DEVELOPMENT OF TEMPERATURE SENSING FABRIC

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List of Abbreviations

4WRM  Four Wire Resistance Measurement
2WRM  Two Wire Resistance Measurement
ADC   Analogue to Digital Converter
ANS   Autonomic Nervous System
ANSI  American National Standards Institute
ASHRAE American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BS    British Standards
CDX, 95% 95% Confidence Deviation of Parameter X
CNT   Carbon Nano Tubes
Cu plate Copper Plate
CVD   Callender-Van Dusen
DAE   Differential Algebraic Equations
DAQ   Data Acquisition
ECG   Electro-Cardio-Graphy
EU    European Union
GTWM  Georgia Tech Wearable Motherboard
HBT   Human Body Temperature
HTE   Human Thermal Environment
IC    Integrated Circuit
IPRT  Industrial Platinum Resistance Thermometer
IR    Infra-Red
ISO   International Standard Organization
LabVIEW Laboratory Virtual Instrumentation Engineering Workbench
LCM   Lumped Capacitance Method
LED   Light Emitting Diode
NPL   National Physical Laboratory
NTC   Negative Temperature Coefficient
PRT   Platinum Resistance Thermometer
PRT   Platinum Resistance Thermometer
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>PTC</td>
<td>Positive Temperature Coefficient</td>
</tr>
<tr>
<td>PVDF</td>
<td>Polyvinylidene fluoride</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>RR</td>
<td>Resistance Ratio</td>
</tr>
<tr>
<td>RTAQS</td>
<td>Resistance Temperature Acquisition Software</td>
</tr>
<tr>
<td>RTD</td>
<td>Resistance Temperature Detector</td>
</tr>
<tr>
<td>SCI</td>
<td>Serial Communications Interface</td>
</tr>
<tr>
<td>SE</td>
<td>Sensing Element</td>
</tr>
<tr>
<td>SPRT</td>
<td>Standard Platinum Resistance Thermometer</td>
</tr>
<tr>
<td>TR or T-R</td>
<td>Temperature-Resistance</td>
</tr>
<tr>
<td>T-RYZER</td>
<td>Temperature-Resistance Analyzer</td>
</tr>
<tr>
<td>TSF</td>
<td>Temperature Sensing Fabric</td>
</tr>
<tr>
<td>TTC</td>
<td>Thermal Time Constant</td>
</tr>
<tr>
<td>VI</td>
<td>Visual Instrumentation</td>
</tr>
<tr>
<td>WHMS</td>
<td>Wearable Health Monitoring System</td>
</tr>
<tr>
<td>WLIC</td>
<td>William Lee Innovation Centre</td>
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Abstract

Human body temperature is an important indicator of physical performance and condition in terms of comfort, heat or cold stress. The aim of this research was to develop Temperature Sensing Fabric (TSF) for continuous temperature measurement in healthcare applications. The study covers the development and manufacture of TSF by embedding fine metallic wire into the structure of textile material using a commercial computerised knitting machine. The operational principle of TSF is based on the inherent propensity of a metal wire to respond to changes in temperature with variation in its electrical resistance. Over 60 TSF samples were developed with combinations of different sensing elements, two inlay densities and highly textured polyester yarn as the base material. TSF samples were created using either bare or insulated wires with a range of diameters from 50 to 150 μm and metal wires of nickel, copper, tungsten, and nickel coated copper.

In order to investigate the Temperature-Resistance (T-R) relationship of TSF samples for calibration purposes, a customised test rig was developed and monitoring software was created in the LabVIEW environment, to record the temperature and resistance signals simultaneously. TSF samples were tested in various thermal environments, under laboratory conditions and in practical wear trials, to analyse the relationship between the temperature and resistance of the sensing fabric and to develop base line specifications such as sensitivity, resistance ratio, precision, nominal resistance, and response time; the influence of external parameters such as humidity and strain were also monitored. The regression uncertainty was found to be less than ±0.1°C; the repeatability uncertainty was found to be less than ±0.5°C; the manufacturing uncertainty in terms of nominal resistance was found to be ± 2% from its mean.

The experimental T-R relationship of TSF was validated by modelling in the thermo-electrical domain in both steady and transient states. A maximum error of 0.2°C was found between the experimental and modelled T-R relationships. TSF samples made with bare wire sensing elements showed slight variations in their resistance during strain tests, however, samples made with insulated sensing elements did not demonstrate any detectable strain-dependent-resistance error. The overall thermal response of TSF was found to be affected by basal fabric thickness and mass; the effect of RH was not found to be significant. TSF samples with higher-resistance sensing elements performed better than lower-resistance types. Furthermore, TSF samples made using insulated wire were more straightforward to manufacture because of their increased tensile strength and exhibited better sensing performance than samples made with bare wire.

In all the human body wear trials, under steady-state and dynamic conditions both sensors followed the same trends and exhibited similar movement artifacts. When layers of clothing were worn over the sensors, the difference between the response of the TSF and a high-precision reference temperature were reduced by the improved isothermal conditions near the measurement site.
Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Muhammad Dawood Husain
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This thesis is dedicated to my wife Nuzhat Safdar, daughter Azeen Husain and my son Mahd Husain
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Chapter 1  Introduction

1.1  Background Information

1.1.1  Wearable Health Monitoring Systems (WHMS)

Healthcare monitoring is a general concern for patients requiring continuous medical assistance and treatment. In order to boost the mobility of such patients, considerable effort is being invested worldwide in the development of Wearable Health Monitoring Systems (WHMS) to measure vital physiological signs such as respiration movements, cardiac activity, pulse oxymetry and body temperature. The primary requirements of such systems centre on their ability to perform long-term health monitoring and to provide constant feedback to remote healthcare professionals while remaining unobtrusive in respect of the daily activities of the patients. These requirements are best realised by a wearable monitoring system that is truly integrated into everyday clothing. Being comfortable close to the body, textiles offer a flexible platform for the prospective embedding of sensing functions.

The current technologies used for developing a sensing platform for these WHMS have been named “Electronic Textiles (Kirstein, Cottet et al. 2005). During recent years, intensive research has been carried out in the area of electronic textiles for building up sensing platforms for WHMS intended for continuous usage to monitor the human body for vital signs over extended periods of time.

The sensing platform has to deal with the sensors, interconnection technologies, and routing methods for power and signals. One of the key components of this sensing platform is the sensor which gathers data from the wearer and passes it on for further processing. This information could be used to create a health picture for various medical purposes.

1.1.2  Importance of Human Body Temperature Measurement

The core temperature of the human body is one of the four vital signs, used in conjunction with heart rate, blood pressure and respiratory rate for medical assessment of the state of health. Abnormal core temperature information can be an indicator of illness at an initial stage and can be a useful guide to take suitable action. Only few degrees deviation, from the core body temperature i.e. 37 °C, can have serious consequences. Along with core body
temperature, skin temperature is also an important indicator of the physical condition of the human body and relates to comfort, performance, and heat or cold stresses.

In most clinical settings, the core and skin temperatures of the human body are measured in an episodic manner; a few times, on a daily basis. However, there are certain medical conditions when it is important to measure the human body temperature continuously, along with other vital signs. Continuous body temperature measurements are sometimes also performed in non-clinical settings e.g. sports, military, general healthcare, firefighting situations and studies related to biorhythms and assessment of thermal strain in extreme environments.

1.1.3 Research Gap and Motivation

Despite significant research in the context of Wearable Health Monitoring, only a few systems have been commercialised, while several more are still at the development stage. Almost all commercial products are based on removable components and lack the true spirit of electronics-textile integration; however, progress is being made in truly integrated electronic textile-based WHMS. The detailed literature review in Chapter 2 demonstrates that most research has concentrated on the area of ECG and respiration sensors.

However, for temperature sensing, the majority of research work has relied on the temperature sensor (mainly thermistors or ICs) as an external attachment to a smart garment. Few attempts have been made to develop a textile-based temperature sensor. However, those that have been made are preliminary in nature and lack the content relating to the characterisation of the sensor in a laboratory or in its application environment, the effect of material and manufacturing parameters on sensor performance, the effect of external parameters e.g. strains and humidity on sensor performance, the defining baseline specification of the sensor i.e. accuracy, precision, sensitivity, response time, self heating, insulation resistance, effect of human and environmental thermal parameters on sensor performance or the evaluation of sensor performance through thermal modelling.

As there appears to be no previous PhD research dedicated to textile-based temperature sensors, the present study is exploratory in nature. The investigation covers the design, development and manufacture of the Temperature Sensing Fabric (TSF) on an industrial basis, using a computerised knitting machine. The Temperature Sensing Fabric was developed by
embedding fine metallic wire (to act as sensing element) into the structure of textile material. The operational principle of the TSF is based on the inherent propensity of metal wire to respond to changes in temperature with corresponding variation in its electrical resistance. TSF samples have been tested in various thermal environments, under laboratory conditions, to analyse the relationship between the temperature and resistance of the sensing fabric and to develop the base line specifications such as sensitivity, precision, nominal resistance, response time, self heating etc; and to observe the influence of external parameters such as humidity and strain. The performance of the sensing fabric was also compared to a reference sensor by measuring the human body skin temperature under steady-state conditions and in a dynamic environment.

1.2 Aims and Objectives

The primary aim of the research is to develop Temperature Sensing Fabric (TSF), for continuous healthcare monitoring of human body temperature. However, there are different areas of investigation involved in fulfilling the aim. Therefore subsidiary objectives have been set up accordingly.

- Design and construction of TSF by integrating a fine metal wire as a sensing element in a knitted structure.
- Manufacture of TSF samples on a commercial flat-bed knitting machine.
- Development of a test rig to measure the effect of temperature on the resistance of the TSF and creation of testing software to acquire the temperature and resistance from their respective instruments.
- Statistical analysis of the experimental repeats of temperature-resistance data in order to determine the regression, repeatability and manufacturing uncertainties of the TSF samples.
- Defining the baseline characteristics of the TSF (nominal resistance, sensitivity, precision, self heating, resistance ratio, and response time).
- Validation of experimental results by thermal modelling (in the thermo-electrical domain) of test rig components in steady and transient states.
- Investigation of the influence of the external environment (humidity and strain) on TSF sensing performance.
• Testing of the TSF in a practical environment.

1.3 Thesis Organisation

An explanation is provided of the flow of the material contained in this thesis and the contents of this work.

The literature review in Chapter 2 provides an intellectual context for this study. This chapter was divided into four sections: section 1 describes the importance of and the measurement of human body temperature, thermoregulation and continuous temperature measurement; section 2 explains the effect of the human thermal environment on the measurement of human body temperature; section 3 explains the status of temperature sensing in the context of Wearable Health Monitoring Systems (WHMS) along with the identification of gaps in current research; section 4 overviews the most common temperature sensors available on the market with special emphasis on the operational principles, the sensing element and the construction of Resistance Thermometers (RTDs).

Chapter 3 is devoted towards the design, construction and manufacture of Temperature Sensing Fabric (TSF). Initially, the chapter presents the process of conceptualisation of TSF based on the Resistance Temperature Detector (RTD). Latterly, the chapter describes the manufacturing process of TSF on an industrial scale computerised flat-bed knitting machine.

Chapter 4 explains in detail the design, development and behaviour analysis of the test rig which was used to create the Temperature-Resistance (TR) relationship of the TSF sample for calibration purpose. The chapter also elucidates the creation of testing software based on LabVIEW, for the continuous measurement of temperature and the corresponding resistance of TSF samples.

Chapter 5 presents an in-depth analysis of the Temperature-Resistance (T-R) relationship of TSF samples by taking into consideration the uncertainties within experimental repeats (regression uncertainty), amongst repeats of the same sample types (repeatability uncertainty), and amongst samples of the same sample type (manufacturing uncertainty). Prior to analysing the T-R data, this chapter also provides the statistical foundation in terms of the statistical parameters applied to the Temperature-Resistance relationship for comparative purposes.
In chapter 6, the T-R relationship of a TSF will be reproduced by modelling a T-R experiment in the thermo-electrical domain. The chapter describes: the development of a steady state mathematical model of test-rig components through the application of basic heat transfer principles; and the development of a transient version of the model in the Simscape environment.

Chapter 7 investigates the effect of strain and humidity on TSF performance in the laboratory environment. This chapter also includes the comparison of the thermal time constant (thermal response) of TSF samples.

Chapter 8 provides information about the TSF behaviour in an actual application scenario over an extended period of time and its comparison with the reference temperature sensor. The performance of the TSF will be analysed by measuring the human body skin temperature under steady-state and dynamic conditions.

The final chapter summarises and concludes this study. This chapter also suggests future work and further development of Temperature Sensing Fabrics.
Chapter 2 Literature Review

2.1 Introduction

The literature review provides an intellectual context for this study. This chapter was divided into four sections: Section 01 describes the importance and measurement of human body temperature, thermoregulation and continuous temperature measurement; Section 2 explains the effect of human thermal environment on measurement of human body temperature; Section 3 enlightens the status of temperature sensing in context of Wearable Health Monitoring Systems (WHMS) along with the identification of research gap; Section 4 overviews the most common temperature sensor available in market with special emphasis on the operation principle, sensing element and construction of Resistance Thermometers (RTDs).

2.2 Human Body Temperature

2.2.1 Temperature and Temperature Scale

Temperature is the most measured environmental quantity because most physical, electronic, chemical, mechanical, and biological systems are affected by temperature (McGee 1988). Max Planck defined temperature as the “Degree of hotness or coldness of a body”. It can be considered to be the level of thermal energy, having an ability to transfer it to other bodies. Hot bodies transfer heat to cold bodies. Both bodies tend to equalise their temperatures by approaching a new common intermediate temperature. So we can say that temperature is the driving force for heat flow, just like voltage is the driving force for electrical flow and hydrostatic head is the driving force for fluid flow. Heat transfer considerations are very important in every temperature measuring situation (Michalski, Eckersdorf et al. 1991).

The two primary degree units for measurement of temperature in use today are based on the Centigrade and Fahrenheit scales. In between the ice point and the boiling point of water, the Centigrade scale is divided into a hundred equal parts (from 0 °C to 100 °C) while the Fahrenheit scale is divided into 180 equal parts (from 32 °F to 212 °F). That makes the Fahrenheit degree comparatively smaller i.e. 1 degree Centigrade equals to 1.8 degrees Fahrenheit. Kelvin and Rankine are absolute temperature scales based on Centigrade and
Fahrenheit scales respectively (McGee 1988). In this thesis, in order to avoid any confusion, temperature is represented using only the Centigrade scale.

Body temperature is one of the four vital signs which are standard in medical settings in addition to heart rate, blood pressure and respiratory rate. Vital signs are measurements of the physiological condition of the human body and reveal the body’s ability to regulate body temperature, maintain blood flow and oxygenate body tissues (Funnell, Koutoukidis et al. 2008).

Human body temperature is an important indicator of its physical condition and is related to comfort, heat or cold stress and performance. Only few degrees deviation (± 3.5 °C), from the normal body temperature i.e. 37 °C, can cause impairments and fatality to the human body (Parsons 2003) (Jardine 2007).

2.2.2 Human Thermoregulation

Human body temperature may be referred to by various terms i.e. core, shell, skin, and mean body temperature. These terms are not interchangeable; therefore it is desirable to understand them to have good insight of the human thermoregulatory system.

The body can be considered conceptually in two parts; a core and a shell (see Figure 2.4). Humans are homeotherms and attempt to maintain core body temperature around 37 °C through their sophisticated feedback control system known as the Thermoregulatory system. And as part of the thermoregulation, the shell temperature \( T_{sh} \) varies (Parsons 2003). Core temperature is generally considered to be the inner body temperature or the temperature of the vital organs including the brain (Funnell, Koutoukidis et al. 2008). The temperature of the shell (outer tissues of the body) varies with external environmental conditions and the thermoregulatory state of the body (vasodilated, sweating, etc). Shell temperature is often taken as the mean skin temperature \( T_{sk} \) over the body. Mean skin temperature is commonly calculated by taking a weighted, average of temperature from a number of body sites (ISO 9886 2004). Local skin temperature may vary from the mean. In cold conditions, for example, the feet and hands can have much lower skin temperatures than the trunk or forehead.
There are numerous proposed models of the human thermoregulatory system (Parsons 2003). Although they may be different in their composition, some of the parameters are identical and explain the human thermoregulatory system well. All models recognise that when the body becomes hot, it loses heat by vasodilation and if required, by sweating. If the body becomes cold then heat is preserved by vasoconstriction and, if necessary, generated by shivering. Another fundamental point of agreement is that the primary control centre for thermoregulation is the Hypothalamus (Charkoudian 2003). The Hypothalamus is a region of the brain, that functions as the main control centre for the Autonomic Nervous System (ANS) by regulating sleep cycles, body temperature, appetite, etc (Dictionary.com 2002).

![Figure 2.1: Simplified diagram of human thermoregulatory system](image)

The hypothalamus maintains the core body temperature by controlling the rate of heat production, and heat loss from the skin to the environment. For this it requires a constant feedback from the thermo sensors, distributed across the human body (see Figure 2.1). If the core temperature rises above the set point the hypothalamus causes vasodilation and sweating and lowers the heat generation. Similarly, reduction in core temperature increases the heat generation and vasoconstricts the skin (Charkoudian 2003).

Counter-current heat exchange is an extremely efficient way of minimising heat loss through the skin’s surface because some percentage of metabolic heat is recycled instead of being dissipated completely. The vessels carrying blood, to the skin (arteries), and away from the skin (veins) are very close to each other. These vessels are close enough that when arterial blood loses heat, the returning cold blood picks up the heat and increases in temperature (see Figure 2.2). This system helps to conserve heat in extremely cold environments (Ash 2000).
2.2.3 Human Body Core Temperature

Core temperature has no definition, as core tissues are not defined. However it is generally considered to be the inner body temperature or the temperature of the vital organs including the brain. However temperature differences are likely within the core depending on: local heat generation; concentration of vascular networks; and local changes in blood flow. These core tissues are maintained within a narrow range of temperatures by thermoregulation (Parsons 2003) (ISO 9886 2004).

If core temperature rises or falls by some degrees from the set value then hyperthermia (an abnormally high core body temperature) or hypothermia (an abnormally low core body temperature) may occur and can have serious consequences on human health (Parsons 2003) (see Figure 2.3). Hyperthermia is often caused by infection (known as fever), use of certain drugs and illness related to heat stress (Bridges and Thomas 2009) (ISO 9886 2004). Although both fever and heat related illnesses are classified as hyperthermia, there are fundamental differences in their thermoregulatory process and medical treatments. Hypothermia is often caused by prolonged exposure to cold (Sung, DeVaul et al. 2004).
Fever is usually accompanied by infections and other diseases. In the case of infection, the thermoregulation system is set erroneously at a new elevated level by pyrogens; however, the core temperature remains under the control of the central thermoregulatory system. In order to maintain that new level, metabolic heat generation is remarkably increased and dissipation of heat from the body is inhibited by peripheral vasoconstriction and decreased blood flow. In spite of the high fever, a patient feels cold and shivers (Jardine 2007).

Abnormal core temperature information can be an indicator of illness at an initial stage and can be a useful guide to take suitable action. Besides infectious diseases, fever is also a common symptom of many other medical conditions e.g. skin inflammations, immunological diseases, tissue destruction, reaction to incompatible blood products, certain cancers, metabolic disorders and thromboembolic processes (Pusnik and Miklavc 2009; Van Vliet, Donnelly et al. 2010).

When the thermoregulatory system cannot retain the body core temperature within its set point limits, thermal stress may occur. Thermal stress is not caused by any diseases but results from a combination of various factors such as extra metabolic heat generation within the body during exercise, prolonged exposure to an extremely hot thermal environment (high air and radiant temperature and high humidity), low air velocity and reduced evaporation of sweat. When the body becomes unable to cool itself, heat-induced illness such as heat stress and heat exhaustion may result. At this stage, if the situation is not treated quickly, it may lead to a deadly form of heat illness called heat stroke. This usually happens when the core body temperature exceeds 40 °C (Wexler 2002) (Jardine 2007).

The medical condition in which a person’s body core temperature drops to less than 35°C is known as hypothermia. This may greatly impair the functioning of the thermoregulatory system and further leads to the decreased activity of cells, less production of metabolic heat, sleepiness or coma. This could happen to post operative clients who were cooled during surgery or to any person subjected to long-term exposure to extreme cold conditions (Sung, DeVaul et al. 2004) (Funnell, Koutoukidis et al. 2008).

2.2.3.1 Thermometers for core temperature measurement

Clinical thermometers used for core body temperature measurement are usually required to cover a temperature range from 35 °C to 42 °C as most physiological and pathological
temperature variations occur within this range (Togawa 1985). The accuracy requirement of clinical thermometers depends upon the diagnostic and monitoring criteria. However, an absolute accuracy of 0.2 °C is acceptable for most purposes (Draft ISO 80100 2006).

A number of methods (by using different temperature sensors on various body sites) can be used to estimate core temperature for diagnosis and monitoring purpose. Temperatures can be measured from the internal organs or from the skin surface (Draft ISO 80100 2006). Most common body sites include axilla, mouth, rectum, forehead and tympanic membrane (Parsons 2003). Temperature sensors include thermistors, thermocouples, resistance thermometers, crystal resonators, infrared detectors, microwave radiometers, liquid crystals and chemical indicators. (Togawa 1985). A couple of decades ago, the oral site (mouth) along with a mercury-in-glass thermometer was the most common standard clinical setting which has gradually been replaced by the use of infrared thermometers at the tympanic site (Funnell, Koutoukidis et al. 2008).

Clinical thermometers can be invasive or non-invasive depending upon their usage in a particular medical environment. Usually invasive methods are more accurate than non-invasive methods (Draft ISO 80100 2006). The current “gold standards” in medical thermometry are invasive in nature i.e. oesophageal temperature measurement and pulmonary artery temperature measurement by pulmonary artery catheterisation. The discomfort that accompanies these approaches has discouraged their widespread use. However, during surgical procedures where minute changes in temperature are significant, doctors still rely on the “gold standards” (Parsons 2003).

