial substance (Copper, 2015). New ways for designing bus bars and knitting copper into textiles could be well studied in the future.

Another important future trend in heated textiles is the development of more efficient heating yarns. FabRoc® yarn used in current research has variable resistance and conductivity. Future research should concentrate on reducing the variations and on how to produce finer even yarn.

Another area for development is the power supply. Lithium-ion battery technology has been there for quite a long time, and it is time to develop a more compact and efficient battery system that could be used to develop lightweight heating textiles.

6.6 Conclusions

Textile-heating fabrics are one of the important developments in wearable electronic textiles. The integration of electrical heating systems with textiles dates back to 1911 where the concept of attaching metal wires to a glove has been patent. This chapter has demonstrated the development of polymer-based knitted heated textile which could provide a platform for the development of a new generation of heating textiles which could be aesthetically pleasing, lightweight and washable.

6.7 Sources of further reading and advice

The following information site might be useful for further reading about heating textiles:

- http://www.ntu.ac.uk/apps/research/groups/22/home.aspx/group/143751/overview/advanced_textiles.

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