Non-invasive medical thermometry includes oral, ear-based, forehead-based and axilla-based methods. Measurement of core temperature by placing a thermometer in the axilla is the least commonly used site in hospitalised patients however it is the most convenient site for variety of situations (Giuffre, Heidenreich et al. 1990). Rubia-Rubia et al. investigated the variety of clinical thermometers in terms of their accuracy, reliability and validity in common clinical environments. They concluded that the use of a compact digital sensor at the right axilla is the most appropriate setting when considering patient comfort, ease of use, safety, speed, durability and costs (Rubia-Rubia, Arias et al. 2001).
In comparison with other invasive and non-invasive methods, axilla-based core temperature measurement may be prone to environmental effects and could take a longer time to register the temperature. Therefore it is important to close the axilla region completely while measurement is in progress. It has been widely reported that axilla temperatures are usually 0.5 °C lower than the core body temperature measured by “gold standard” methods (Bridges and Thomas 2009) (Pusnik and Miklavec 2009).

Some studies have reported new ideas about non-invasive measurement of human body core temperature. e.g. (Steck, Sparrow et al. 2011) investigated the new non-invasive approach by deploying a foam pad thermal resistor on the forehead. The thermal resistor detects the heat flux coming through forehead and calculates the core temperature according to the designed algorithm.

### 2.2.4 Human Body Skin Temperature

The skin is the human body’s largest organ, accounting for about 16% of body weight and is also the most responsive organ for detecting heat, touch and pain. On average skin is about 1 mm thick and consists of two distinct layers of tissue i.e. the epidermis and the dermis. The epidermis is the outermost layer of the human body and serves as the body’s initial barrier against invading foreign substances. Below the epidermis layer, there is a thicker dermis layer made of dense connected tissue. This layer contains sweat glands blood vessels, and thermo receptors which detect temperature change (BBC Science 2012) (Funnell, Koutoukidis et al. 2008).

Skin temperatures vary considerably over the surface of the human body because the balance between heat generation and heat exchange with the environment is different for different body parts (Charkoudian 2003). This variation is more pronounced in cold conditions than in moderate or hot conditions. Therefore a distinction should be made between the local skin temperature measured on a specific body part, and the mean skin temperature over the entire surface of the body (ISO 9886 2004).
Skin temperature is influenced by: the heat exchanges at the surface of the skin by conduction, convection, radiation and evaporation; the variations in skin blood flow; the temperature of the arterial blood reaching the particular body site; and the metabolic heat generation (ISO 9886 2004). The temperature of the skin varies between ambient and body core temperature (Togawa 1985); this could be as low as 15 °C and as high as 43 °C because of extreme thermal stress.

The skin temperature profile on the surface of the human body offers various kinds of information valuable for clinical diagnosis. Abnormalities of skin temperature distribution are often studied together with unusual peripheral blood circulation (Charkoudian 2003), vascularisation or heat production in the underlying tissue (Togawa 1985), or diagnosis of nerve compression (Anbar 1998). Measurement of skin temperature is also important for the assessment of thermal stress in cold, moderate and hot environments (ISO 9886 2004).

2.2.4.1 Thermometers for skin temperature measurement

Depending upon the medical condition, and diagnosis & monitoring requirements, human body skin temperature may be measured by contact or non-contact methods; at single body point or over a particular body area. Whatever the method used, measurement should be made by an instrument with a precision of ± 0.1 °C in the range of 25 °C to 40 °C. (ISO 9886 2004)

Contact thermometers can be employed at the skin surface under clothing and are suitable for continuous measurement for extended durations (Giansanti and Maccioni 2007).
The sensor should be flat, asymmetrical and in good contact with the skin. In order to reduce the contact thermal resistance, the sensor can be attached to the skin with thermally conductive adhesive tape. In order to avoid environmental effects, any part of the sensor surface not in contact with skin, should be thermally isolated.

Radiation thermometers, however, provide temperature information about the human body, on the surface (Infrared thermography), and under the surface (Microwave thermography) by non-contact measurement (Mustata, Baltag et al. 2009) (Barrett, Myers et al. 1980). Microwave radiation can penetrate human tissue; therefore the emission provides temperature distribution at a subcutaneous level. Infrared radiation is incapable of such penetration and hence relates only to skin temperature distribution. However infrared thermography yields much finer spatial resolution (of the order of 1 mm) than microwave thermography (of the order of 1 cm) (Barrett, Myers et al. 1980).

Non-contact methods are preferred over contact thermometry whenever technically possible. However, this necessitates the subject to be naked and requires knowledge of the exact emissivity value of the skin area to be measured (ISO 9886 2004) (Togawa 1985). On a positive side, non-contact methods do not subject the patient to radiation exposures, pain, and physical discomfort. (Barrett, Myers et al. 1980). The most popular use of thermography is for breast cancer screening (Mustata, Baltag et al. 2009).

2.2.5 Continuous Temperature measurement

In most clinical settings, the core or skin temperature of the human body is measured in an episodic manner; a few times, on a daily basis. However, there are certain medical conditions when it’s important to measure the human body core temperature continuously along with other vital signs e.g. during surgical procedures (Parsons 2003). (Van Vliet, Donnelly et al. 2010) reported the importance of continuous skin temperature measurement of neutropenic patients. These patients are at risk of inflammatory response syndrome, infection or even death. Continuous skin temperature measurement can help to initiate the required therapy to deal with the infection, by earlier detection of fever.

Hyperthermia or hypothermia treatments both involve continuous measurement of body temperature to achieve the required core body temperature e.g. hypothermia-treatment after
cardiac arrest (Nolan, Morley et al. 2003). The hypothermia treatment repairs and preserves vital brain cells that have been damaged due to the cardiac arrest and maintains neurological function. A non-invasive hypothermia treatment is usually done by cooling blankets which work both as a cooling medium and as a sensing platform and maintain the body temperature within limits of 32-34 °C for 12-24 hours. In a similar way, a person subjected to hypothermia because of cold stress, may required hyperthermia-treatment to regain the normal body temperature. (MTRE 2012) (Lewis 2011)

In a clinical environment, patients may be monitored round-the-clock without involving extra personnel by the use of continuous temperature measurement. Similarly continuous body temperature measurements are sometimes also performed in non-clinical settings e.g. sports, military, general healthcare, firefighting situations and studies related to biorhythms and assessment of thermal strain in extreme environments (Sung, DeVaul et al. 2004) (ISO 9886 2004) (van Marken Lichtenbelt, Daanen et al. 2006) (Oliveira, Gehin et al. 2009) (Corbellini, Ferraris et al. 2008).
2.3 Human Thermal Environment

The skin temperature of the human body can be estimated/determined by application of a basic heat transfer model across the [Human body—Clothing—Environment] system. The primary modes of heat transfer in these models are conduction, convection, radiation and evaporation. The rate of heat transfer via these modes depends upon the parameters of the Human Thermal Environment (HTE). Environmental parameters include the air temperature, radiant temperature, air velocity, and relative humidity. Human parameters include heat generation within the body to maintain core temperature and clothing insulation properties. Effective clothing insulation may be influenced by body size, posture, fitting of clothes and body movement. Therefore in order to estimate the skin temperature it is necessary to develop an understanding of the effect of environmental and personal variables on the various modes of heat transfer.

2.3.1 Basic parameters of Human Thermal Environment

Often people evaluate environmental limits only in terms of air temperature, which is inadequate in many situations, as all other HTE parameters are important as well. The human body interacts with the environment in a dynamic way and this determines the human response. If the human response is not appropriate in respect of the environmental parameters or if energy levels are beyond the survival limits, then this may lead to death (Parsons 2003). This section will briefly explain the parameters of the human thermal environment and their effect on skin temperature.

Air Temperature is the driving force for heat transfer between the human body and the surrounding air. Keeping the rest of the HTE parameters constant, there is a direct relationship between skin temperature and air temperature (ANSI/ASHRAE 55-2004; Parsons 2003). Besides air temperature, Radiant Temperature also influences the human body skin temperature. It’s the particular orientation of the human body towards a radiating surface which has the greatest influence on the effect caused by radiant energy (Parsons 2003).

Humidity may be defined as the density of water vapour in the air at a particular air temperature. The difference in absolute humidity between the surface of the skin and the
environment is the driving force for the vapour or mass transfer from the skin of the human body. Humidity is one of the most important environmental factors for the adsorbed water content of clothing and does influence the rate of evaporation of sweat from the skin (Parsons 2003) (Fourt and Hollies 1970). Depending upon the skin wetness, humidity can have a slight affect on skin temperature (Onofrei, Rocha et al. 2011). For a high skin wetness index (which could be because of high air temperature or high activity levels), skin temperature is directly proportional to the humidity in the environment. When humidity is low, dry air acts like a sponge and soaks up moisture faster from a sweating human body. Depending upon the rate of evaporation, skin temperature will drop and create a cooling effect at the human skin (Fbeeman and Lengyel 1938; Anonymous 2011).

**Air Movement** (in combination with air temperature) controls the rate at which warm air or vapour is taken away from the body, thus affecting the body temperature. Air movement can best be described in terms of mean air velocity intensity over an exposure time of interest and integrated over all directions (Parsons 2003). Keeping the rest of the HTE parameters constant, there is an inverse relationship between skin temperature and air movement (Havenith, Holmer et al. 2002). High air velocity may cause local unwanted cooling, termed as draft. Unclothed skin is more sensitive to draft (ASHRAE 2009).

**Clothing** provides a thermal resistance between the human body and its environment. Besides cultural, physiological and psychological aspects of clothing, one of its functional roles is to maintain the body in an acceptable thermal state in a variety of environments (Parsons 2003). Overall clothing resistance depends upon the number of clothing layers, material, thickness, air permeability and bulkiness (Fourt and Hollies 1970; Parsons, Havenith et al. 1999). Certainly body movements, body postures and body geometry along with size and fit of clothing could have significant impact on the effective clothing resistance to energy transfer. Keeping the rest of the HTE parameters constant, there is a direct relationship between skin temperature and clothing insulation (ISO 9920 2009).

Heat production within the body is related to the activity of the individual. A person takes-in oxygen while breathing which is transported by the blood to the cells of the body. This oxygen is used to burn food which releases heat energy, termed as **Metabolic Heat** (Parsons 2003).
Keeping the rest of the HTE parameters constant, there is a direct relationship between skin temperature and metabolic heat generation (ISO 8996 2004E).

2.3.2 Modes of Heat Transfer

Heat can be transferred from the skin or through clothing ensembles to the environment using the transfer mechanisms of conduction, radiation, convection and evaporation.

Conduction is a process in which heat is transferred through a body by faster moving molecules of higher temperature to slower moving molecules of lower temperature. The process can occur in either the solid, fluid or gaseous states. According to Fourier’s law, heat conduction \( Q_{\text{cond}} \) through a body is directly proportional to the difference of temperature \( \Delta T \) across the body and the heat transfer area \( A \), but is inversely proportional to the thickness \( L \) of the body (Saville 1999).

\[
Q_{\text{cond}} = \frac{KA\Delta T}{L}
\]  

(2.1)

Where the constant of proportionality \( (k) \) is the thermal conductivity of the material, which is the measure of a material's ability to conduct heat. Textile fibres usually have their thermal conductivity values in between 0.1-0.2 W/m°C however thermal conductivities of fabrics are generally lowers than 0.1 W/m°C mainly because of the presence of less conductive air pockets within the fabric (Cengel 2003).

Convection is a process in which heat is transferred from one point to another within a fluid, or from solid body to fluid, by bulk movement of fluid molecules. The motion of the fluid may be entirely the result of differences of density due to the temperature differences, as in natural convection; or produced by an external force, as in forced convection. According to Newton’s law of cooling, heat convection \( Q_{\text{conv}} \) from the surface of solid body to the environment can be expressed as (Lienhard IV and Lienhard V 2008):

\[
Q_{\text{conv}} = h_c A_s (T_s - T_\infty)
\]

(2.2)

Where:

- \( h_c \) is the convective heat transfer coefficient in \( \frac{W}{m^2 \ C} \);
- \( A_s \) is the surface area through which transfer of heat by convection takes place;
$T_s$ is the surface temperature; and

$T_\infty$ is the temperature of the fluid sufficiently far from the surface.

Note that the fluid temperature at the surface of solid equals to the surface temperature of the solids. The convective heat transfer coefficient does not depend entirely on fluid properties. It usually measured experimentally and its value is influenced by surface geometry, surface roughness, nature of fluid motion, and properties of fluid (Sukhatme 2008).

**Radiation** is the heat exchange between a hotter and a colder body by emitting and absorbing radiant energy. Heat exchange by radiation depends only on the temperature and the nature of the surface of the radiating objects. The radiant heat exchange ($Q_{rad}$) between a solid surfaces and its surrounding can be expressed as (Cengel 2003):

$$Q_{rad} = \varepsilon \sigma A_s (T_s^4 - T_\infty^4)$$  \hspace{1cm} (2.3)

Where:

- $\varepsilon$ is the emissivity of solid surface;
- $\sigma$ is the Stephen Boltzmann constant \( \left( \sigma = 5.67 \times 10^{-8} \text{W/m}^2 \cdot \text{K} \right) \);
- $A_s$ is the surface area completely enclosed by its surroundings;
- $T_s$ and $T_\infty$ are the absolute temperatures of the solid surface and the surroundings respectively.

The radiation heat exchange expression can be expressed in the form of Newton’s law of cooling as (Sukhatme 2008):

$$Q_{rad} = h_r A_s (T_s - T_\infty)$$  \hspace{1cm} (2.4)

Where $h_r$ is the radiative heat transfer coefficient in $W/m^2 \degree C$.

**Evaporation** is the latent heat transfer process in which heat is carried from one place to another by the movement of a substance which absorbs or dissipates heat by a change of phase. The evaporative heat transfer ($Q_{evap}$) between a solid surface and the environment can be expressed as (Parsons 2003):

$$Q_{evap} = h_e A_s (P_s - P_\infty)$$  \hspace{1cm} (2.5)
Where $h_e$ is the evaporative heat transfer coefficient and relates to the convective heat transfer coefficient by the Lewis number (ISO 9920 2009) i.e. $h_e = 16.5h_c \, m^2kPa/W$, $A_s$ is the surface area through which evaporation takes place, $P_s$ is the saturated vapour pressure at the surface of the body, and $P_\infty$ is the partial vapour pressure in the environment.

Equations (2.1)(2.2)(2.3)(2.4) represent the dry heat transfer while equation (2.5) represents the latent heat transfer.

### 2.3.3 Heat Balance Equation

Metabolic heat is distributed throughout the body mainly by blood to maintain the core body temperature. Excessive heat is lost into the environment via a complex dynamic process. If there is no heat loss to the environment, the heat will be stored and body temperature will rise by 1 °C per hour for a resting person (Parsons 2003). To maintain the body temperature at 37 °C, the excess heat dissipates through various mechanisms as described in the heat balance equation. If the heat loss and the heat generation are equal, the person will achieve a heat balance condition. The heat balance indicates how well humans can maintain thermal comfort conditions at the skin and core temperature near to 37 °C (ASHRAE 2009).

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the heat balance equation at the skin surface of a human body can be expressed as (ASHRAE 2009):

$$M - W = Q_{sk} + Q_{res} + S = (C + R + E_{sk}) + C_{res} + E_{res} + (S_{sk} + S_{cr})$$

(2.6)

The metabolic rate of the body (M) provides the energy to enable the body to do mechanical work (W) and the remainder (M-W) is released as heat to the environment through the skin surface ($Q_{sk}$) and as a result of the respiratory process ($Q_{res}$), with any extra or deficit stored ($S$), causing the body’s temperature to increase or decrease. Where:

- $M$ is the rate of metabolic energy production,
- $W$ is the rate of mechanical work,
- $Q_{sk}$ is the total rate of heat loss from the skin,
- $Q_{res}$ is the total rate of heat loss from respiration,
- $S$ is the heat stored in the body in surplus or deficit,
- $C$ is the rate of convective heat loss from the skin,
R is the rate of radiative heat loss from the skin,  
E_{sk} is the rate of total evaporative heat loss from the skin,  
C_{res} is the rate of convective heat loss from respiration,  
E_{res} is the rate of evaporative heat loss from respiration,  
S_{sk} is the rate of heat storage in skin compartment and  
S_{cr} is the rate of heat storage in core compartment.

Heat dissipates from the body to the immediate surroundings by several modes of heat transfer:  
Sensible heat flow from the skin (C+R) and during respiration (C_{res}); and Latent heat flow from the skin (E_{sk}) and during respiration (E_{res}). These modes of heat transfer are all influenced by the shape of the human body and the clothing assembly which may not be exactly described. They are also affected by the conditions of the human body such as skin temperature, skin wetness, and body movement along with the HTE parameters discussed before. Human body heat exchange avenues are illustrated in Figure 2.5.

Figure 2.5: Energy exchange of the human body within the environment (Derchak, Ostertag et al.)

2.3.4 Basic Heat Transfer Model

According to the Heat balance equation, heat loss from the skin can be categorised into sensible heat loss and latent heat loss. For a clothed person, sensible heat flow from the skin is a complex mixture of conduction, convection and radiation but at the outer clothing surface, it is
equal to the sum of convection and radiation heat transfer. However, latent heat transfer is achieved by moisture transmission which is derived from the difference in partial water vapour pressure between the skin surface and the environment.

### 2.3.4.1 Sensible Heat Loss from Skin

The sensible heat flow from the skin passes through the clothing to the surrounding environment. The path of heat flow can be divided into two thermal resistance layers which can be connected in series as shown in Figure 2.6:

1. Layer A - from the skin surface, through the clothing insulation, to the outer clothing surface; and
2. Layer B - from the outer clothing surface to the environment.

The actual transport of sensible heat through clothing involves conduction, convection, and radiation. It is usually most convenient to combine the individual thermal resistance components of each heat transfer mode into a single thermal resistance value i.e. $R_{ct}$. By applying Fourier’s law, heat transfer across clothing can be expressed as:

$$Q_{cond} = \frac{A(T_{sk} - T_{ct})}{R_{ct}} \quad (2.7)$$

According to Newton’s law of cooling, both convective $Q_{conv}$ and radiative $Q_{rad}$ heat losses from the outer surface of a clothed body can be expressed in terms of their respective heat transfer coefficients and the difference between the temperature of the outer surface of the clothing $T_{ct}$ and the appropriate environmental temperature.

$$Q_{conv} = h_c A (T_{ct} - T_a) \quad (2.8)$$
$$Q_{rad} = h_r A (T_{ct} - T_r) \quad (2.9)$$

Where:

$h_c$ and $h_r$ are the Convective and Radiative heat transfer coefficients (evaluated at the clothing surface);

$T_a$ and $T_r$ are the Environmental air temperature and the mean radiant temperature.
Equations (2.8) and (2.9) may be combined to describe the total sensible heat loss by these two modes in terms of an operative temperature $T_o$ and a combined heat transfer coefficient $h$, hence:

$$Q_{rad} + Q_{conv} = hA(T_{cl} - T_o) \quad (2.10)$$

Where, the Operative temperature $T_o$ can be defined as the average of the mean radiant and ambient temperatures, weighted by their respective heat transfer coefficients.

$$h = h_c + h_r \quad (2.11)$$

$$T_o = \frac{h_r T_r + h_c T_a}{h_r + h_c} \quad (2.12)$$

In a steady state condition, total heat flow through the clothing $Q_{cond}$ should be equal to the total heat flow escaping from the clothing ($Q_{rad} + Q_{conv}$). Therefore equation (2.7) and (2.10) can be combined to eliminate the clothing surface temperature $T_{cl}$ which is quite often inconvenient to measure.

$$Q_{cond} = Q_{rad} + Q_{conv} = \frac{A(T_{sk} - T_o)}{R_{cl} + R_a} \quad (2.13)$$

or

$$T_{sk} = T_o + \frac{Q_{cond}(R_{cl} + R_a)}{A}$$

Where $(R_a = 1/h)$ is the combined convective and radiative thermal resistance of the environment.

---

**Figure 2.6:** A simple thermal sensible heat loss model of a heated body
2.3.4.2 Evaporative Heat Loss from Skin

Evaporative heat loss ($E_{sk}$) from the skin depends upon the amount of moisture on the skin and the difference between the water vapour pressure at the skin and in the ambient environment:

$$E_{sk} = \frac{Aw(P_{sk,s} - P_a)}{R_{ecl} + R_{ea}}$$  \hspace{1cm} (2.14)

Where:

- $w$ = skin wetness (dimensionless);
- $P_{sk,s}$ = saturated vapor pressure at skin (at $T_{sk}$);
- $P_a$ = vapor pressure in ambient air;
- $R_{ecl}$ = evaporative heat transfer resistance of clothing;
- $R_{ea} = 1/h_e$ evaporative heat transfer resistance between the clothing and the environment.

Skin wetness is the ratio of the actual sweating rate to the maximum possible sweating rate that would occur if the skin were completely wet. Skin wetness is important in determining evaporative heat loss. Maximum evaporative potential $E_{max}$ occurs when $w=1$. The minimum the evaporative heat loss from the skin surface occurs when $w = 0.06$. At this value evaporation occurs entirely due to the diffusion of water vapour through the outer layers of the skin (Parsons 2003).

Among all heat losses, the most important means to dump heat to the environment is by Evaporation ($E_{sk}$) (Onofrei, Rocha et al. 2011). Evaporation removes a relatively a large amount of energy and can effectively cool the body across a wide range of ambient temperatures and
workloads. In fact, as long as evaporation can continue from the surface of the skin, the body can cool itself in all but in the most extreme environments. Body temperature can increase dramatically to dangerous levels if due to any reason evaporation cannot occur. This may happen when there is high humidity in the environment or sweating is inhibited due to dehydration (Derchak, Ostertag et al.).

2.3.4.3 Total Skin Heat Loss

When dry and latent heat transfer exist simultaneously, the total skin heat loss \( Q_{sk} \) can be estimated by combining equations (2.13) and (2.14).

\[
Q_{sk} = Q_{conv} + Q_{rad} + E_{sk} = A\left[\frac{(T_{sk} - T_o)}{R_{cl} + R_a} + \frac{w(P_{sk,s} - P_a)}{R_{ecl} + R_{ea}}\right]
\]  

(2.15)

In the above formula, dry and latent heat transfer are treated independently, and this only describes the main principles involved in the transfer of heat through clothing. Under many circumstances, by using the above formula, the heat transfer may well be underestimated due to the effect of adsorption of water, buffering and the pumping effect (Fan 1989; Parsons 2003; ISO 9920 2009). Various British/ISO standards (ISO 7726 2001; ISO 8996 2004E; ISO 9920 2009) are available regarding the required instrument characteristics and measurement procedures needed to acquire the parameters of this heat loss equation.

ISO 8996 explains the different methods for the determination of metabolic rate in the context of the ergonomics of the climatic working environment (ISO 8996 2004E). Heat loss from the skin may be estimated by the deduction of energy required to perform work from the total metabolic heat production (ASHRAE 2009).

ISO 7726 provides guidance about the instrument requirements and methods of measurement of environmental parameters i.e. air temperature, radiant temperature, and humidity (ISO 7726 2001).

ISO 9920 provides methods to determine clothing thermal characteristics i.e. resistance to dry heat loss \( R_{cl} + R_a \) and resistance to evaporative heat loss \( R_{ecl} + R_{ea} \) under a steady state.
conditions. The standard provides tables of thermal resistance values of various clothing types and for separate garments. The thermal resistance values of garments can be added to create the required clothing type (ISO 9920 2009).

The standard also provides a description of how to actually measure the thermal resistance values of clothing using a thermal or sweating mannequin in a standard conditions, defined as, a static mannequin with marginal air movement (typically less than 0.2m/s) in an indoor environment. The older version of the standard does not take account of air velocity or human body movement (ISO 9920 1993).

However, several researchers reported that air and body movements can notably influence heat transfer through clothing (Parsons, Havenith et al. 1999; Havenith, Holmer et al. 2002). This means that using the static thermal clothing values, in a dynamic environment, as presented in an older versions of ISO 9920 will lead to an overestimation of the actual thermal resistance and the real heat loss will be higher than suggested by these values. The 2009 version of ISO 9920 examines the influence of body movement and air penetration on the dry resistance of clothing and vapour resistance values.

Usually there is a gap between the clothing and human body which acts as a warm thermal boundary layer and provides an additional thermal insulation to the human besides that of the clothing. In the case of body movement, cold air from the environment forces through the openings (e.g. collars and cuffs) and clothing layers and replaces the warm air in the boundary layer. This phenomenon is called the “pumping effect” and this increases the heat loss from the skin by reducing the clothing resistance values (Havenith, Holmer et al. 2002).

The current version of ISO 9920 provides guidance for estimating the effect of body motion and wind on the thermal resistance of clothing; a movable thermal/sweating mannequin may be used in a simulated windy environment. Empirical equations are provided in the standard for an air velocity range from 0.2 to 18 m/s and for walking speeds of 0-1.2 m/s to calculate the correction factors for thermal resistance values; these can be used to calculate the total heat loss from a human body in dynamic conditions. (ISO 9920 2009).
Heat and mass transfer through clothing is a very complex phenomenon. In reality, the overall heat transfer through a textile specimen is the sum of the heat transfer through the fiber plus the heat transfer through the air gaps, which may involve various transport mechanisms including conduction, radiation and convection. Similarly, the overall mass transfer includes the transport of water vapour and liquid water, by involving the mechanism of evaporation/condensation, vapour diffusion, moisture sorption/desorption, and capillary effects (Li and Zhu 2003). Considering the domain of this thesis, it may not be possible to explain the complex mechanisms of heat and mass transfer as they are beyond the scope of this work. However it has been discussed that by considering the [human body—clothing—environment] system in the form of lumped components, heat loss from the skin through the clothing to the environment (when dry and latent heat transfer are treated independently) at steady state standard conditions can be modelled by the application of basic heat transfer models.
2.4 Temperature sensing in context of WHMS

This section of literature review provides a solid foundation and purpose to carry out this study by identifying a research gap in the emerging territory of “Electronic Textiles”, specifically in the context of Wearable Health Monitoring Systems (WHMS). The importance and requirements of WHMS along with the use of metallic yarns in the development of WHMS is discussed in an initial review. Subsequently, temperature sensing in the context of WHMS is discussed in detail; starting with a brief review of WHMS projects which have employed external temperature sensors, a review of tiny temperature sensors developed especially to embed in WHMS garments and finishing with studies which have dealt with the development of totally textile-based temperature sensors. Considering the lack of knowledge in the above mentioned context, some studies related to "WHMS for fire-fighters" are also discussed with particular emphasis on the measurement of thermal parameters. On the basis of the discussed literature, a research gap is identified.

2.4.1 Wearable Health Monitoring Systems

Wearable technology can be defined as something that may be worn on the body that incorporates embedded technology. The wearable device is more than simply a portable device because it is worn just like clothes, shoes, jewellery or spectacles and is not carried like any other hand-held device. They are more closely connected to us and hence are not considered as a separate item. Thus they are not thought of as being an added weight or hindrance that must be remembered to be taken and to be used. Wearable technology is particularly intended to be worn close to the body for extensive periods of time. The factors associated with human-machine communication i.e. issues of comfort, mobility, usability and aesthetics are important considerations in the context of wearable technology (Tao 2005).

Products, under the heading of wearable technology may be classified in different categories. The following discussion is limited to textile-based sensing platforms of Wearable Health Monitoring Systems (WHMS) in general, while focusing on the research status of human body temperature sensing in the context of WHMS.
Healthcare monitoring is a general concern for patients requiring continuous medical assistance and treatment. In order to boost the mobility of such patients, an enormous effort is being pursued worldwide for the development of wearable monitoring systems to measure vital physiological signs such as respiration movements, cardiac activity, pulse oxymetry and body temperature (Tröster 2005). The primary requirements of such systems centre on their ability to do long-term health monitoring and to provide constant feedback to remote healthcare professionals while remaining unobtrusive in respect of the daily activities of the patients. These requirements are best realised by a wearable monitoring system that is truly integrated into everyday clothing. Being close to the body, textiles offer a flexible platform for the smooth embedding of sensing functions.

The current technologies used for developing a sensing platform for these WHMS have been named “Electronic Textiles” (Kirstein, Cottet et al. 2005). During recent years, intensive research has been carried out in the territory of electronic textiles for building up sensing platforms for WHMS intended for continuous usage to monitor the human body for vital signs over extended periods of time (Pantelopoulos and Bourbakis 2010).

The sensing platform has to deal with the sensors, interconnection technologies, and routing methods for power and signals. One of the key components of this sensing platform is the sensor which gathers data from the wearer and passes it on for further processing (Lam Po Tang 2007). This information could be used to create a health picture for various medical purposes (Funnell, Koutoukidis et al. 2008). Sensing functions can be imparted into textiles at different levels i.e. during the manufacture of fibre, yarn, fabric or as an externally-attached component.

The era of electronic textiles was initiated by the attachment of printed circuit boards on textiles by various means of textile manufacturing i.e. sewing, soldering and gluing (Rantanen, Altham et al. 2002; Ottenbacher, Romer et al. 2004). These approaches suffer from the rigidity of the electronic components, which makes the fabric stiff, difficult to bend and uncomfortable to wear. This review will not cover such early level technologies but rather focuses on integrated electronics at yarn or fabric level to create flexible sensing platforms for WHMS.
2.4.1.1 Metallic Yarns for Routing and Sensing Purpose

Embedding of metallic yarns into textile structures for sensing purposes, by various fabric forming techniques such as weaving and knitting, has been documented by several researchers. Catrysse et al. used stainless steel fibres to create textile electrodes for measuring ECG signals, in conjunction with a belt containing elastane and this structure was used for measuring the respiration rate, of the human body (Catrysse, Puers et al. 2004). Wijesiriwardana et al. reported knitted sensors being used for measuring the human body vital signs including ECG, respiration rate and motion sensing. They developed a resistive strain gauge by using a carbon filled elastomeric fibre (Wijesiriwardana, Dias et al. 2003) and capacitance sensors for switching purpose, by using CuS polyester Yarn (Wijesiriwardana, Mitcham et al. 2005). Zhang et al. demonstrated the development of a conductive knitted fabric for strain sensing purposes by use of stainless steel fibre and carbon fibre yarns (Zhang, Tao et al. 2006). Martin et al. embedded stainless steel wires into a fabric structure as a pressure sensor as a part of their prototype jumpsuit based on e-textile architecture (Martin, Jones et al. 2009). The Mermoth consortium (2006) developed knitted electrodes made of stainless steel yarn for ECG purpose. They also developed a respiration sensor based on inductance plethomography by embedding a copper yarn onto a elastic polyester-based belt (F.Pirotte and F.P. Klefstad-Sillonville 2005). As a result of a number of EU financed projects, a smart shirt with an integrated sensor has been developed, for the measurement of human body vital signs (Caldani, Pacelli et al. 2008). For respiration monitoring a piezoresistive sensor has been created by using conductive yarn coupled with elastic fibres. Also, a stainless steel wire twisted around textile yarn has been employed to develop knitted electrodes for ECG purposes.

Metallic wires can also be used to carry power to and signals within the sensing platform of the WHMS. A number of studies have been conducted towards the development and characterisation of routing methods for power and signal transmission in woven electronic textiles, by introducing the network of metallic wires at specified distances along the warp and weft (Martin, Jones et al. 2009) (Zysset, Cherenack et al. 2010) (Cherenack, Zysset et al. 2010) (Locher and Troster 2007) (Cottet, Grzyb et al. 2003).
2.4.2 Temperature sensing in context of WHMS

The first example of a smart wearable garment in connection with monitoring of human vital signs was developed and patented by researchers at the Georgia Institute of Technology; it was named the Georgia Tech Wearable Motherboard (GTWM) (Park and Jayaraman 2003). The shirt incorporated conductive pathways with a totally integrated respiration sensor. The system uses conventional electrodes to acquire ECG signals. For the measurement of human body temperature, a thermistor or temperature measuring IC could be attached to the conductive pathways as an external attachment. However, details were not provided about the exact placement of a temperature sensor and its required performance. The IP of the GTWM was later purchased by Sensatex (Sensatex).

Dias, et al., from the University of Manchester, developed knitted sensors based on resistive, capacitive and inductive principles (Wijesiriwardana, Dias et al. 2003) (Wijesiriwardana, Mitcham et al. 2005). By utilising the knowledge-base of knitted sensors, they developed a vest capable of obtaining information relating to the human body physiological vital signs along with information relating to the body movements and gestures of the wearer (Dias, Beattie et al. 2004; T. Dias, R. Wijesiriwardana et al. 2004). Among various incorporated sensors, ECG, respiration and motion sensors were truly integrated textile sensors. The Smart Vest was produced on a flat bed weft knitting machine in a single step using Fully Fashioned Garment technology, while sensors and pathways were integrated locally using intarsia techniques. It was mentioned that thermocouples or thermistors could be placed in the vest for temperature measurement, however, no information was furnished on the sensor performance.

On the same research line, various European Union co-financed projects started under the 5th and 6th framework of the R&D program. This enabled the establishment of a dedicated and competitive research community to provide innovative wearable health solutions for better disease management, disease prevention and health promotion. The first dedicated project towards the development of a smart biomedical garment was initiated in 2002 and named WEALTHY. Upon completion of a project in 2005, the consortium was able to develop a smart shirt. ECG electrodes, a respiration sensor and conductive pathways were integrated via a Santoni Whole Garment circular knitting machine (Paradiso, Loriga et al. 2005) (Paradiso, Loriga et al. 4/2005) (Scilingo, Gemignani et al. 2005) (Caldani, Pacelli et al. 2008) (Smartex
For temperature measurement of the skin, core and environment, they relied on temperature sensors as an external attachment to the shirt. However, they did not provide any information about sensor performance. After the completion of WEALTHY, several more EU funded collaborative projects were initiated including MyHEART, OFFSETH, ConTEX and ProeTEX (Gatzoulis and Iakovidis 2007).

Apart from EU financed projects, several other studies have been conducted towards the development of WHMS. Some of them could be capable of developing textile based ECG and respiration sensors for their sensing garments. However, for temperature measurement, they mainly employed thermistors as an external attachment (F.Pirotte and F.P. Klefstad-Sillonville 2005) (Weber and Pirotte 2006) (Noury, Dittmar et al. 2004) (Mu-Huo Cheng, Li-Cheng Chen et al. 2008) (P.S. Pandian, K. Mohanavelu et al. 2008) (Yıldız, Önel et al. 2005) (Corbellini, Ferraris et al. 2008). They did not furnish any information about the required performance of a temperature sensor.

In 2001 Rantanen, et al. (Rantanen, Vuorela et al. 2001), from Tampere University of Technology, Finland, developed a system comprising a heating jacket and a sensing shirt to provide a conducive thermal environment for the human body in an extreme cold environment. Heating elements were sewn into different regions of jacket. A 1-wire digital thermometer from Dallas Semiconductors was used for measuring the skin temperature at ten different places on the upper part of the human body. Conductive pathways between temperature sensors were made using metal-clad aramid yarn. It was concluded that the incorporated temperature sensors measured the microclimate temperature (the temperature of the boundary layer between the skin and the shirt) instead of the true skin temperature. Therefore the fitting of a sensor shirt would be an important parameter in estimating true skin temperature values. Connections between the metal yarn and the temperature sensors were unreliable because of the brittleness of the encapsulation of the connecting points. This resulted in regular breakage of the connections.

Unlike the shirts developed by SmartLife, Sensatex and the WEALTHY consortium, the Lifeshirt system (by VivoMetrics) is based on removable components that are not an integral part of the garment. The Lifeshirt does not offer human body temperature sensing as a default. By using an optional serial expansion module, a third party temperature sensor may be
connected with the life shirt system as shown in Figure 2.8 (VivoMetrics 2012). However there is no documented evidence about the performance of a temperature sensor when connected to the Lifeshirt system.

![Image of life shirt system](image1)

![Image of temperature sensors](image2)

**Figure 2.8:** A) Subject wearing LifeShirt  B, C) Temperature sensors as external attachments to the LifeShirt

A few other researchers have developed wrist-worn wireless health monitoring devices for measuring vital signs and activity: A Wearable Multiparameter Medical Monitoring and Alert (AMON) System has been developed (Lukowicz, Anliker et al. 2002); the SenseWear arm band has been developed by Bodymedia (Andre and Teller 2005); and a Wrist band has been developed by Chang et al. (Chang, Fang et al. 2008). A thermistor was embedded in these products for measurement of skin temperature. However they did not provide any information about the performance of the temperature sensor in an actual working environment.

### 2.4.3 Temperature sensing fabric (Textile based)

Some individual studies have been reported in respect of the development of textile based temperature sensors. They do not belong to any WHMS or any project, as discussed in the last section. All of them are preliminary studies and limited in their depth of characterisation and performance of the sensor in either the laboratory or in the real environment.

A conductive textile for the purpose of measuring strain and temperature was first documented by De Rossi (De Rossi, Della Santa et al. 1999). The **sensing fabric** was developed by coating a polypyrrole on a Lycra fabric and claimed to exhibit temperature sensitivity, comparable to that of ceramic thermistors. However they have not provided further characterisation in order to use it in a practical environment. Another major drawback was that this fabric was also highly sensitive to strain as well which could be major source of unwanted artifacts during temperature measurement in a dynamic environment.
Locher et al. developed a woven temperature sensor (based on the resistance principle) by weaving insulated copper wires (as a sensing element) into the warp and weft along with polyester yarn (Ivo Locher, T. Kirstein et al. 2005) as shown in Figure 2.9. In order to make a sensing patch of the required resistance, a routing technique was devised by which the insulating coating on the wires was removed and the wires were then connected with conductive adhesive at the defined intersections followed by cutting of the wires in close proximity. Finally, mechanical and electrical protection was added by encapsulating the sensor with insulating epoxy resin (Locher, Kirstein et al. 2004). Preparing a sensing patch is a manual and cumbersome process which is itself a source of error with regard to the electrical characteristics of the sensor. They claimed that an accuracy of 1 °C could be achieved by 2-point calibration. However, errors due to the effect of external parameters e.g. strain or moisture were not considered in their accuracy analysis. Furthermore, the sensors were only tested under steady state conditions at specific temperature points.

Ziegler et al. reported a preliminary piece of research into the structure and thermometric characteristics of a textile thermocouple (Ziegler and Frydrysiak 2010). Their textile thermocouple is made of conductive fabric, non-conductive fabric and conductive yarn/wire as shown in Figure 2.10. These thermocouples are characterised by low accuracy and sensitivity when compared with classical metallic wire thermocouples. Providing a reference junction into the fabric is another problem for textile thermocouples. Fabricating a textile thermocouple is a manual and unwieldy process and can add errors in respect of its performance.
A recent study about the development of "thermistor yarn" was carried out by (Sibinski, Jakubowska et al. 2010). They developed a "thermistor yarn" by depositing a thermo-resistive paste, based on multiwalled Carbon Nano Tubes (CNT) polymer, on a Polyvinylidene fluoride (PVDF) yarn of diameter of 150 microns as shown in Figure 2.11. They mentioned that the resistivity and the temperature coefficient of resistivity of their sensor yarn can be changed according to the yarn length and the content of CNT. However they did not shed light on how elasticity/strain in PVDF yarn would affect the resistance characteristics of thermistor yarn. It has been well documented that the piezoelectric behaviour of PVDF fibre can be exploited to use it as a strain sensor (Holmes-Siedle, Wilson et al. 1984). Therefore it would be necessary to quantify the effect of elasticity on the sensor performance. Further they did not discuss the integration of "thermistor yarn" into the fabric and the testing procedure to calibrate it.

Figure 2.10:  Textile Thermocouple

Figure 2.11:  A) Thermistor yarn structure B) Thermistor yarn with contact connectors
2.4.4 Temperature sensing fabric (fabric embedded with external temperature sensor)

A few studies related to the development of tailor-made miniature temperature sensors to be embedded into textile structures have also been conducted.

Kinkeldei et al. developed a temperature sensing fabric by embedding a minute foil RTD (Resistance Temperature Detector) into a fabric. First, foil RTDs were developed by depositing a platinum layer on flexible kapton; and then integrated into the woven structure in the weft direction (Kinkeldei, Zysset et al. 2009) as shown in Figure 2.12. The foil RTDs themselves showed a stable and linear relationship between temperature and resistance. However, while embedding them into the textile, they were not able to survive the strain due to bending. This resulted in cracking of the sensing lines and degradation of the sensing performance.

A foil thermistor was developed by (Bielska, Sibinski et al. 2009) for the purpose of embedding it within a fabric. The sensor was developed by applying a thermo-resistive paste via a screen printing process onto a Kapton (polyamide) foil as presented in Figure 2.13. A thermo-sensitive paste made of carbon-polymer composites was used with a binder material of rubber and polyethylene modified polystyrene. Laboratory results showed a near-linear relationship between temperature and normalised resistance with temperature between 30 and 42 °C. However they did not discuss the effect of manufacturing and material parameters on the sensor performance. Neither had they devised any method to integrate it into textile material. Furthermore, it was important to characterise the effect of foil bending on the sensor performance as bending of a foil thermistor (while embedding it into fabric) may develop cracks within the paste as was highlighted in the study (Kinkeldei, Zysset et al. 2009) discussed earlier.
A recent study, conducted at ETH, demonstrated a prototype of temperature sensing woven fabric (Cherenack, Zysset et al. 2010; Zysset, Cherenack et al. 2010). The sensing fabric was developed by introducing an “IC embedded plastic yarn” in the weft direction and power and data lines in the warp direction as shown in Figure 2.14. Plastic fibre is made by the patterning of IC contact pads and connection lines on a flexible composite called Pyralux (by DuPont). A temperature sensing IC is soldered afterwards to the dedicated IC contact pads. They carried out drapability, mechanical stability and washability tests and claimed that sensing performance remained unchanged after tests. The patch of sensing fabric can be sewn to the inside of under garments to measure the skin temperature of the human body. However they did not discuss the accuracy of temperature sensing in an actual environment in terms of movement artifacts.

Some studies have been carried out regarding the development of textile based strain gauges by the coating of fabric with conductive polymers or metallic ions (D. De Rossi, F. Carpi et al. 2005) (Zhang, Tao et al. 2006) (Enzo Pasquale, Lorussi et al. 2003) (Cochrane, B. Kim et al. 2006). They also considered the effect of external parameters on the sensitivity of the strain...
gauges. However the effect of temperature was not found to be significant enough to exploit the same product as temperature sensor.

2.4.5 Thermal parameter measurement of firefighter’s clothing

In the context of WHMS, the majority of studies have focused on the development of a sensing platform for health care applications e.g. general health management, disease management or rehabilitation, by remote monitoring. As has been highlighted in earlier sections, there has not been much information published about the performance of WHMS system in a practical working environment, especially in the context of temperature sensing. However, a few studies have been directed towards the development of dedicated WHMS for fire-fighters. Limited literature is available regarding the performance of these systems in an outdoor environment. This section will summarise the key findings accompanied by a critical analysis. The main goal of a firefighter WHMS is the improvement of the safety of firefighters while they perform their duty in an extremely harsh environment. Therefore a wearable system should be capable of detecting not only human vital signs, but also environmental and activity-related variables (Gniotek K., Gołębiowski J. et al. 2009).

The current form of firefighting suit separates the firefighter from the harsh environment for some time but lacks the technology to identify the severity of the heat exposure hazard early enough. As a result of long exposure, heat flux from the environment can enter into the human body via protective clothing and increase the body core temperature. This mechanism can subject a firefighter to a critical situation and more specifically to heat stroke (Ilmarinen and Mäkinen 1992). Early detection of the onset of such a critical situation, by monitoring of thermal parameters, is therefore very important. Critical thermal parameters to be measured are core temperature, skin temperature, heat flux through the clothing and the environmental temperature. An increase of a few degrees of core temperature can put the firefighter under threat. Measurement of heat flux can provide information about heat transfer between the fireman and the external environment while monitoring skin temperature can provide details about the state of dilation or constriction of the skin. A fire-fighter’s WHMS could be fitted with wireless transmission, a data analysis algorithm and a sensing platform, in order to continuously monitor thermal parameters. This would identify an increasingly risky situation.
and could generate an alarm signal to warn a firefighter to escape from that situation (Oliveira, Gehin et al. 2009).

(Gniotek K., Gołębiowski J. et al. 2009) presented a system for measurement of the thermal parameters of an active fire-fighter including the design of a sensing platform, wireless transmission of data and visualisation of results. The design of the sensing garment comprised attached temperature sensors as external components: T-type thermocouples for environmental temperature measurement; a thermistor for skin temperature measurement; and an IC sensor for internal clothing temperature measurement. However, they did not demonstrate the performance of their system in an actual working environment

ProeTEX is the European Union co-financed project involving 23 partners across the EU and is dedicated to micro and nano-technology-based wearable products for emergency operators like firefighter or first responders. Three different wearable systems were developed to monitor the physiological signals of firemen, to detect environmental conditions and to perform triage analysis on victims during emergencies (Paradiso, Pacelli et al. 2007) (Caldani, Pacelli et al. 2008). The ECG and respiration sensors of ProeTEX products are based on the knowledge created during the WEALTHY project (Paradiso, Loriga et al. 2005). They conducted various studies over the course of the project in connection with the measurement of a firefighter’s thermal parameters i.e. skin temperature, core temperature, environment temperature and heat flux across clothing (Bonfiglio, Carbonaro et al. 2007) (Curone, G. Dudnik et al. 2008) (Curone, Secco et al. 2010) (Oliveira, Gehin et al. 2009) (Oliveira, Gehin et al. 2010; Magenes, Curone et al. 2011)

In an earlier study they presented the sensing platform for a firefighter suit (Bonfiglio, Carbonaro et al. 2007). For core body temperature measurement, a monolithic temperature sensor chip (LM92 from National Semiconductor) was placed in a dedicated pocket in the axilla area of the inner vest, as illustrated in Figure 2.15. In order to create isothermal conditions in close proximity to the temperature sensor and to accurately estimate core temperature, polyamide foil encapsulation was used as shown in Figure 2.15. For measurement of the environment temperature, a thermocouple was placed in the neck area of the jacket.
Multiple laboratory and outdoor tests were performed with different thermal environments (i.e. 20 °C, 35 °C and 45 °C) to investigate the performance of embedded sensors by comparing them with standard core temperature sensors (Curone, G. Dudnik et al. 2008) (Curone, Secco et al. 2010) (Magenes, Curone et al. 2011). The field trials demonstrated that the thermocouple is not suitable in extreme thermal environments, as some of the sensors failed and signals were also not stable. For core body temperature measurement, they concluded that their embedded sensor overestimated the actual core when the environmental temperature was 45 °C and underestimated the actual core temperature when the environmental temperature was 20 °C.

In previous sections it has already been established that the human body maintains its core temperature at around 37 °C. However, skin temperature is noticeably affected by parameters pertaining to the human thermal environment, especially the ambient temperature. Therefore skin temperature could not be used to estimate the core temperature in an extreme thermal environment.
In another ProeTEX study, (Oliveira, Gehin et al. 2009) measured the core, skin and environmental temperature by embedding two thermistors in an inner garment at the axilla and one thermistor in an external garment. For measurement of the heat flux across a clothing ensemble, two heat flux sensors were sewn into the inner and outer garment. In order to test the performance of their ProeTEX garment in an actual harsh environment, an intense fire was simulated in a container and fire-fighter was allowed to remain in front of the simulated fire for about 10 minutes while thermal parameters were being measured.

They observed that with the increase of environment temperature, the heat flow from the body to the environment drops. In fact negative heat flow started and increased the body skin temperature greatly and raised the core temperature marginally. The sensors could be able to measure the thermal parameters without any degradation. However, the study was conducted on a single fireman with a static posture. In order to develop a baseline specification of their sensing garment they probably need to perform more tests and carry out detailed statistical analysis.

Another ProeTEX study reported a method of measurement of heat flux by temperature difference (Oliveira, Gehin et al. 2010). They embedded two foil Platinum Resistance Thermometers (PRTs) across the middle layer of a three layer clothing system (inner layer-middle layer-outer layer). The test was performed on clothing-worn-mannequin by introducing an Infra-Red (IR) heat source directed towards the mannequin. The recorded temperature values were used to calculate the heat flux by Fourier's Law. They claimed their results were comparable with those of a standard heat flux sensor.

However, they did not present the method by which they measured the thermal resistance of the clothing or any alternative method for estimating it, such as from the clothing “thickness and thermal conductivity”. It was also discussed earlier that measurement of heat flux by a temperature difference method would only be possible in an ideal scenario when a human body is in thermal equilibrium with the environment. In real situations, due to air velocity and human movement, the thermal resistance value of clothing would change accordingly and the measured heat flux would inevitably be underestimated.
2.4.6 Discussion and Identification of Research Gap

Despite a lot of research in the context of Wearable Health Monitoring, only a few systems have been commercialised while several more are still at the development stage. Almost all commercial products are based on removable components and lack the true spirit of electronics-textile integration; however progress is being made in truly integrated electronic textile-based WHMS. The detailed literature review has demonstrated that most of the research has been carried out in the area of ECG and respiration sensors.

However, for temperature sensing, the majority of research work has relied on the temperature sensor (mainly thermistors or ICs) as an external attachment to a shirt. Few attempts have been made to develop a textile-based temperature sensor. However those that have been made are preliminary in nature and lacked the content relating to: the characterisation of the sensor in a laboratory or in its application environment; the effect of material and manufacturing parameters on sensor performance; the effect of external parameters e.g. strains and humidity on sensor performance; the defining baseline specification of the sensor i.e. accuracy, precision, sensitivity; response time, self heating, insulation resistance; effect of human and environmental thermal parameters on sensor performance; or the evaluation of sensor performance through thermal modeling.
2.5 Overview of Temperature sensors

2.5.1 Classification of Temperature Sensors

Temperature sensors can be classified in terms of their application areas, operating range, structure, or by their principles of measurement. An important criterion for structural classification is the method of heat transfer between the temperature measuring instruments and the body under measurement (Michalski, Eckersdorf et al. 1991). Heat may be transferred by conduction, convection and radiation. Those temperature sensors which depend upon heat transfer by contact are known as **contact** thermometers (see Figure 2.16). In contact thermometers the heat transfer between the temperature sensor and the medium to be measured occurs by conduction and convection. Where radiation heat transfer is the means of energy exchange the temperature sensors may be called **non-contact** thermometers or simply pyrometers (McGee 1988). Detailed classification of temperature sensors is presented in Figure 2.16.

The class of contact thermometers may be grouped upon the energy form of the output signal. Non-electrical thermometers are based on physical expansion effects i.e. solid expansion, liquid expansion or gas/vapour expansion. They are still of significance today. The class of contact thermometers which transduces into the electrical energy form is important, as electrical signals are relatively easily manipulated and processed using analogue and digital techniques. The measurement instrumentation measures the electrical effect that is related to the temperature of the thermometer (Michalski, Eckersdorf et al. 1991). Within the domain of contact-electrical thermometry, the most common temperature sensors are thermocouples, thermistors and **Resistance Temperature Detectors (RTDs)**.

2.5.1.1 Thermocouples

The combination of two dissimilar conductors, which may be metals, alloys or non-metals, connected at one end is known as a thermocouple. Their point of connection is called the measuring junction and their free ends are referred to as the reference junction, which is also known as the Cold Junction (see Figure 2.17) (Michalski, Eckersdorf et al. 1991). When the two junctions are at different temperatures, a low DC thermoelectric voltage is produced by the thermocouple due to the temperature gradient (known as the Seebeck effect) along the
thermocouple wires (Bluestein 1999). The thermoelectric voltage is approximately proportional to the difference in temperature between the reference junction and the measurement junction. That difference increases with temperature, and can typically be between 1 and 70 microvolts per degree Centigrade (µV/ °C) for the modern range of available metal combinations (National Instruments 2011) (dataTaker)

Figure 2.16: Classification of temperature measuring instruments

Figure 2.17: Typical Thermocouple type J circuit (dataTaker)
Thermocouples may be constructed of several different combinations of materials. According to the American National Standards Institute (ANSI) thermocouples are categorised according to their composition and temperature range as presented in Table 2-1.

### Table 2-1: Letter designation, composition and temperature range of standardised Thermocouples

(Childs 2001).

<table>
<thead>
<tr>
<th>Thermocouple Type</th>
<th>Conductors-Positive</th>
<th>Conductors-Negative</th>
<th>Practical Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Platinum-30% rhodium</td>
<td>Platinum-6% rhodium</td>
<td>20 °C to 1820 °C</td>
</tr>
<tr>
<td>E</td>
<td>Nickel-chromium alloy</td>
<td>Copper-nickel alloy</td>
<td>-270 °C to 910 °C</td>
</tr>
<tr>
<td>J</td>
<td>Iron</td>
<td>Copper-nickel alloy</td>
<td>-210 °C to 1200 °C</td>
</tr>
<tr>
<td>K</td>
<td>Nickel-chromium alloy</td>
<td>Nickel-aluminum alloy</td>
<td>-270 °C to 1370 °C</td>
</tr>
<tr>
<td>N</td>
<td>Nickel-chromium-silicon alloy</td>
<td>Nickel-silicon-magnesium alloy</td>
<td>-270 °C to 1300 °C</td>
</tr>
<tr>
<td>R</td>
<td>Platinum-13% rhodium</td>
<td>Platinum</td>
<td>-50 °C to 1760 °C</td>
</tr>
<tr>
<td>S</td>
<td>Platinum-10% rhodium</td>
<td>Platinum</td>
<td>-50 °C to 1760 °C</td>
</tr>
<tr>
<td>T</td>
<td>Copper</td>
<td>Copper-nickel alloy</td>
<td>-270 °C to 400 °C</td>
</tr>
</tbody>
</table>

### 2.5.1.2 Thermistors

The thermistor is a device, made of semiconductor materials whose resistance varies (positively or negatively) as a function of temperature. Although Positive Temperature Coefficient (PTC) units are available, most thermistors have a Negative Temperature Coefficient (NTC); that is, with increasing temperature, their resistance decreases (Agilent Technologies 2012). Since thermistors are normally manufactured in miniaturised form, they therefore respond quickly to temperature changes. However, they are also susceptible to self-heating errors because of their small mass (National Semiconductor 2008).

Thermistors are manufactured usually by the combination of two or more of the following oxides i.e. cobalt, copper, iron, magnesium, manganese, nickel, tin, titanium, vanadium, and zinc (Childs 2001). The fabrication of NTC thermistors uses basic ceramics technology. Powder of two or more metal oxides are first mixed and then combined with suitable binders in order
to form a desired geometry. Then they are dried and sintered at an elevated temperature (Sapoff 1999). Thermistors of an extensive range of resistivities and temperature coefficients of resistivity can be obtained by varying the types of metal oxides and their relative proportions used, the sintering temperature, and the sintering atmosphere (Thermometrics).

2.5.1.3 Resistance Thermometers

Resistance Thermometers, also known as Resistance Temperature Detectors (RTDs) functions on the inherent tendency of metal to exhibit change in electrical resistance as a result of a change in its temperature (Garvey 1999). The RTD’s Resistance vs. Temperature (RT) characteristics are stable, reproducible and have almost linear positive temperature coefficient in the range of -200 °C to 800 °C which in effect makes RTDs the industry standard (Childs 2001). Platinum has become the metal of choice for RTDs because of its high chemical stability, availability in a pure form and highly reproducible electrical properties (Michalski, Eckersdorf et al. 2002). Platinum-based RTDs are also known as PRTs (Platinum Resistance Thermometers). RTDs are further explained in detail under the heading 2.5.3 to 2.5.5 later in this chapter.

2.5.2 Comparison of Temperature Sensors

This heading presents the comparative characteristics of the most common electrically-based temperature sensors in terms of their range, stability, accuracy, sensitivity and response time.

Depending upon the operating principle and the construction, temperature ranges vary for each sensor type. The thermocouple family possesses the widest temperature range, spreads across multiple thermocouple types (Childs 2001). Thermistors can work over a temperature range from about -100 °C to +350 °C however most are rated for maximum operating temperatures between 100 °C and 150 °C (Hagart-Alexander and Boyes 2003).

Accuracy depends upon basic sensor characteristics. Apart from laboratory standard RTDs, Industrial RTDs and thermistors demonstrate higher accuracy than thermocouples (Childs 2001). That is why thermocouples need to be calibrated and checked frequently (Noam 1986).
### Table 2-2: Characteristics of temperature sensors (Thermistor, RTD and Thermocouple) (Measurement Specialties 2003)

<table>
<thead>
<tr>
<th></th>
<th>NTC Thermistor</th>
<th>Platinum RTD</th>
<th>Thermocouple</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensor</strong></td>
<td>Ceramic (metal-oxide spinel)</td>
<td>Platinum wire-wound or metal film</td>
<td>Thermoelectric</td>
</tr>
<tr>
<td><strong>Temperature Range (typical)</strong></td>
<td>-100 to +325°C</td>
<td>-200 to +650°C</td>
<td>-200 to +1750°C</td>
</tr>
<tr>
<td><strong>Accuracy (typical)</strong></td>
<td>0.05 to 1.5 °C</td>
<td>0.1 to 1.0°C</td>
<td>0.5 to 5.0°C</td>
</tr>
<tr>
<td><strong>Long-term Stability @ 100°C</strong></td>
<td>0.2°C/yr (epoxy)</td>
<td>0.05°C/yr (film)</td>
<td>Variable, some types very prone to aging</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>NTC Resistance</td>
<td>PTC resistance 0.00385Ω/°C</td>
<td>Thermovoltage 10μV to 40μV/°C</td>
</tr>
<tr>
<td></td>
<td>-4.4%/°C typical</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Linearity</strong></td>
<td>Exponential</td>
<td>Fairly linear</td>
<td>Most types non-linear</td>
</tr>
<tr>
<td><strong>Power Required</strong></td>
<td>Constant voltage or current</td>
<td>Constant voltage or current</td>
<td>Self-powered</td>
</tr>
<tr>
<td><strong>Response Time</strong></td>
<td>Fast 0.12 to 10 seconds</td>
<td>Generally slow 1 to 50 seconds</td>
<td>Fast 0.10 to 10 seconds</td>
</tr>
<tr>
<td><strong>Susceptibility to Electrical Noise</strong></td>
<td>Rarely susceptible High resistance only</td>
<td>Rarely susceptible</td>
<td>Susceptible/Cold junction compensation</td>
</tr>
<tr>
<td><strong>Lead Resistance Effects</strong></td>
<td>Low resistance parts only</td>
<td>Very susceptible. 3 or 4-wire configurations required</td>
<td>None over short runs. TC extension cables required.</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Low to moderate</td>
<td>Wire-wound – High Film - Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

**Response time** is the ability of a sensor to react to a change in temperature; this depends upon the sensor’s thermal mass and heat transfer from the material being tested (Thomsen 1998). Platinum wire-wound elements are the slowest temperature sensors, whilst platinum film RTDs, thermistors and thermocouples are available in small packages, and thus have high-speed options (Childs 2001).

While the RTD is the most stable temperature transducer and the thermocouple is the most versatile, the word that best describes the thermistor is ‘sensitive’ (Usher 1985; Agilent Technologies 2012). In comparison to other sensors, a thermistor exhibits by far the largest temperature coefficient of the sensing parameter which may be as large as several percent per degree centigrade. Due to high sensitivity, a thermistor circuit can detect minute temperature changes which could not be observed with a thermocouple or RTD circuit. (Sapoff 1999).
**Stability** is an ability of a sensor to produce a consistent output when a steady input is applied and is dictated by the basic physical properties of the sensor. Stability is typically worsened by exposure to high temperatures or unintended physical and thermal shocks which can cause a small, one time shift (Zwack 2008). The standard platinum RTD element expands or contracts differentially, however this does not cause any shift in calibration (Goldstein, Chen et al. 1998). Within the class of industrial thermometers, wire-wound platinum (Michalski, Eckersdorf et al. 2002), and glass-encapsulated thermistors (John and Jon 2005) are the most stable sensor types while thermocouples are the least stable ones (Childs 2001).

**Linearity** defines how well, over a range of temperature, a sensor’s output consistently changes. Thermistors are exponentially non-linear, exhibiting a much higher sensitivity at low temperatures than at high temperatures (Sapoff 1999). Therefore it is necessary to perform substantial linearisation if thermistors are to be used over a wide range of temperatures. The Platinum RTD curve is fairly linear over its wide temperature range (-200 °C to 800 °C) and in between 0 and 100 °C it may be accepted as being completely linear, thus avoiding expensive correction circuitry (Measurement Specialties 2003).

**Electrical noise** inducing errors in temperature indication is a problem mostly with thermocouples (Childs 2001), although thermistors, with very high resistances may present a problem in some cases (Hagart-Alexander and Boyes 2003).

**Lead resistance** may cause an offset error in thermistors and RTDs. When using a two-wire sensing circuit, serious lead wire resistance errors can occur and this effect is more pronounced with low resistance devices such as 100 Ω platinum elements or low resistance thermistors (Childs 2001). In RTDs, it is highly recommended to use three or four wire lead configurations when high accuracy is required. A four-wire configuration is always more expensive than two or three wire configurations. For thermistors, typically choosing a higher resistance value minimises and almost eliminates the lead resistance effect (John and Jon 2005). Thermocouples must use extension leads and connectors of the same material as the device itself, as the leads may themselves induce an error (Measurement Specialties 2003).

When **powering**, either thermistors or platinum elements, constant voltage or constant current supplies are required, which inevitably heat the sensor (Childs 2001). This is known as $I^2R$.
heating or Joule heating. Due to this effect, the temperature displayed by the transducer would be higher than the actual temperature. This difference in temperature is also known as a self-heating error. It may be negligible or as high as 1 °C. In order to minimise this error, the smallest drive current (less than 1 mA) should be employed as a sensing current along with maximised thermal contact between the sensor and the application (Burns 1999).

In comparison with RTDs and thermocouples, thermistors are more fragile and must be carefully mounted in order to avoid crushing or separation of the bond (National Semiconductor 2008). A major advantage of RTDs is that for normal laboratory measurements, up to 100 °C, the extreme linearity of the sensor means that calibration can be performed using only two temperature points and at the same time offers accuracy while preserving high stability (Goldstein, Chen et al. 1998).

### 2.5.3 Resistance Thermometer - Principle of Operation

The operating principle of a resistance thermometer is based upon the dependence of the resistance of the sensing element (a fine metal wire of defined length) upon temperature. The resistance of the element \( R \) directly relates with the metal resistivity \( \rho \) and length \( l \) while it inversely relates to the cross-sectional area \( a \):

\[
R = \frac{\rho l}{a} \quad (2.16)
\]

Whilst resistivity characterises the resistance of any given material and may be expressed as (Dataforth Corporation):

\[
\rho = \frac{1}{e\eta\mu} \quad (2.17)
\]

where \( e = \) electron charge \((1.6 \times 10^{-19} \text{ coulombs})\);

\( \eta = \) electron density (number per unit volume);

\( \mu = \) mobility, relates to how electron moves through conductor by interacting with other electron and molecular structure of conductor.
As the electron charge is always the same, so the resistivity of any metal depends upon the product of $\eta$ and $\mu$. For most metals over a large range of temperatures, the product of $\eta$ and $\mu$ decreases with increasing temperature, thus an increase in resistance establishes a positive temperature coefficient.

\[ T \uparrow \quad \eta \ast \mu \downarrow \quad \rho \uparrow \]
\[ T \downarrow \quad \eta \ast \mu \uparrow \quad \rho \downarrow \]

The dynamic behaviour of an increase in resistivity because of temperature has been explained (Michalski, Eckersdorf et al. 1991) in these terms: “As the temperature of a metal increases, the amplitude of thermodynamic vibrations of its autonomic nuclei increases. Simultaneously, the probability of collisions between its free electrons and bound ions undergo corresponding increases. These interruptions of the motions of free electrons due to crystalline collisions, cause the resistance of the metal to increase”

The resistance of a metal at a particular temperature will depend upon its resistivity value at the corresponding temperature. Usually standard resistivity values of metals are defined at 0 °C or 20 °C. Depending upon the standard resistivity values, the resistivity of a metal with increasing temperature can be expressed as (Dogan 2002):

\[ \rho_T = \rho_0 (1 + \alpha (T - T_0)) \quad (2.18) \]

If $R_0$ is the resistance at 0 °C and $R_T$ is the resistance at temperature $T$ °C, equation (2.16) can be expressed as

\[ R_0 = \frac{\rho_0 l}{a} \quad (2.19) \]
\[ R_T = \frac{\rho_T l}{a} \quad (2.20) \]

By combining equations (2.18)(2.19) and (2.20), the relationship between the temperature and resistance of a metal conductor may be expressed as:

\[ R_T = R_0 (1 + \alpha (T - T_0)) \quad (2.21) \]
where

\[ R_T = \text{resistance at temperature } T \, ^\circ\text{C}; \]
\[ R_0 = \text{resistance at } 0 \, ^\circ\text{C (at reference temperature)}; \]
\[ \alpha = \text{temperature coefficient of resistivity (alpha value) taken at } 0 \, ^\circ\text{C}. \]

Hence, equation (2.21) can be expressed in terms of alpha i.e.

\[ \alpha = \frac{R_T - R_0}{R_0(T - T_0)} \tag{2.22} \]

Inserting \( T_0 = 0 \, ^\circ\text{C}, T = 100 \, ^\circ\text{C}, \) and \( R_T = R_{100} \) in equation (2.22) gives:

\[ \alpha = \frac{R_{100} - R_0}{100R_0} \tag{2.23} \]

Hence, the temperature coefficient of the resistivity of a metal, \( \alpha \), may be defined as “the element’s change in resistance per \(^\circ\text{C} \) change in temperature per ohm of sensor resistance over the range of 0 \(^\circ\text{C} \) to 100 \(^\circ\text{C} \)” (Burns 1999). The larger the temperature coefficient, the greater the change in resistance for a given change in temperature. Thus, the alpha value can be represented as the sensitivity of the sensing element.

According to Matthiessen’s rule, apart from temperature, resistivity of a pure metal can also be influenced by impurities or lattice deformation arising from mechanical stress (Childs 2001) (Burns 1999). For example a slight impurity in the sensing element of RTD (such as Platinum) will shift its resistivity and temperature coefficient of resistivity. Sometimes impurities are added to achieve the desired/standard resistivity in order to make the sensors interchangeable.

Equation (2.21) represents the simplified relationship between temperature and the resistance of a RTD conductor. In practice, this relationship is approximated by a modified form of the Callender-Van Dusen (CVD) equation which gives the results with an accuracy of \( \pm 0.0001 \, ^\circ\text{C} \) (McGee 1988). The CVD equation is written in the following form:

\[ R_T = R_0[1 + AT + BT^2 + C(T - 100)T^3] \tag{2.24} \]

where \( A, \, B, \) and \( C \) are constants which depend upon the material. This equation works for all types of metals.
The first two terms \((1 + AT)\) of the CVD equation (2.24) simply define the linear relationship between temperature and resistance. The second term \((BT^2)\) is a small correction term, which when added to the first term, gives a true estimate of the temperature. The last term \([C(T - 100)T^3]\) improves the accuracy over the range of temperature from -200 °C to 0 °C.

Above 0°C the constant \(C\) is equal to zero, so the behaviour of the CVD equation (2.24) simplifies to:

\[
R_T = R_0[1 + AT + BT^2]
\]

(2.25)

The constants \(A\) and \(B\) are defined like this (Honeywell):

\[
A = \alpha + \frac{\alpha \delta}{100}
\]

\[
B = -\frac{\alpha \delta}{100^2}
\]

\(\alpha\) and \(\delta\) are constants and are defined as (Honeywell):

\[
\alpha = \frac{R_{100} - R_0}{100R_0}
\]

(2.26)

\[
\delta = \frac{R_0(1 + 260\alpha) - R_{260}}{4.16R_0\alpha}
\]

This shows that if the resistances \(R_0, R_{100}\) and \(R_{260}\) of any sensing element could be measured, then its R-T curve over the temperature range from 0 to 800 °C may be defined by the CVD equation. Resistances \(R_0, R_{100}\) and \(R_{260}\) are measured empirically, usually in primary temperature measurement laboratories (McGee 1988).

Depending upon the purity of the platinum, these constants may have different values. Following are the constants for platinum defined in (BS EN 60751 2008)

\[
A = 3.9083 \times 10^{-3} \degree C^{-1}
\]

\[
B = -5.775 \times 10^{-7} \degree C^{-2}
\]

\[
C = -4.183 \times 10^{-12} \degree C^{-4}
\]
Usually the T-R relationship of a sensing element between 0 and 100 °C is fairly linear and can be represented by the first two terms of the CVD equation (2.24) or by equation (2.21). The temperature coefficient can also be calculated by using equation (2.23).

### 2.5.4 Resistance Thermometer - Sensing Element

RTDs consist of three main components, namely the temperature sensing element, the connecting wires, and the electrical resistance measurement device. The temperature sensing element is usually a coil of fine wire or a metal film. It is most commonly constructed of platinum but palladium, nickel, nickel alloys and copper are sometimes also used. Platinum is used to measure temperature from -200 to about 800 °C. Palladium is suitable from 200 to 600 °C, nickel from -100 to 300 °C, and copper from -100 to 200 °C (McGee 1988).

Platinum is considered to be unequalled as the metallic element for an RTD thermometer for three reasons. It follows a very linear resistance-temperature relationship; it follows its resistance-temperature relationship in a highly repeatable manner over its temperature range and it has the widest temperature range among the metals used to make RTDs (Michalski, Eckersdorf et al. 2002; Hagart-Alexander and Boyes 2003). Platinum is not the most sensitive metal; however it is the metal that offers the best long term stability (Burns 1999).

The resistance-temperature characteristics of copper are fairly linear, within 0.1 °C over its operating range, and this can have advantages in terms of the cost of the associated electronic measuring or control circuitry. Due to copper’s low resistivity, copper-based RTDs are less accurate and low in sensitivity. Another disadvantage is that copper is susceptible to corrosion (Childs 2001).

Nickel has a ferroelectric Curie temperature that prevents it from being used over 300 °C. Nickel RTDs are relatively cheaper than platinum RTDs but offer high sensitivity (Dogan 2002). The resistance temperature characteristics for nickel RTDs have been standardised by DIN 43760 (withdrawn now) for the range of -60 to 180 °C. In terms of the CVD equation it may be defined as follows (DIN 43760 1987):

\[ R_T = R_0[1 + AT + BT^2 + CT^4], \]

Where:
$R_0 = 100 \, \Omega$;
$A = 5.450 \times 10^{-3} \, \degree C^{-1}$;
$B = 6.65 \times 10^{-6} \, \degree C^{-1}$;
$C = 2.695 \times 10^{-11} \, \degree C^{-1}$.

Nickel-iron RTDs with a composition of 70% nickel and 30% iron are available under the trade name of Balco. Balco RTDs are available having a base resistance from 2 kΩ to 10 kΩ. In comparison with Nickel, it has a slightly smaller temperature coefficient but twice the resistivity (Pelican Wire Company). Figure 2.18 shows the relative temperature-resistance curves of platinum, copper and nickel sensing elements. Resistivity, temperature coefficient of resistivity and specific heat capacity of various metals are presented in Table 2-3.

Metals used for an RTD should exhibit the following properties (Michalski, Eckersdorf et al. 1991):

- high resistance temperature coefficient for high sensitivity;
- high resistivity to enable the construction of physically small RTD;
- high melting temperatures;
- stable physical properties;
- high corrosion resistance;
- easy reproducibility of the metal with identical properties;
- continuous and smooth dependence of resistance versus temperature without any hysteresis;
- sufficient ductility and mechanical strength.

Platinum fulfils all of these requirements in the best way; that is why it is the most commonly used metal in RTDs.
Table 2-3: Resistivity, temperature coefficient of resistivity and specific heat capacity of several metals (Michalski, Eckersdorf et al. 1991).

<table>
<thead>
<tr>
<th>Metal</th>
<th>Temperature of $p$ ($^\circ$C)</th>
<th>Resistivity $p$ ($\Omega \cdot m \times 10^{-8}$)</th>
<th>$\alpha$ ($\Omega/K$)</th>
<th>Temperature of $\alpha$ ($^\circ$C)</th>
<th>Specific Heat Capacity (KJ/Kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>20</td>
<td>2.6548</td>
<td>0.00429</td>
<td>20</td>
<td>0.91</td>
</tr>
<tr>
<td>Copper</td>
<td>20</td>
<td>1.6730</td>
<td>0.0034</td>
<td>20</td>
<td>0.39</td>
</tr>
<tr>
<td>Gold</td>
<td>20</td>
<td>2.35</td>
<td>0.004</td>
<td>0-100</td>
<td>0.13</td>
</tr>
<tr>
<td>Iron</td>
<td>20</td>
<td>9.71</td>
<td>0.00651</td>
<td>20</td>
<td>0.46</td>
</tr>
<tr>
<td>Lead</td>
<td>20</td>
<td>20.648</td>
<td>0.0036</td>
<td>20-40</td>
<td>0.13</td>
</tr>
<tr>
<td>Nickel</td>
<td>20</td>
<td>6.84</td>
<td>0.0069</td>
<td>0-100</td>
<td>0.54</td>
</tr>
<tr>
<td>Palladium</td>
<td>20</td>
<td>10.8</td>
<td>0.0037</td>
<td>0-100</td>
<td></td>
</tr>
<tr>
<td>Platinum</td>
<td>20</td>
<td>10.6</td>
<td>0.00393</td>
<td>0-100</td>
<td>0.13</td>
</tr>
<tr>
<td>Rhodium</td>
<td>20</td>
<td>4.51</td>
<td>0.0042</td>
<td>0-100</td>
<td>0.24</td>
</tr>
<tr>
<td>Silver</td>
<td>20</td>
<td>1.59</td>
<td>0.0041</td>
<td>0-100</td>
<td>0.23</td>
</tr>
<tr>
<td>Tin</td>
<td>0</td>
<td>11.0</td>
<td>0.0047</td>
<td>0-100</td>
<td>0.21</td>
</tr>
<tr>
<td>Tungsten</td>
<td>20</td>
<td>5.6</td>
<td>0.0045</td>
<td>0-100</td>
<td>0.13</td>
</tr>
</tbody>
</table>

2.5.5 Resistance Thermometer - Construction

The design of an RTD requires a compromise between accuracy and practical robustness. The RTD should be constructed in such a way as to be unaffected by the environmental factors e.g. handling, pressure, humidity etc. As was mentioned previously, the resistance of metals can
also be influenced by the strain causes by mechanical shock and thermal expansion. A freely wound wire around an insulator would not be affected by thermal expansion but this construction would make it more sensitive to handling and shocks. However, an RTD design mounting a supported wire around an insulator would increase its mechanical robustness but this construction would make the wire sensitive to differential expansion and ultimately affect the resistivity of wire (Burns 1999) (Childs 2001) (Goldstein, Chen et al. 1998). Platinum RTDs (PRTs) may be classified according to their basic application as:

- Standard Platinum Resistance Thermometer (SPRT);
- Secondary Standard Platinum Resistance Thermometer (Secondary SPRT);
- Industrial Platinum Resistance Thermometers (IPRT);
  - wire-wound IPRT;
  - thin-film IPRT;

Table 2-4: Classification of platinum resistance thermometers (Burns 1999)

<table>
<thead>
<tr>
<th>Probe</th>
<th>Basic Application</th>
<th>Temperature range ( °C)</th>
<th>Probe style</th>
<th>Handling</th>
<th>Accuracy (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPRT</td>
<td>Calibration of secondary SPRT</td>
<td>-200 to 1000</td>
<td>Immersion</td>
<td>Very fragile</td>
<td>±0.0001</td>
</tr>
<tr>
<td>Secondary SPRT</td>
<td>Lab use</td>
<td>-200 to 500</td>
<td>Immersion, Air</td>
<td>Fragile</td>
<td>±0.03</td>
</tr>
<tr>
<td>Wire-wound SPRT</td>
<td>Industrial field use</td>
<td>-200 to 650</td>
<td>Immersion, Air, Surface</td>
<td>Rugged</td>
<td>±0.25</td>
</tr>
<tr>
<td>Thin-film IPRT</td>
<td>Industrial field use</td>
<td>-50 to 260</td>
<td>Immersion, Air, Surface</td>
<td>Rugged</td>
<td>±0.25 to ±2</td>
</tr>
</tbody>
</table>

SPRTs are highly accurate, stable and repeatable platinum thermometers (see Figure 2.19). However they are fragile and used only in laboratory environments. They are costly due to their material requirement and expensive production techniques. SPRT elements are wound from strain-free, high-purity platinum wire. Internal lead wires are usually made from platinum and internal supports from quartz or fused silica. SPRT probes can be accurate to ±0.001 °C, if properly used (Goldstein, Chen et al. 1998).
Figure 2.19: Standard Platinum Resistance Thermometer (SPRT).

Secondary SPRTs are also used in laboratory environments. They are constructed like the SPRT, but the materials used are less expensive. The Secondary SPRT can withstand some handling but rough handling, vibration, and shock may cause a shift in calibration. They are accurate to ±0.03 °C over their designated working temperature range (Childs 2001).

Industrial PRTs are designed to withstand industrial environments and are almost as durable as thermocouples. Standard models are interchangeable to an accuracy of ±0.25°C to ±2.5 °C over their designated working temperature range (BS EN 60751 2008).

One common configuration of Industrial PRTs is the wire wound element in which a very fine platinum wire (10 to 50 μm) wound around a ceramic mandrel. In order to provide the electrical insulation and mechanical protection, the sensing element is covered with a thin coating (usually Teflon or glass fibre). Since the sensing element wire is tightly supported, it cannot expand and contract as freely as the SPRTs’ relatively unsupported platinum wire. This offers higher durability than SPRTs and secondary SPRTs (Michalski, Eckersdorf et al. 2002).
Thin-film elements are manufactured by similar techniques to those used to manufacture integrated circuits. First, a thin film of platinum is deposited onto a suitable ceramic substrate. Then, the element’s surfaces are covered with insulation to protect it from humidity and environmental contaminants. Because of their extremely small size, their response time is much faster than the rest of the PRTs. They are mounted on a surface by glue or solder. Usually they have an accuracy from 0.5 °C to 2.0 °C. The accuracy and stability might not be as good as some wire-wound elements due to hysteresis, long-term stability errors, and self-heating errors (Burns 1999) (John and Jon 2005).

2.5.6 Surface Temperature Sensors

A contact thermometer measures only its own temperature. Upon bringing the contact thermometer close to the surface to be measured, heat will transfer via conduction or convection from the body to the thermometer. Upon reaching the steady state, the contact thermometer would give an estimate of the surface temperature. Surface Temperature Measurement is a highly desired and difficult measurement mainly because of the issue of thermal contact resistance between the sensor and the body to be measured (Liu, Feng et al. 2010). Unlike applications in which the sensor is wrapped in protective tubes immersed in a fluid of controlled circumstances; surface measurements need that sensor to be outside of the process vessel where environmental conditions may affect its measurement accuracy (National Physical Laboratory 2010).

Selection criteria for surface temperature sensors include range, precision, ruggedness, thickness, sensitivity to substances likely to contact the sensing element, contact pressure and the flexibility of the unit and finally the presence of thermal gradients in close proximity to the sensor (Liu, Feng et al. 2010) (Bluestein 1999). In order to measure the surface temperature accurately, the following rules should be considered. (Rdf Corporation):

- Sensor should have maximum thermal contact and permit minimal mechanical strain;
Sensor must be insulated or isolated from the external environment, in order to make its temperature as close as possible to that of the surface.

Insulation may be placed over the sensor in order to avoid environmental exposure. The sensor can be mounted over the surface mechanically or using adhesive. In the case of using adhesive: the operating temperature; thermal expansion of the surface, sensor, and adhesive are important factors to consider (Rdf Corporation) (ISO 9886 2004).
Chapter 3 Development of Temperature Sensing Fabric (TSF)

3.1 Introduction

This chapter concentrates on the design, construction and manufacturing of Temperature Sensing Fabric (TSF). Initially, the chapter presents the process of conceptualisation of TSF based on the Resistance Temperature Detector (RTD). Subsequently, the desirable characteristics of TSF are listed and the reasons for choosing knitting over weaving technology for TSF fabrication are discussed. A modified relationship between resistance of the TSF and temperature is also established. Various types of metal wire identified as potential sensing elements for TSF are compared in conjunction with the selection criteria. The manufacture of two types of TSF along with their needle notation is discussed in detail in the end of this chapter.

3.1.1 Conceptualisation of Temperature Sensing Fabric (TSF)

It has been discussed in detail in the literature review that researchers have employed external temperature sensors in Wearable Health Monitoring Systems (WHMS) to measure the core and skin body temperatures. A few studies have been reported in respect of the development of textile-based temperature sensors but lacked the contents related with characterisation of baseline specifications and validation of experimental results through modeling. So the purpose of this study was to embed temperature sensing functionality into a textile substrate without much loss of the flexibility of the fabric. In order to achieve this, a detailed review has been conducted to identify what are currently the most commonly used temperature sensing technologies i.e. the Resistance Temperature Detector (RTD), thermistor and thermocouple. The review was conducted with emphasis on their design, construction, measurement principles, baseline specifications, and application scenarios and especially from the point of view of their integration into textiles.

The review has demonstrated that the design and measurement principles of the RTD can be applied in the development of a textile-based temperature sensor. In comparison with the thermistor and thermocouple, an RTD is probably the most suitable type of device to integrate
into a textile substrate, and could ultimately be fabricated on an industrial scale fabric forming machine without much manual input. Thermistors are fragile semiconductor devices - usually encapsulated in glass. Thermocouples incorporate a welded joint and require relatively complex “conditioning” electronics. Neither is as accurate as the RTD. They would have to be sewn into place, whereas the RTD wiring is very simple and can become a part of the fabric. The associated electronic circuit (to measure resistance) is relatively simple.

Technically, textile-based RTD sensors can be developed by integrating a piece of metal wire (as a sensing element) into a textile fabric. However, various factors have to be taken into account. For example, an appropriate alloy for the sensing wire has to be selected and the most suitable textile structure for embedding the sensing element must be found. It is also necessary to select the most appropriate material for the base fabric and identify which textile process should be used in manufacture. A suitable method of integrating the sensing wire into the textile structure must be devised and it would be useful to model the temperature-resistance relationship of the fabric-based RTD.

The desirable characteristics for a textile based RTD are as follows:

- high sensitivity (for maximal resolution and accuracy);
- insignificant sensitivity to external interference (e.g. strain, moisture, wear & tear);
- stability (for reproducible and reliable measurements);
- small thermal mass (for fast response time);
- minimal hysteresis;
- straightforward textile processing and reproducibility;
- stretchable (to be able to conform on body shape).

3.1.2 Knitting vs. Weaving (Structures and Technology)

As discussed in Chapter 2, both knitted and woven fabrics have been used for the development of sensors and as sensing platforms for wearable health monitoring systems (Lam Po Tang 2007) (Pantelopoulos and Bourbakis 2010). Considering the required application (human body skin temperature measurement), knitted structures ostensibly offer a better choice than woven structures. Moreover knitting technology offers excellent advantages over other fabric forming systems in respect of the development of textile sensors.
Woven fabrics are usually characterised by their high dimensional stability, poor skin contact, and limited elastic recovery. In those sensor applications where close contact with the body is not required, e.g. environmental temperature, human GPS, then woven structures are preferred over knitted structures. The construction of woven fabrics (interlacing of warp and weft) may also be readily exploited to develop power and signal lines at specified locations.

Knitted structures are the most suitable for undergarments because of their ability to conform to body shape. The elastic properties and breathability of knitted structures make them comfortable to wear. In those sensor applications where close contact to the body is required, e.g. respiration sensors, then knitted structures are preferred over woven structures. Towards the development of temperature sensing fabric, various types of knitted structure can be used as a platform for the laying-in of metal wire. Double jersey knitted structures are more suitable than single jersey structures because they would provide a better protection for the metal wire from wear and tear. Secondly, the metal wire would not be visible and does not affect the aesthetic properties of the fabric.

After investigating the textile manufacturing processes suitable for embedding a sensing wire into fabric, knitting was found to be an obvious choice. Knitting technology may be classified into warp knitting and weft knitting technologies according to the yarn path in the knitted structure. Amongst the various types of available knitting machine, circular weft knitting, flat knitting and warp knitting machines are mainly used to produce knitted articles. The knitting laboratory at The University of Manchester is equipped with state-of-the-art electronic flat bed knitting machines. All mechanical movements are controlled electronically via CAD/CAM systems while Intarsia and Fully-Fashioned technologies provide a suitable platform for creating knitted sensors. Knitting technology offers more advantages than weaving technology in the development of textile-based sensors. Some of them are listed here:

- knitted sensors require simple preparation and manufacture as a result of the flexibility of knitting technology, whilst time-consuming preparatory processes are a major feature of weaving technology, such as warping and sizing;
- knitting technology allows a wide selection of conductive yarns to be used for sensor manufacturing whilst the strength requirements of warp yarn mean that weaving offers limited options of conductive yarn;
• knitting offers WholeGarment or Fully Fashioned technologies which facilitate manufacturing the sensor-based garment (e.g. a shirt or vest) in one step, whilst weaving technology does not offer any such capabilities;

• knitting technology offers the facility of exact positioning of an integrated sensor, data lines and power lines within the garment pattern, thanks to the Intarsia technique and thus minimises the manufacturing time and pre & post manufacturing processes, while woven sensors would require manual post weaving operations which include the insulation, encapsulation and soldering of data lines to sensors – such manual processes add variance to the sensor characteristics;

• knitting also offers the possibility of laying-in weft wise and warp wise yarns which broadens the scope of sensor manufacturing.

3.2 Design and Construction

The design of the TSF is based on an idea (used in some RTD designs) of inlaying a fine metal wire (as a sensing element) within the knitted fibrous structure. Laying-in is a technique, usually used for the structural modification of knitted fabrics as shown in Figure 3.1. The idea is to pack the metal wire within the courses as densely as possible and at the same time preventing the surface of individual strands of wire from touching, to achieve the maximum ratio of “wire length to sensor area”.

The measurement principle of the TSF is based on the inherent property of metal wire to change its electrical resistance with change in temperature. The classic equation showing the relationship between the resistance of metal wire and its length, diameter and resistivity is stated in equation (3.1) (Burns 1999):

![Figure 3.1: TSF showing in-laid sensing wire in a rib knitted structure](image-url)
Where, $R_{\text{ref}}$ and $\rho_{\text{ref}}$ are the resistance (wire function) and resistivity (metal function) respectively at a reference temperature. $R_{\text{ref}}$ is also known as the Nominal Resistance. While the length ($l$) and diameter ($d$) are functions of the wire. A mathematical relationship between the length of the metal wire (sensing element) and the dimensions of the sensing fabric has been derived as:

$$l = (W_s L_s D_c) + L_s$$  \hspace{1cm} (3.2)

Where $L_s$ and $W_s$ are the length and width of the TSF and $D_c$ represents the inlay density of the sensing wire. From equation (3.2), it can be seen that, a 4 x 4 cm$^2$ patch of TSF with an inlay density of 6 cm$^{-1}$ can easily contain a one metre length of sensing wire. Combining equations (3.1) and (3.2) gives a modified relationship for TSF resistance in terms of its dimensional parameters:

$$R_{\text{ref}} = \frac{4\rho_{\text{ref}} [(L_s W_s D_c) + L_s]}{\pi d^2}$$  \hspace{1cm} (3.3)

Equation (3.3) could be used to optimise the dimensions of a TSF patch for a required reference resistance, once the resistivity and diameter of the wire are known. The higher the resistivity and the finer the sensing wire, the smaller may be the sensing area within which a target reference resistance may be achieved. It is thus important to lay-in the sensing element as densely as possible to achieve the maximum ratio of reference resistance to sensor area. High reference resistance is desirable in order to achieve high sensitivity while small sensor area is desirable for fast response time. The effect of temperature ($T$) on the resistance of a metal ($R_T$) conductor can be expressed as (Dogan 2002):

$$R_T = R_{\text{ref}} (1 + \alpha_{\text{ref}} (T - T_{\text{ref}}))$$  \hspace{1cm} (3.4)

Where $\alpha_{\text{ref}}$ is the temperature coefficient of resistivity for a given temperature range starting from the reference temperature ($T_{\text{ref}}$). After combining equations (3.3) and (3.4), the temperature-resistance relationship of a TSF can be described in the form:
\[ R_T = \frac{4\rho_{\text{ref}}[(L_s W_s D_c) + L_s]}{\pi d^2} (1 + \alpha_{\text{ref}}(T - T_{\text{ref}})) \] (3.5)

### 3.3 Sensing Element

The sensing element is a material that changes its properties when introduced to a stimulus e.g. light, pressure, heat etc. In RTDs a very fine & relatively short temperature-sensing-element (<25 micron in diameter) is employed, which changes its resistance upon change in temperature. Hence, metallic wire could be used as a sensing element of a TSF. Metallic wire could be in the form of bare wire, enameled wire or textile wrapped (braided) wire. Enamel and textile wrapping provides the insulation from the external environment and increases the textile character of a TSF.

#### 3.3.1 Requirements

Various metal wires could be used as the sensing element of the TSF. The desirable properties for the sensing element of a temperature sensing fabric include the following items.

- **Nominal (reference) resistance**: nominal resistance is one of the most important baseline specifications of the RTD. RTDs are available from 10 Ω to 10,000 Ω of nominal resistance but 100 Ω is the most common Figure. Nominal resistance depends upon the resistivity and dimensions of the TSF as stated in equation (3.3). High nominal resistance is desirable and could be achieved by choosing a long, fine wire of high resistivity.

- **Sensitivity**: sensitivity is directly related with the temperature coefficient of resistivity and nominal resistance. High sensitivity is desirable for developing a sensor of high accuracy and resolution, with minimal circuitry.

- **Response time**: temperature sensors with fast response times are desirable especially during the measurement of the temperature in a dynamic environment. The response time of sensor may be minimised by keeping the thermal mass of the sensing element as low as possible. Thermal mass is calculated as the product of the mass of the sensing element and the specific heat capacity of its material, and typically measured in units of J/°C.
• **Self heating:** sensing elements may be prone to a self heating (Joule heating) error if the excitation currents of 10 mA or over are used. High thermal conductivity of the sensing element is desirable to minimise this error by dissipating the heat rapidly.

• **Repeatability:** continuous and smooth dependence of resistance on temperature without any hysteresis is important for high precision, accuracy and interchangeability.

• **Mechanical properties:** sensing wire should have sufficient ductility for smooth bending along the edges and high tensile strength to meet the requirements of tension required during the inlaying process of machine knitting, without any breakages.

• **Availability and Reproducibility:** sensing wire should be low in price and easily available in the form of fine diameters of wire and easily reproducible with identical properties.

• **Stable physical properties:** the metal selected should have a high melting point and an ability to resist the effects of corrosion.

### 3.3.2 Comparison

The most commonly used metal as a sensing element in RTDs is platinum, however copper, nickel and palladium based RTDs are also available on the market. The temperature-resistance curves of all metals are fairly linear in the required temperature range i.e. 20 to 50 °C. Figure 3.2 presents a comparative chart of the important properties of sensing elements.

Platinum exhibits the highest resistivity among all metals. Therefore, a sensing element made of platinum would require reduced length in order to achieve any desired nominal resistance; copper would require a much longer length to achieve the same nominal resistance. High resistivity, along with high temperature coefficient of resistivity, also contribute to high sensitivity, as shown by nickel and platinum elements. Because of their low thermal mass, the response time of tungsten and platinum would be faster than nickel and copper. Tungsten is the strongest sensing element of all, in terms of its tensile strength. This would be helpful while processing on a knitting machine.
In terms of price, copper is least expensive of the possible sensing elements and is easily available in range of diameters in a bare and insulated form. Tungsten and nickel may not be easily available in their purest form, and this can result in large variations in the values of resistivity and temperature coefficient of resistivity. In comparison with copper, it is relatively difficult to find tungsten and nickel of the required purity and they may have to manufactured to order. Platinum is regarded as the best sensing element for RTDs due to its high resistivity,
low thermal mass, its availability in its purest form and its stability over a wide range of temperatures; it is, however, quite expensive.

A comparison of the temperature-resistance relationship of all sensing elements is presented in Figure 3.3 along with their nominal resistances and sensitivity values. Standard values of resistivity and the temperature coefficient of resistivity are used while modelling this relationship. The length of the wire and its diameter were taken as 1 m and 100 μm respectively. A one metre length of wire can be easily placed in a (4 x 4) cm² patch of TSF.

### 3.3.3 Selection

Considering its price band, platinum was completely ruled out for purchase. In terms of the properties presented in Figure 3.2, each element i.e. copper, nickel and tungsten possess some advantages over the others. It was thus decided to make use of all these metals as sensing elements for TSF. These sensing elements, in the form of bare and insulated wire, were purchased from different companies in various diameters, as shown in Table 3-1. Table 3-1 lists all the sensing elements used for the development of TSF along with their form factor and manufacturer’s name.

All wires were purchased from manufacturers during the course of this study except the 4% Nickel coated Copper wire of 127 μm dia. (4NC127) and the 27% Nickel coated Copper wire of 125 μm dia. (27NC125) as these were already available in the laboratory.
## Table 3-1: Sensing elements of Temperature Sensing Fabric (TSF)

<table>
<thead>
<tr>
<th>Wire Tag</th>
<th>Form</th>
<th>Metal</th>
<th>Diameter (Micron)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>N100</td>
<td>Bare</td>
<td>Nickel</td>
<td>100</td>
<td>Scientific Wire</td>
</tr>
<tr>
<td>N90</td>
<td>Bare</td>
<td>Nickel 270~</td>
<td>90</td>
<td>Alloy Wire</td>
</tr>
<tr>
<td>W80</td>
<td>Bare</td>
<td>Tungsten</td>
<td>80</td>
<td>Good Fellow</td>
</tr>
<tr>
<td>W50</td>
<td>Bare</td>
<td>Tungsten</td>
<td>50</td>
<td>Good Fellow</td>
</tr>
<tr>
<td>4NC127</td>
<td>Bare</td>
<td>4% Nickel coated copper</td>
<td>127</td>
<td>Temco</td>
</tr>
<tr>
<td>27NC125</td>
<td>Bare</td>
<td>27% Nickel coated copper</td>
<td>125</td>
<td>Temco</td>
</tr>
<tr>
<td>C150</td>
<td>Bare</td>
<td>Copper</td>
<td>150</td>
<td>Scientific Wire</td>
</tr>
<tr>
<td>EC150</td>
<td>Enameled*</td>
<td>Copper</td>
<td>150 (170 including enamel)</td>
<td>Scientific Wire</td>
</tr>
<tr>
<td>BEC150</td>
<td>Braided and Enameled*</td>
<td>Copper</td>
<td>150 (220 including enamel and Braid)</td>
<td>Scientific Wire</td>
</tr>
<tr>
<td>BEN61</td>
<td>Braided and Enameled</td>
<td>Nickel</td>
<td>61 (120 including enamel and Braid)</td>
<td>Scientific Wire</td>
</tr>
</tbody>
</table>

* Double artificial silk covered
- Double Nylon covered
* Solderable polyurethane 156 °C enamel
~ A high purity grade of nickel
3.4 Manufacturing of Temperature Sensing Fabric

3.4.1 Introduction

The main requirement of the TSF structure include the smooth embedding of wire in the middle of the textile layers so that it neither contacts itself, nor protrudes from the main body or the edges of the fabric. It was also desirable to pack a high density of wire in order to achieve high nominal resistance in a small sized TSF. The most suitable way for smooth embedding of wire is by in-laying, as it offers the possibility of introducing those yarns which are difficult to process in the knitting machine due to their physical properties. The inlaying technique involves trapping the inlay between the needle and the sinker loops on a double needle bed machine.

Various types of knitted structure can be used as a platform for laying-in metal wire. Double layer knitted structures are more suitable than single layer structures because they provide a better cover for the metal wire from wear and tear. Secondly, metal wire would not be visible and does not affect the aesthetic properties of the fabric. Moreover, the wire will assume a straight configuration which avoids any distortion or flow towards an area of the fabric under tension.

To inlay a metal wire within a double layer knitted structure, an initial attempt was made on a hand knitting machine. Usually knitted fabric shrinks after passing through the needle bed of hand knitting machine. This shrinking effect could be minimised by knitting a tighter structure. However, hand knitting machines are usually low gauge machines and do not offer the possibility of producing a tighter structure. It was seen in the hand knitted samples that an inlaid metal wire did not stretch back to the width of the fabric, resulting in metal wire protruding from both edges of the TSF. It was therefore decided to fabricate samples on a 10 gauge Shima Seiki computerised flat-bed knitting machine, as shown in Figure 3.5.

3.4.2 TSF manufacturing on computerized flat knitting machine

In order to meet the requirement, a double layer structure of TSF was designed in Shima Seiki Knit Paint software; it comprised knit courses, spacer courses and metal inlays. Two feeders were used to fabricate the samples. The first feeder was responsible for knitting spacer and knit courses, by taking five ends of highly textured 167 tex polyester yarn. The second feeder was
used for inlaying metal wire along with three ends of the same polyester. Considering the test rig requirements, all the samples were developed with a sensing area of 8 x 8 cm². Each sample comprised 39 wales; 33 for the inlay area and 6 for the edges. Since it is a double layer structure, therefore 39 needles of the front needle bed and 39 needles of the lower needle bed were utilised. The non-sensing part of the TSF comprised full cardigan stitch (top and bottom) to minimise relaxation of the fabric.

Samples were developed with combinations of various metal wires (as mentioned earlier) and inlay densities. Two types of sample were developed in terms of inlay density i.e. 4.7 inlays/cm (low inlay density) and 6.4 inlays/cm (high inlay density). High density TSF has 46 courses of metal inlay while low density TSF has only 34 inlays. It was difficult to pack the sensing element in every course of fabric without it shorting to itself; therefore some spacer yarn was added to keep them separated in between courses. In the low inlay density samples, extra spacers were required between the knit courses in order to preserve the compactness of the structure. Samples with different combinations of metal wires and inlay densities also provided a useful range of nominal resistances from 3 to 130 Ω.

The wires purchased from manufacturers were on small spools due to the shortness of the length. It was not advisable to use these small spools directly on the knitting machine because of two problems. Firstly, excessive wire breakage occurred due to interaction with the flanges of the spool while withdrawing. Secondly, it was difficult to maintain constant tension in the wire. In order to address these issues, the metal wire was wound manually on a hank winder as shown in Figure 3.6.

Care was exercised while winding on the hank winder in order to maintain constant tension in the wire. The hank winder was fastened to a stand and placed at the top of the machine.

Smooth withdrawal and constant tension in the wire is a prime requirement for inlaying. In the initial phase of manufacturing, frequent breakages had been observed. Sometimes excessive tension in the wire caused breakage and sometimes interference between the needles and the slack wire caused breakages. Reduced tension in the wire was also responsible for excessive bending at the fabric edges which resulted in wire poking out at the edges and sometimes from the main body.
Figure 3.4: A 34 inlay TSF sample of 8 x 8 cm² sensing area along with a magnified view of knit structure

Figure 3.5: Shima Seiki computerised flat knitting machine

Figure 3.6: Hank winder

Figure 3.7: Special feeder for wire inlay
In order to rectify this issue the following actions were taken.

- Wire feed was moved to the side from the top of the machine; this reduces the angular path, resulting in uniform tension and smooth feeding.
- A negative let off mechanism was developed at the hank winder, comprising tension plates and a spring system, to minimise discontinuities in the feed and to ensure even tension in the wire before, after and during inlaying.
- Extra polyester yarn was used as an inlay along with the metal wire to increase the strength of the inlay.
- The machine was programmed to run at an extremely slow speed (0.05 m/s) while inlaying the metal wire.
- A special feeder (see Figure 3.7) was used to inlay the metal wire, as the ordinary feeder did not meet the requirements of straight laying-in and smooth bending of wire at the edges of the TSF. This special feeder is tubular and was set at a lower height so that during the knitting cycle, the needles go over the wire without causing breakage of the wire. This inlay feeder must not be used for knitting as it would crash into the needles because of its lower adjusted height. The stitch presser was not used due to the risk of it interfering with the inlay wire.

### 3.4.3 Needle notation of TSF structure

The TSF knit structure was designed using the Shima Seiki Knit Paint software. The structure had to change frequently in order to define the wire inlay density in the required dimension and to minimise errors due to shorting of wires and protrusion along the edges. In terms of inlay density, two types of 8 x 8 cm² samples were developed i.e. 4.7 and 6.4 inlays/cm. The high density TSF has 46 courses of metal inlay while the low density TSF has only 34 inlays.

The needle notation of the TSF structure of 46 inlays is shown in Figure 3.8. Two feeders were used to fabricate the samples. Feeder 4 was responsible for knitting spacer and knit courses as drawn in blue lines. Feeder 5 was used for inlaying metal wire along with three ends of polyester as shown by the magenta lines. It was difficult to pack the sensing element in every course of fabric without shorting; spacer yarn was added to keep them separated between the courses.
The needle notation of the TSF structure of 34 inlays is shown in Figure 3.9. In the 34 inlay samples, more spacer yarn was used because of the low wire inlay density. Since structural compactness was required, it was necessary to add extra spacer courses in the knit structure. In the 34 inlay samples, extra spacer yarn was used between the knitted courses in order to preserve the compactness of the structure.

For ease of understanding, the TSF structure can be represented in a simplified form by reducing the number of knitting and spacer courses as shown in Figure 3.10. Bear in mind it is not a true representation of the TSF structure in terms of the number of knitted and spacer courses, or their order. However, it gives a clear idea of the structural concepts. Detailed construction details of the 34 and 46 inlay TSF structures are shown in Figure 3.8 and Figure 3.9.
Figure 3.8: Needle notation of the 46 inlay TSF structure
Figure 3.9: Needle notation of the 34 inlay TSF structure.
3.4.4 Processability of metallic wire

Table 3-2 presents an overview of the processability of metallic wire during TSF manufacture, in terms of wire breakage, manual handling and the quality of inlaying. “Wire breakages” means the average number of machine stoppages because of wire breakages during knitting. Manual handling of the wire includes all manual processes prior to and during manufacture and preparation of samples for testing. The quality of inlaying was considered good if the metal wire was smoothly embedded exactly in the middle of the double layer structure without any protrusion at the surface or the edges.

It was subsequently found that the sensor performance was directly related with the quality of inlaying. Frequent wire breakages related to excessive tension whilst poor quality of inlaying related to slackness in wire. For smooth bending of the wire at the edges, and a straight configuration of inlay, relatively high tensions were found to be preferable; provided the wire could able to sustain them. That is the reason that coarser wires (over 100 microns) showed better overall processability than their finer counterparts.
Although the metallic core diameter of the BEN61 wire is 61 microns; however due to its increased tensile strength because of addition of the enamel and the braiding layers; wire showed good processability during manufacturing.

Table 3-2: Metallic wire process-ability during TSF manufacturing

<table>
<thead>
<tr>
<th>Metallic Wire</th>
<th>Wire Breakages</th>
<th>Quality of inlaying</th>
<th>Manual Handling</th>
<th>Process-ability (Overall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEC150</td>
<td>Nil</td>
<td>Good</td>
<td>Easy</td>
<td>Good</td>
</tr>
<tr>
<td>EC150</td>
<td>Nil</td>
<td>Good</td>
<td>Easy</td>
<td>Good</td>
</tr>
<tr>
<td>C150</td>
<td>Nil</td>
<td>Good</td>
<td>Easy</td>
<td>Good</td>
</tr>
<tr>
<td>4NC127</td>
<td>Nil</td>
<td>Good</td>
<td>Easy</td>
<td>Good</td>
</tr>
<tr>
<td>27NC125</td>
<td>Nil</td>
<td>Good</td>
<td>Easy</td>
<td>Good</td>
</tr>
<tr>
<td>BEN61</td>
<td>Less</td>
<td>Good</td>
<td>Easy</td>
<td>Good</td>
</tr>
<tr>
<td>W80</td>
<td>Less</td>
<td>Poor</td>
<td>Medium</td>
<td>Poor</td>
</tr>
<tr>
<td>N100</td>
<td>Less than frequent</td>
<td>Medium</td>
<td>Medium</td>
<td>Moderate</td>
</tr>
<tr>
<td>N90</td>
<td>Less than frequent</td>
<td>Medium</td>
<td>Medium</td>
<td>Moderate</td>
</tr>
<tr>
<td>W50</td>
<td>Frequent</td>
<td>Poor</td>
<td>Difficult</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Among the smaller diameter wires i.e. N100, N90 and W80, nickel demonstrated smooth bending at the edges (because of its high ductility) but slight more breakages (because of its low tensile strength) in comparison with tungsten wire. Tungsten wire is inherently strong and brittle in nature; therefore tungsten inlaying suffered fewer breakages but displayed the poor behaviour in respect of bending at the edges. In some of the samples, wire protruded from the surface of the edges, as shown in Figure 3.11. The 50 micron tungsten wire was found to be relatively difficult to handle and to set into the feeder, as it got accumulated whenever any breakage occurred.
3.5 Discussion

A Modified Temperature-Resistance relationship for the TSF in terms of its dimensional parameters could be used to optimise the dimensions of a TSF patch for a required reference resistance. That will facilitate the specification and visualisation of the sensor characteristics. For example, the nominal resistance of a $5 \times 5 \text{ cm}^2$ of TSF could be calculated. Similarly, the area of TSF could be predicted that would be required in order to make $100 \, \Omega$ sensor. The derived relationship (Equation (3.2)) between the length of sensing element and the dimensions of the TSF is only valid for rectangular sensing areas.

The Sensing Element diameter, processability and sensitivity may be taken into account during element design, considering the compromise between manufacturing limitations and the desire to achieve high nominal resistance and sensitivity in a small-sized TSF. RTDs are commonly specified with their nominal resistance which is usually $100 \, \Omega$ at $0 \, ^\circ\text{C}$. In order to achieve $100 \, \Omega$ a very fine and relatively short sensing element (<0.025 mm in diameter) is employed in RTDs. It was desirable to achieve high nominal resistance with a small-sized TSF. However, initial manufacturing trials demonstrated that it would be difficult to go finer than 50 microns because of the issues related to the processability of the wires. However, coarser wire would heavily reduce the nominal resistance and sensitivity values. Therefore diameters of wire within the range of 50 to 150 microns were considered while selecting the wire. The drawback in choosing coarse wire is that of designing of relatively big patch in order to achieve higher nominal resistance. This problem was solved by employing a braided-enameled sensing element. The textile wrapping around the wire improved not only the textile character of the sensing element.
but also its tensile strength. The overall diameter of a highly sensitive sensing element BEN61 (Braided enamelled Nickel of 61 microns diameter) totalled around 120 microns, and proved resilient enough to be processed without problems in the knitting machine.

**Insulated Sensing Element:** whilst most of the TSF samples were developed with sensing elements in the form of bare wire, the idea of using insulated wire as a sensing element developed during the later stages of the research. Insulation would help in protecting the sensing element from external influences such as moisture, corrosion etc. In the case of textile insulation (braided wire); it would appear to improve the textile character of the sensing element and the TSF.

In order to investigate the effect of insulation of sensing element on the sensing performance of a TSF, it was desirable to purchase the insulated sensing element of the same kind, which had already been deployed in a TSF in the bare form. It brought into focus the fact that insulated sensing elements, especially made of nickel and tungsten, may not be easily available. However, it was possible to have them manufactured to order with suitable insulation, but at very high cost.

There was little possibility of insulating the sensing elements in-house. An attempt was made to wrap textile around bare metallic wire on a small industrial scale braiding machine, available in the textile laboratory. Unfortunately, the machine was not designed to work with wire of such fine diameter and frequent breakages were encountered. It was ultimately decided to purchase identical sensing wires in both bare and insulated forms and compare their performance.

Copper wires are easily available in different diameters and with a variety of insulation types. These wires are normally used for winding purposes and are often called “Magnet Wires”. So copper wire with the same sensing diameters, in three different forms (bare, enamelled and braided), were purchased from the same manufacturer. This helped to investigate the effect of insulation on the sensing performance of the TSF. Considering the time frame of this study, it was not possible to manufacture an extensive range of samples by using insulated sensing wire.

In manufacturing of TSF the most important issue yet to be optimised is the protrusion of wires from the edges, especially in case of finer wires. This issue could be addressed by manufacturing compact, high stitch-density TSF samples on **knitting machines of finer gauge (>10).** As explained earlier, the compactness of the structure is the prime requirement in order to hold the wire...
within the textile structure. As the stitch density of the fabric is increased, it undergoes less shrinkage after passing through the needle bed and the chances of wire poking out from the edges is greatly reduced.

**The TSF Structure and base material** have been finalised following a “trial and error” approach, in order to meet the fundamental requirement of smooth embedding of sensing wire in the middle of fabric, without shorting. The developed TSF structures may not be the most suitable/optimised constructions but they do meet the basic requirements of the research.

Bearing in mind that the ultimate purpose of the work was to develop TSF and ensure it works properly. For the said purpose, the effects of selection of the wire composition, the fineness of the wire, and the inlay density, on the manufacturing and sensing performance were investigated by producing a range of samples having nominal resistances from 3 to 130 Ω. The influence of fabric structure and base material on the sensing performance are not the major considerations at the present stage. This is in accordance with the current pattern of research in electronic textiles as reported by (Lam Po Tang 2007). Therefore all TSF samples are made with only two different structures (34 and 46 inlay) and one base material (polyester).

High textured polyester yarn was employed as the base material of the TSF. Polyester was preferred over cotton because of its extremely low moisture regain and high tensile strength. The low absorbency and better wicking properties of polyester fabrics assist the transfer of moisture from the skin to the outer surface of a garment where it evaporates. Moreover, the textured characteristics of the yarn increased the fabric bulkiness and provided better cover to the sensing element.

The use of **Metallic yarn as a Sensing Element** is being investigated. Some researchers have developed textile-based sensors by utilising conductive yarn (coated with conductive polymer or metal-loaded rubber). In order to improve the textile character of the TSF, development of metallic yarn was also investigated, in the initial phase of study. However, this route was discarded for two reasons: firstly, it is difficult to maintain the metallic yarn diameter and the coating percentage along the length of yarn; secondly the strain-induced electrical characteristics considerably affect the temperature-induced electric characteristics.
Chapter 4  Development of Test Rig System

4.1 Introduction

One of the primary objectives of this study was to calibrate the TSF by investigating the effect of temperature on the resistance of TSF. In order to quantify this effect, an ohm-meter and a reference temperature sensor were the primary requirements of the test rig. In addition, a heating system to artificially create a thermal environment at the required temperature was also essential. A test rig has been designed by using the instruments and accessories which were already available at the Smart laboratory. This chapter explains the design, development and behaviour analysis of the test rig system in detail. Later on, creation of LabVIEW based testing software for the continuous measurement of temperature and the corresponding resistance is also elucidated.

The proposed testing methodology is based on contact temperature measurement across the TSF and four wire measurement of resistance. The designed rig employs a constant temperature hotplate in order to maintain the TSF fabric at the required temperature, and consists of two copper plates across the TSF so that the temperature of the fabric surface can be calculated without direct measurement. Each copper plate was instrumented with four K-type thermocouples and a Picotech TC-08 data logger was used for recording the temperature. The temperature of the sample was approximated by averaging out the temperatures of the top and the bottom copper plates. An Agilent multimeter and 4-wire resistance measurement system was set up to measure and record the minute changes in electrical resistance. Special software has been created in the LabVIEW environment, in order to record and visualise the temperature and resistance signals side by side

4.2 Rationale

Calibration of the TSF is a prerequisite, before deploying it for the measurement of human body skin temperature. According to the literature review, any standard procedure or apparatus for the calibration of temperature sensing fabric has not been reported. Therefore the development of the test rig system along with the procedure for calibration was set as one of the core objectives of this study.
Usually RTDs are calibrated in primary or secondary temperature laboratories by fixed point or by comparison methods (Ayres and Blundell). A calibration method is chosen, depending upon the accuracy requirement and the temperature range. These calibration methods are usually performed for wide temperature ranges when nonlinearity also comes into play. Fixed point calibrations are performed for primary standard thermometers by the use of fixed point cells in order to attain the lowest possible uncertainties. It’s an expensive and time consuming process. Comparison calibrations are performed by the use of temperature-controlled baths (dry or liquid) and a reference standard thermometer. It’s a less expensive process and can be performed in a laboratory or at the site. In both types of calibration, sophisticated resistance bridges are used to measure resistance.

However in both these calibration methods, the sensor to be calibrated should be immersed either in a liquid thermal environment or in a dry thermal environment (standard sized metal blocks). Considering the material and construction of TSF, liquid thermal environments would not be appropriate. However, the size of a TSF does not correspond to the dimensions of standard sized metal blocks (used for calibration in dry thermal environments).

According to standard temperature laboratories (NPL 2012) (ISOTECH 2012) , the dedicated fixed point cells or metal block may be adapted for the calibration of TSF. This approach could be used to calibrate TSF up to 300 °C with a calibration accuracy of ±0.1 °C by considering any non-linearities. However, it is important to note that the relevant temperatures range extends from only 20 to 50 °C. Moreover errors associated with the construction of TSF and its application environment (movement artifacts, influences of environmental parameters etc) may be large. Therefore it would not be appropriate to purchase such a sophisticated system considering the study budget constraint.

4.3 Test Rig Components

A test rig has been designed by using the instruments and accessories which were already available at the Smart laboratory. Following is the brief introduction of the instruments which were used as components of the test rig.
4.3.1 PicoTech TC-08 Data Logger

A TC-08 Data logger by PicoTech was used to measure and record temperature readings via thermocouples (see Figure 4.1). Up to eight thermocouples can be connected in a single data-logging unit. It works with all popular thermocouple types (B, E, J, K, N, R, S, T) and offers a wide temperature sensing range (-270 °C to 1870 °C). TC-08 does not require extra cold junction unit because it has built-in cold junction compensation. It offers a temperature measurement accuracy of ±0.2% of the reading plus ±0.5 °C. It makes an interface with the PC using USB cable and does not require any separate power supply. Picolog is a data acquisition program designed for collecting, analysing and displaying data from the TC-08 data logger (PicoTech 2012).

4.3.2 Agilent 34401 Multimeter

The Agilent 34401A is an industry standard benchtop Digital MultiMeter (DMM) and provides a combination of high resolution, accuracy and speed (see Figure 4.1). Its measurement capability includes 6.5 digits of resolution with 0.01 % basic ohms accuracy. For resistance measurement a 34401 multimeter offers the maximum resolution of 100 µΩ on its 100 Ω range. It can be interfaced with the PC via GPIB or RS-232 connectors. Agilent IntuiLink is data acquisition software which allows the captured data to work easily using commercial PC applications (Agilent Technologies 2011).

4.3.3 Fischer Scientific Hotplate

A Fischer Scientific Hotplate was used as a heating source for the test rig which provides contact heat to the samples. Its top plate (7 x 7 in.) is made of reflective white ceramic, providing a maximum of 540 °C for its temperature setting. An LED display shows the actual and set point temperatures which can be adjusted with increments of 1 °C (Fischer Scientific 2012).
4.4 Development of Test Rig Methodology

This section explains how the individual components/instruments were utilised to develop the test rig. The main objective of the test rig was to record resistance and the corresponding temperature values of the TSF in order to develop an empirical relationship between resistance and temperature for calibration purposes. Following were the general requirements of the test rig:

- creation of a uniform thermal environment for TSF within a temperature range of 20 °C to 50 °C;
- accurate temperature measurement of TSF by thermocouple via the contact measurement method;
- measurement of minute change in resistance, of TSF, as a consequence of change in temperature by attachment of multimeter leads to the sensing element.

But the requirement was to find the best way to provide these facilities. For example, how might a uniform thermal environment be offered to the TSF at specified temperature settings? How to attach thermocouples to the sensing element? How to offset the initial resistance of the
multimeter leads? How to remove the error in resistance due to effect of test rig temperature fluctuations on the multimeter leads? How to minimise the handling requirement in the testing procedure?

Since the observations involve the measurement of precise readings of resistance and temperature, therefore the contact quality in the test rig settings is important and should be uniform in all the testing procedures.

4.4.1 Thermal Environment Provision & Temperature Measurement

Accurate temperature measurement of TSF (either its surface or the embedded sensing wire) may not be as straightforward as it seems. TSF consists of three interacting components i.e. air, textile, and the sensing element. Each component has different thermal properties and unless the TSF is in a steady state, accurate temperature measurement of the sensing element may not be possible.

4.4.1.1 Preliminary approaches

In the earlier stages of this study, temperature measurement of the TSF was performed at various thermal environments between 20 and 50 °C, by using a variety of techniques, especially the contact method i.e. attaching the temperature sensor, at the surface of the TSF or, directly with the sensing element. Under uniform thermal conditions of 50 °C, the surface temperature of the TSF was measured with variations of ±3 °C. Similarly, direct temperature measurement of the sensing element was also not consistent and this resulted in large variations. The main problem in both cases was the quality of thermal contact between the temperature sensor and the TSF surface (or sensing element).

The quality of contact could be improved by permanent fastening of the temperature sensor on the sensing element (e.g. soldering) or at the surface of the TSF (e.g. gluing). However, this invasive approach was not entertained as the quality of thermal contact would not be the same for different samples and would be a source of variation. Therefore the goal was to develop a plain non-invasive method to measure temperature having uniformity in procedure, with minimised manual handling.
Test rig concerns were also discussed with the contact thermometry section of the National Physical testing Laboratory (NPL), UK (NPL 2012). According to them, surface temperatures are notoriously difficult to measure and it’s even more complicated when the subject being measured is smaller than the temperature sensor. They advised the creation of a uniform thermal environment at specified temperature points by circulating hot air in a closed chamber. The heating source should be outside the chamber as it would generate thermal gradients. For temperature measurement, thermocouples may be placed in close proximity to the wire to measure the air temperature which would be at the same temperature as the wire. However, this procedure does not guarantee the actual TR measurement in a dynamic environment. However it would facilitate measurement in a steady state environment by taking into account the 0.5 °C error.

4.4.1.2 New Methodology

A new approach was worked out by understanding and adapting the methodology of the standard parallel hotplate method for measurement of thermal resistance of textiles (BS 4745 2005). In this method two thin metal plates would not only provide a uniform thermal environment to the sample by sandwiching the sample within (see Figure 4.2), but also provides a temperature sensing platform. The bottom metal plate would be placed on the surface of a standard laboratory hotplate. Heat energy transfers via conduction from the hotplate to the environment by passing through the bottom metal plate, the sample under test and the top metal plate, respectively. By measuring the temperature of the top and bottom metal plates, the temperature of the sample would be approximated. At the same time the heat flux across the sample may also be calculated. This contact-based methodology is closer to the intended application (measuring human body temperatures) than the technique based on a closed chamber. Therefore it was decided to use this method.

4.4.1.3 Copper Plates Development

Copper plates were developed not only to provide a thermal environment but also to measure the temperature across the TSF. In order to provide a uniform thermal environment to the samples, it’s important that the temperature distribution between the metal plates is uniform axially and radially at steady temperature settings from 20 to 50 °C. Therefore the choice of
metal and the thickness of plate was an important consideration. Copper was chosen as metal plate because of its high thermal conductivity and ease of availability. In order to improve the uniformity of temperature within each copper plate, it was desirable to select the thinnest possible plate. However it was also wished to fasten the thermocouples in the middle of the Cu plates for sensing purposes. Therefore the thickness of the metal plates was decided by considering the thickness of thermocouples. A Cu plate of 4 mm thickness would not only able to embed the thermocouple but because of its low Biot number, also exhibit excellent temperature homogeneity (for details, see chapter 6)

![Diagram of thermocouples in copper plates]

**Figure 4.2:** Placement of TSF between the top and bottom Cu plates

![Diagram of thermocouple positions]

**Figure 4.3:** Position of thermocouples in the top and bottom Copper plates
Each copper plate was fitted with four k-type thermocouples as shown in Figure 4.3. The thermocouples were fixed with thermally conductive adhesive, into shaped grooves, so that a thermocouple probe and some part of the thermocouple wire remains in full contact with the copper plates. This connection was further protected by fixing a thin copper strip on the same side of copper plate, where the thermocouples were fastened. The overall thickness of the copper plates was 4 mm. The temperature data logger could acquire signals from eight thermocouples simultaneously. An average of eight thermocouples could be used to provide a close approximation of the temperature in the middle of the TSF or sensing element.

4.4.2 Resistance Measurement

Initial modelling and experimental results indicated that a 1 °C change in temperature caused a resistance change, only of the order of milli-ohms, especially when the nominal resistance of the TSF is low. Measuring such a low resistance accurately is not a straightforward task. In preliminary testing, the resistance was measured using a standard hand-held multimeter with a crocodile clip. However, considerable variations were observed due to the lead resistance, contact resistance and limitations in the accuracy of the multimeter.

The following concerns were the main contributors of error in the resistance measurement and need to be rectified: how to nullify the initial resistance of the multimeter leads? How to make reliable contact between the multimeter probes and the ends of the sensing element? How to reduce the effect of temperature on the resistance of the multimeter leads if the contact points of the multimeter probe and the ends of the sensing element are very close to the test rig thermal environment? These issues were resolved by taking following actions:

- introducing Four Wire Resistance Measurement (4WRM) over Two Wire Resistance Measurement (2WRM);
- developing a special connector for 4WRM;
- using an Agilent Bench-top Multimeter instead of a handheld multimeter.

4.4.2.1 Two wire vs. Four wire Resistance Measurement

In the 2WRM, passing a current and measuring the voltage drop across the device under test is performed by two leads. This method normally gives reasonable accuracy and is adequate for
most applications. Moreover it is easier to handle two probes and measurement is much faster. Another widely known method is the 4WRM; which provides the most accurate way to measure small resistances. Lead resistances and contact resistances are automatically reduced using this method. In 4WRM two leads are used to pass current, while the remaining two are used to measure the voltage drop (see Figure 4.4).

![Figure 4.4: Circuit diagrams of 2-wire (top) and 4-wire (bottom) resistance measurement.](image)

### 4.4.2.2 Development of 4WRM Connector

Thus the requirement was to develop a 4WRM system for reliable resistance measurement which includes four lead wires, a connector, and a bench top multimeter. The 4WRM connection was developed by fixing the screw type connectors on a plastic strip, and then soldering the current and voltage lead wires at the bottom of the connector as shown in Figure 4.5. A firm contact between the sensing element of the TSF and the 4W connector can be made from the top side via a pressure screw. This system has resolved the previously discussed issues to a great extent. It is important that the ends of the sensing element should not make contact with the copper plates, as it would affect the resistance readings.
The temperature throughout the whole sample would be uniform. The factors which might be considered before starting the actual Temperature-Resistance (TR) testing, it was necessary to perform a number of preliminary tests in order to draw the limitations and estimate the inaccuracies by understanding the test rig behaviour under steady and dynamic states. It was important to ascertain the extent to which it might be possible to make a close approximation to the actual temperature of the sensing element. It was equally important to discover whether the temperature throughout the whole sample would be uniform. The factors which might be
capable of disturbing the thermal environment of the test rig would also have to be found. It was also important to find whether the test rig could record actual T-R values in a dynamic thermal environment. It might alternatively be necessary to rely on steady measurements at certain temperature points. Hence, the test rig behaviour under steady state conditions and in dynamic environments will be discussed now by analysing the temperature profile across the copper plates.

4.5.1 Observations in steady state environment

The steady state measurements were carried out with the hotplate at a temperature of 50 °C. Observations were noted and only key points are listed here.

- The measured surface temperatures are usually less than the actual surface temperature primarily because of environmental influences and the thermal contact resistance between the temperature sensor and the surface to be measured. In order to estimate this error in the test rig settings, both top and bottom Cu plates were placed on the hotplate without any fabric sample. At 50 °C, the temperatures of the hotplate, averaged for top and bottom Cu plates were recorded as 44.5 °C and 45 °C respectively. The 0.5 °C drop in temperature between both the Cu plates was primarily because of the contact thermal resistance. The 5 °C drop in temperature between the hotplate and bottom Cu plate could be related to various factors. It was believed that the indicated temperature of the hotplate was actually the temperature of the internal heating elements located just underneath the hotplate surface. Due to the thermal contact resistance between the hotplate’s internal heating elements and the surface, the displayed temperature would always be little more than the actual surface temperature of the hotplate. This means that a 5 °C drop in temperature between the hotplate and the bottom Cu plate was partially because of: the contact thermal resistance between the hotplate surface and the bottom Cu plate; and also the contact thermal resistance between the hotplate’s internal heating elements and its surface.

- A few tests were carried out in order to see the effect of various kinds of insulating layers on the temperature drop between the top and bottom Cu plates at the steady state hot plate temperature. The detailed analysis of one such experiment is presented in Figure 4.7. In this test the hotplate temperature was set at 50 °C and then a single
jersey fabric was placed in between the two Cu plates. The temperature readings of both Cu plates were noted for about eight minutes once the rig components achieved the equilibrium stage. A similar procedure was performed for the other settings (i.e. a cardboard frame and two single jersey fabrics) as mentioned in Figure 4.7. The average temperature of each thermocouple channel, the standard deviation in each channel, the difference between the average of the top and bottom Cu plates, and the standard deviation among the channels of each Cu plate were also calculated and presented in Figure 4.7. The difference between the average temperature of the Cu plates increases to 1.5 °C by sandwiching a single jersey fabric and to 7.5 °C by sandwiching a single jersey fabric and cardboard frame.

- All the thermocouples belonging to each respective Cu plate showed the same behaviour and their average relative differences were noted to be not more than 0.5 °C at various hotplate steady temperature settings. This means that the temperature distribution within the Cu plates is uniform and there is no significant temperature gradient within the Cu plate.

- In order to see the effect of 'the thermocouple connection position within the data logger input' on the temperature reading, some tests were carried out by swapping the thermocouple channel positions for both Cu plates. It was observed that the relative error due to the channel position in the data logger connector would always be part of the reading. The maximum error was estimated to be around 0.2 °C.

- Tests were also carried out with another temperature data-logger unit to estimate the variance between the two data-loggers. The maximum average difference with the same set of thermocouples was estimated to be less than 0.4 °C.
Figure 4.7: Effect of Single jersey and cardboard layers on Cu plates’ temperature profile at 50 °C hot plate temperature

**Without any layer**

<table>
<thead>
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**With one single jersey layer**

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<th>Bott2</th>
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**With a cardboard layer**

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</table>

**With a cardboard & two single jersey layers**

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<th>Top2</th>
<th>Bott1</th>
<th>Bott2</th>
<th>Bott3</th>
<th>Bott4</th>
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<td></td>
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<tr>
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<td></td>
</tr>
</tbody>
</table>

§ = Standard deviation within each channel
ж = Standard deviation among channels of same Cu plate
4.5.2 Observations in dynamic environment

Up until now, the variation of temperature profile in the Cu plates in a steady state environment has only been discussed. Some tests were also carried out by providing a dynamic environment for the Cu plates and recording their temperature values. A dynamic environment was provided by increasing or decreasing the temperature of the hotplate. In the dynamic environment the following points were observed.

- At the start of every step increment of hotplate temperature, the bottom plate temperature profile shows a sharper upward trend than the top plate temperature profile. However, with the passage of time, the difference between the Cu plates’ temperatures reduces, as shown in Figure 4.8. It was observed that the higher the step value, the higher would be the difference in temperature between the top and bottom Cu plates.

- The downward trend of the temperature profile (cooling profile) of the Cu plates was also measured by switching off the hotplate and allowing the Cu plates to cool. The result shows much stability and less variance within the Cu plates’ temperature profile.

![Temperature profiles of Cu Plates](image)

Figure 4.8: Temperature profiles of Cu Plates upon step input.
4.6 Development of Testing Software

This section explains the development of a customised PC interface for the acquisition and recording of temperature and resistance data. It was mentioned earlier that TC-08 data-logger and Agilent multimeter offers the facility to interface with the PC. They both have their respective software for measuring and recording data, however this does not serve the purpose of a test rig. The requirement was to visualise the temperature and resistance signals side by side in one application. In order to cater for this requirement, it was essential to develop customised software.

4.6.1 RTAQS: Conception to Creation

Both the data logger and the multimeter provide the facility to develop a customised interface in most of the popular programming languages i.e. C, C++, Delphi, Excel Macros, LabVIEW or Visual Basic.

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a platform and development environment for a visual programming language which is offered by National Instruments. The graphical language is named "G". LabVIEW is commonly used for data acquisition, instrument control, and industrial automation on a variety of platforms including Microsoft Windows, UNIX, Linux, and Mac OS. LabVIEW programs are called Virtual Instruments (VIs) because their appearance and operation imitates physical instruments, such as oscilloscopes and multi-meters. Every VI uses functions that manipulate the input from the user interface or other sources and displays that information or moves it to other files or other computers.

A VI contains the following three components: a Front panel, which serves as the user interface; a Block diagram, which contains the graphical source code that defines the functionality of the VI; the Icon and connector pane, which identifies the interface to the VI so that the VI can itself be used in another VI. A VI within another VI is called a subVI. A subVI corresponds to a subroutine in text-based programming languages.

The TC-08 data logger is supplied with driver routines and a selection of examples of how to use these drivers. The driver files are in the form of Windows DLL which uses the C stdcall

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calling convention. These files can be used to develop a customised interface in major programming language such as C, C++, Delphi, Excel Macros, LabVIEW or Visual Basic. In order to keep the work uncomplicated, only essential routines were used in the customised interface which could provide the minimum necessary control of the TC-08 unit. The following routines were used in order to successfully get the temperature data in LabVIEW:

- `usb_tc08_open_unit`
- `usb_tc08_set_channel`
- `usb_tc08_get_single`
- `usb_tc08_stop`
- `usb_tc08_close_unit`.

For details of the routines, see the description of developed VIs later in this chapter.

The Agilent Multimeter is supplied with the Agilent IO (Input Output) Libraries Suite, and an example of using them in LabVIEW. Agilent IO libraries are compatible with a variety of programming applications, and development environments such as VISA (Virtual Instrument Software Architecture). The Agilent 34401 can be connected with the PC via RS-232 or GPIB interface cable. GPIB offers a much higher data transfer rate in comparison to RS-232; however RS-232 (9-pin connector) was preferred to develop the connection between Multimeter and PC as the configuration was relatively quick. In order to configure the Agilent 34401 via RS-232, various parameters have to be standardised which includes the Baud Rate, Parity and Databits (see description of Agilent Main SubVI later in this chapter). Values of these parameters should be the same in the multimeter and in the customised software.

The Main VI was created by calling the subVIs for resistance measurement (developed by Agilent), and subVIs for temperature measurement (developed in-house), in order to record the Temperature-Resistance (TR) data from their respective instruments. The front panel of Main VI was styled to view the real time data in various formats. This customised interface was named RTAQS (Resistance Temperature Acquisition Software). Initially it was developed for only two temperature channels and later on it was modified to include the remaining six channels of temperature data.
4.6.2 Software Operation

Initially, it is necessary to ensure that the TC-08 and the multimeter have been successfully connected with the PC and the multimeter has been switched ON. Step by step instructions to run the software are as follows.

- Open the Agilent Main SubVI (see Figure 4.14). Configure the interface & choose the function type and VISA resource name. This file does not require opening every time since suitable default values have already been selected. Configure this file again only when the settings have been changed in the multimeter (for further details see the description of the Agilent Main SubVI later in this chapter). The software generates an error code if the above mentioned tasks have not been carried out.
- Open the Main VI and RUN the program (Figure 4.9). It displays a file dialogue box for initialisation of a text data file at the specified path. Type the file name and save.
- Straight away it starts accepting the temperature and resistance data (with an interval of 10 seconds) along with a time stamp. Real time data can be viewed in:
  - table form (presenting all temperature channels, resistance and a time stamp);
  - graphical form (displaying all temperature channels); and
  - indicator form (indicating each channel in a dedicated indicator).
- Press the STOP button, when the required length of test has come to an end.
- Open the data file in Excel or TRYZER (A Matlab based customized software – See Appendix D) and analyse the data.
4.6.3 Description of VIs and SubVIs

4.6.3.1 Main VI

As its name indicates, Main VI obtains the input from several subVIs and displays the data in various forms. The front panel is self explanatory as shown in Figure 4.9. In order to see the working of the front panel refer to “Software Operation”. In the block diagram of the Main VI (see Figure 4.10) two “while” loops are shown. The bottom “while” loop mainly concerns the TC-08 data processing by acquiring data from three subVIs (marked in the image). The top “while” loop receives the temperature data from the bottom “while” loop, and resistance data from the Agilent Main SubVI, and presents it in a table along with a Time Stamp. The functionality to initiate the text data file was also created as marked in Figure 4.10.

Figure 4.9: Front panel of Main VI (RTAQs)
Figure 4.10: Block diagram of Main VI (RTAQS)
4.6.3.2 SubVI to ‘open’ data-logger

The “open data logger” subVI is mainly responsible for opening the TC-08 unit and configuring its temperature channels (see Figure 4.11). It calls two routines from the TC-08 driver files. The routine `usb_tc08_open_unit` opens the TC-08 unit with a valid handle for positive values. If more than one TC-08 unit needs to be interfaced then this routine has to be called once for each unit that is connected to the PC. The function returns a “0” if it does not find any unit and a “1” if it fails to open the unit.

Every channel needs to be set before taking a reading and this is done by calling the `usb_tc08_set_channel` routine. This routine has to be called separately for each channel. It can be called any time after calling `usb_tc08_open_unit`. Its arguments include the selection of channel and thermocouple types. The function will return a “0” if there is any error and a “1” if the routine runs successfully.

4.6.3.3 SubVI to ‘read’ data-logger

The “read data logger” subVI calls the `usb_tc08_get_single` routine and generates an array of temperature data for each channel (see Figure 4.12). It acquires the data only from those channels which have been set-in before. The function returns a “0” if does not find any error and a “1” if it gets the data successfully.

4.6.3.4 SubVI to ‘close’ data-logger

The “close data-logger” subVI on demand finishes the operation of TC-08 (see Figure 4.13). It calls two routines via a stacked sequence structure. First it calls the `usb_tc08_stop` which stops the unit from streaming and then it calls the `usb_tc08_close_unit` which closes the unit.
Figure 4.11: Block diagram of TC-08 Open SubVI (RTAQs)

Figure 4.12: Block diagram of TC-08 Read SubVI (RTAQs)

Figure 4.13: Block diagram of TC-08 Close SubVI (RTAQs)
4.6.3.5 SubVI to ‘read’ Agilent Multimeter

Before running RTAQS Main VI, the multimeter needs to be configured through the Agilent Main SubVI Front panel (see Figure 4.14). It has been mentioned before that the Agilent multimeter was interfaced with the PC via an RS-232 serial cable. The parameters which need to be configured serially are Baud Rate, Parity and Data Bits.

The rate at which data are sent across a serial bus is termed the **Baud Rate**. The rate may be selected as 300, 600, 1200, 2400, 4800 or **9600**. The **Parity** checks for the incorrect reception of data for all the transmissions sent. Its values are none, even, odd, mark and space. The **Data Bits** setting determines the number of bits used to transmit data. Its values can be taken as **8 bits** or 7 bits. Bold values are the defaults for the software. It should be borne in mind that data would not be acquired, in the case where values of these parameters do not match with the multimeter settings.

In addition to serial parameters, there are control inputs whose values must also necessary be selected. The **VISA Resource Name** specifies which instrument to use. Only those ports will be visible to which instruments have been attached and powered ON. The **Manual Resolution** sets the resolution of the data displayed. It offers the maximum resolution of 6½ digits. The **Enable Auto Range** enables or disables automatic range selection on the instruments. It is enabled as a default. The **Function** sets the measurement function on the instrument which includes DC voltage, AC voltage, DC current, AC current, frequency, continuity etc. The four wire resistance measurement has been set as the default function.

In addition to the parameters icon mentioned above, four subVIs are shown in the Agilent Main SubVI Block Diagram (see Figure 4.14). These subVIs are responsible for initialising, configuring, getting single point data and finally for closing the multimeter upon command.
SubVIs for initializing, configuring, getting single point data and closing Agilent

Figure 4.14: Front panel and block diagram of Agilent Main SubVI (RTAQS)
4.7 Discussion

It is important to determine how accurately the temperature of the sensing element (embedded in the TSF) can be estimated within the temperature range of 20 to 50 °C in the test rig. The temperature measurement methodology i.e. estimation of sensing element temperature by taking an average of the top and bottom copper plates' temperature, may seem straightforward to understand. However it was necessary to validate it by scientific investigation and to estimate the errors in calibration. The methodology was based on following assumptions: that the sensing element is embedded exactly in the middle of the TSF; that the temperature varies linearly across the thickness of the TSF and that the thermal contact resistance and drop in temperature at the interfaces of TSF surfaces to their respective copper plates are the same.

Deviation from these assumptions may contribute errors while estimating the temperature of the sensing element. In terms of TSF structure, not only the positioning of the sensing element is important but also the homogeneity of the textile layers across the sensing element. The thickness of the TSF is also a key factor as thicker samples may add errors in respect of estimation of sensing element temperature by this methodology.

The assumptions may be violated by the presence of large thermal gradients across the copper plates e.g. in the case of a high set point temperature of the hotplate and a lower environment temperature. The proposed test rig has the ability to provide a thermal environment to the TSF as high as 100 °C. However, with the increase of hotplate temperature, the difference between the copper plates' temperature also increases. The higher this difference, the higher will be the error while estimating the temperature of the sensing element by the proposed methodology.

With reference to the above discussion it can be inferred that the temperature of the wire can be closely approximated by taking the average of the top and bottom copper plates' temperature in the steady state environment within the temperature range from room temperature to 50 °C. Moreover this methodology is also valid in a dynamic environment where the temperature changes slowly i.e. when the time constant of temperature change in the thermal environment is equal to or less than the time constant of the TSF.
The test rig apparatus is a simplified version of a standard parallel hotplate method for measurement of thermal resistance of textiles (BS 4745 2005). In the standard parallel hotplate method, metal plates and samples are insulated along the edges in order to prevent any radial heat transfer. This is important for measurement of thermal conductivity (or thermal resistance) of material under steady state conditions.

The proposed test apparatus is not insulated along the sides as it was not considered necessary. In the earlier stages of the research, an attempt was made to insulate the rig components along the edges. However, because of the handling procedure for the test rig, a permanent solution of fixed insulation could not work out, as it would be regularly removed and replaced, suffering handling damage each time. During the process of change of the sample in the test rig, the top copper plate has to be removed from its position. At this moment the thermocouple wires attached to the copper plates, and the sensing element of the TSF, interfered with the sidelong insulation. This meant that the side insulation had to be reset each time a sample was changed. The effectiveness of the insulation was felt to be different in each setting, thereby adding slight variations to the result. Therefore in order to minimise the handling/manual procedure during the sample change in the test rig, insulation was not incorporated.

With the addition of sideways heating, the temperature of the sensing wire may be better approximated. However, it was not really required. In the modelling chapter, the accuracy of the methodology will be validated and it will be seen that insulation adds only a marginal improvement to the results.

The contact point between the ends of the sensing element and the 4WRM connector was almost 3-4 cm away from the thermal environment created by the copper plates. So in total, 8-10 cm (around 2.5% of the total length of the sensing element) of the wire was exposed to the ambient environment. The thermal gradient in the environment would affect the temperature of a sensing element and may contribute an error towards the measured resistance value at a particular temperature. However, this is a systematic error and would be the same for all the test procedures and could be removed once investigated thoroughly. This error could be
reduced to some extent by placing the 4WRM connectors in the same thermal environment in which the whole TSF sample is placed this, however, may not be easy.

In the earlier stages of this study, a handheld Infrared temperature measuring instrument was also employed to measure the temperature of a bare wire. However, large variations in temperature were observed because of the small Field of View offered by the bare wire. Similarly, the measurement of surface temperature of the TSF was also found to be less stable and more inaccurate because of the surface characteristics of the TSF. Due to surface roughness, emissivity values may not be constant and can influence the IR reading. Additionally, it was also not possible to use this instrument for continuous measurement. However, the IR instrument was used in some of the tests for episodic measurement of the surface of the copper plate.

Measured surface temperatures are usually less than the actual surface temperature, primarily because of environmental influences and the contact resistance between the temperature sensor and the surface to be measured. That’s why a drop in temperature was noted (at temperatures higher than room temperature) between the interface of the copper plates and the hot plate. However, this drop in temperature would not affect the methodology in respect of estimating the temperature of the sensing element.

When the sample is sandwiched between the copper plates, then the drop in temperature would be depend upon the thickness and the thermal properties of the sample (Fourier's Law).

The difference between the thermocouple readings belonging to the same copper plate is not more than 0.5 °C. This difference would not be significant once an average of all four thermocouples has been used to calculate the temperature of the copper plate.

It is important to exercise care to ensure that the sensing element should not make contact with the surface of the copper plate while sandwiching the TSF between the copper plates or connecting it with the 4WRM connector. Any contact of sensing element with the copper plates during the testing procedure would lead to error in the resistance measurement.
The instruments used for measurement of the temperature and resistance of the wearable temperature sensing fabric have their respective software suites for measuring and recording data. However the requirement of the research was to visualise the temperature and resistance signals in one application. Therefore customised software (R-TAQS) was developed in the LabVIEW environment. The consequence of this development is the provision of a capability to import nine data channels (one for resistance and eight for temperature) along with a date and time stamp during the RT testing of the TSF samples. In this chapter the standard version of this application has been discussed. There are some additional features introduced during the later stages of the research, for particular, specialised forms of testing. These features will be discussed in the context of the testing in forthcoming chapters.
Chapter 5  Analysis of the Temperature Resistance Relationship

5.1 Introduction

This chapter presents an in-depth analysis of the Temperature-Resistance (TR) relationship of TSF samples. The chapter begins by describing the usage of a test rig to develop the Temperature-Resistance (TR) relationship. Prior to analysing the TR data, this chapter will also provide the statistical foundation in terms of the statistical parameters applied to the Temperature-Resistance relationship for comparative purposes.

Firstly, the uncertainty within experimental repeats (regression uncertainty) will be discussed comprehensively in terms of the effects of the temperature profile, the sensing element and the inlay density. Then uncertainty amongst repeats of the same sample types (repeatability uncertainty) will be discussed in detail. The last section of this chapter will address the uncertainties amongst samples of the same sample type (manufacturing uncertainty). For ease of understanding and for purposes of comparison, uncertainties in the Temperature-Resistance relationship will be presented in terms of “Temperature”, rather than in “Resistance”. Sometimes some global parameters will also be employed to compare the results, such as the coefficient of determination (the \( r^2 \)-value), the temperature coefficient of resistivity (\( \alpha \)), and the length of the inlaid sensing element.
5.2 Analysis of a single test repeat

5.2.1 Testing Methodology

In the last chapter, the development of the test rig has been discussed thoroughly. Here, explanatory details will be provided on how to use this test rig to develop the relation between the Temperature and the Resistance (the TR relationship) of the Temperature Sensing Fabric (TSF). Therefore this information could be used for calibration purpose.

Initially a sandwiched TSF between two Cu plates was placed on a hotplate. At this stage all components of the test rig were at room temperature i.e. 21±2 °C. The Fischer Scientific hotplate does not offer programmable setting of the temperature profile. However, the hotplate can be set to achieve a specific temperature point and maintain it. Considering the temperature range of the intended application, 55 °C was chosen as a set point of the hotplate. Therefore heating was provided to the Cu plates in the form of a step input until it achieved the set point temperature. The TR data were recorded by RTAQS interface during this heating period through their respective instruments until all the components of the test rig achieved the steady state. The TR curve generated from these data is called the “Heating TR curve”.

After this, the hotplate was turned off and the rig components were allowed to cool. The difference in temperature between the rig components and the room provided a natural uniform thermal gradient. The TR curve belongs to the cooling phase of experiment and was termed the “Cooling TR curve”.

The Temperature-Resistance curves of all the experimental repeats were measured in exactly the same way. On average, the TR experiments were performed six times (3 Heating and 3 Cooling) on each TSF sample.

5.2.2 Parameters associated with the TR experiment

It is important to understand that the TR data (belong to a single experimental repeat) may be explained in terms of various parameters. An understanding of these parameters and their relationship to each other is an important conceptual foundation for further analysis and comparison among the various kinds of TSF samples (which have different sensing elements and inlay densities). These parameters will be explained individually.
The **Equation of the fitted line** is the product of linear regression which was applied to the resistance (R) and corresponding temperature (T) data and represented in the form of:

\[ R = MT + B \quad (5.1) \]

Here M and B are the slope and the intercept of the fitted line.

The **Slope** of the line can also be termed as **Experimental Sensitivity** i.e. the rate of change of R with respect to T. The sensitivity is directly related to the temperature coefficient of resistivity of the sensing element and to its nominal resistance. Sensitivity and nominal resistance along with the temperature range are key parameters for the design of sensor circuits.

The **Intercept (Resistance at 0 °C)** is the point at which the fitted line crosses the resistance axis (the y-axis) and is called intercept B. It can also be termed as the Resistance at 0°C \((R_0)\), since the temperature value is 0 °C at this point.

The **Standard error in Resistance** \((SE_{RT})\) is a measure of the amount of error in the prediction of resistance for an individual temperature value. It can be calculated as:

\[ SE_{RT} = \sqrt{\frac{SSE}{n-2}} \quad (5.2) \]

Where, \( SSE \) stands for the “sum of the square of the residuals with respect to the fitted line”. In statistics, \((SE_{RT})\) is usually known as the standard error of regression. The \(SE_{RT}\) gives a 68% confidence range for the unknown true value of R in respect of T.

The **Standard errors in the slope and Intercept**: are the measure of the amount of errors in the prediction of slope \((SE_M)\) and the intercept \((SE_B)\), and these values can be calculated in terms of the standard error in resistance \((SE_{RT})\) as:

\[ SE_M = \frac{SE_{RT}}{\sqrt{\sum(T_i - \bar{T})^2}} \quad (5.3) \]

\[ SE_B = SE_{RT} \sqrt{\frac{\sum T_i^2}{n\sum(T_i - \bar{T})^2}} \quad (5.4) \]
Where, \(T_i\) and \((T)\) represent individual temperature points and the means of all the temperature points, respectively. The number of data points used in the regression process is denoted by \(n\). \((SE_M)\) and \((SE_B)\) are in fact the standard deviation of slope and intercept respectively.

The **Nominal Resistance \((R_{20})\)**: The Nominal (reference) resistance is one of the most important baseline specifications of the RTD. RTDs with a nominal resistance of 100 Ω at 0 °C are the most common configuration available on the market. It was decided to consider the 20 °C point as a reference temperature for the nominal resistance of TSF samples as a thermal environment of 0 °C was not readily available for test purposes.

**R35 (the Resistance at 35 °C):** It has been discussed before that all TSF samples were tested within the temperature range of 20 °C and 50 °C. Although TR data have been analysed over the whole range, the focus of the analysis was the resistance errors associated with operation at 35 °C. It will be noted that 35 °C is not only the middle value of the temperature range but also relates to the intended application scenario i.e. the temperature of human body skin.

The **Temperature Coefficient of Resistivity \((\alpha)\)**, as discussed in the previous chapter (section 2.5.3), is in fact a normalised sensitivity with respect to the initial temperature point (the reference temperature), which can be calculated by:

\[
\alpha = \frac{R_T - R_0}{R_0(T - T_0)} 
\]  

(5.5)

Usually RTD sensing elements are specified with an alpha value between 0 °C and 100 °C:

\[
\alpha_0 = \frac{R_{100} - R_0}{100R_0} 
\]  

(5.6)

The Alpha value may also be calculated directly from the TR equation as:

\[
\alpha_0 = \frac{M}{B} 
\]  

(5.7)

Considering the testing range and the reference temperature, \(\alpha_{20}\) was preferred over \(\alpha_0\) for analysis and comparison of samples. The value of \(\alpha_{20}\) for TSF samples made of the same kind of
sensing element will always be lower than their corresponding \( a_0 \) values; \( a_{20} \) can be calculated by following expressions:

\[
\frac{\alpha_{20}}{\alpha_{20}} = \frac{R_{50} - R_{20}}{30R_{20}} \quad (5.8)
\]

\[
\frac{\alpha_{20}}{\alpha_{20}} = \frac{M}{R_{20}} \quad (5.9)
\]

The **Resistance Ratio Curve** \((RR)\) was calculated by dividing the fitted resistance \( R \) at the temperature \( T \) by its nominal resistance \( R_{20} \). Using \((RR)\) instead of \( R_T \) has several advantages. TSF samples made with the same kind of sensing element with quite different values of nominal resistance \((R_{20})\) can be compared because they should have similar values of \( RR \).

The **\( r^2 \)-value** is known as the coefficient of determination, and is defined as:

\[
r^2 = 1 - \frac{SSE}{SST} \quad (5.10)
\]

Where, SSE stands for “the sum of the square of the residuals with respect to the fitted line” while SST means the “the sum of the square of the residuals with respect to the average resistance value”. The \( r^2 \)-value of the TR curve indicates how good a temperature value is for predicting resistance values or vice versa. The highest value of \( r^2 \) is 1 which means both terms can perfectly predict each other. However, \( r^2 \) should not be used solely to judge the quality of a fitted line. Nonetheless, a fitted line with a high \( r^2 \)-value (over 0.999) can be used for calibration purposes with good accuracy (Currell and Dowman 2009).

The **\( t \)-value** is used in statistics to calculate a confidence deviation or expanded uncertainty of a parameter being studied. In this analysis, the \( t \)-value was calculated according to the \((n-2)\) degree of freedom and the 95% margin of confidence deviation \((CD_{95\%})\).

In each experimental repeat it is possible to get slightly different values of \( R \) and \( T \) due to the randomness of the data. Therefore it is important to generate a confidence interval for this fitted line to estimate the uncertainties associated with the calibration.
The 95% Slope ($CD_M, 95\%$) and Intercept ($CD_B, 95\%$) Confidence Deviation were calculated by multiplying the t-value by their respective standard errors:

\[
CD_{M, 95\%} = (t - \text{value}) \times (SE_M) \quad (5.11)
\]

\[
CD_{B, 95\%} = (t - \text{value}) \times (SE_B) \quad (5.12)
\]

Where, ($SE_M$) and ($SE_B$) are the standard errors of the slope and the intercept respectively. Standard errors are also known as standard uncertainty, and confidence deviation may be referred to as expanded uncertainty.

The 95% Resistance Confidence Deviation ($CD_r, 95\%$) is similar to the confidence deviation of the slope and the intercept and can also be calculated by the product of the t-value and the standard error in resistance ($SE_{RT}$):

\[
CD_{R, 95\%} = (t - \text{value}) \times (SE_{RT}) \quad (5.13)
\]

The 95% Temperature Confidence Deviation ($CD_T, 95\%$) is relevant because the process of linear regression assumes that significant uncertainties only exist in the resistance (y-direction). The temperature values (x-values) for each data point are assumed to be accurate. However, uncertainties in resistance can also be converted into temperature uncertainties by dividing $CD_{R, 95\%}$ by the slope.

\[
CD_{T, 95\%} = \frac{CD_{R, 95\%}}{M} \quad (5.14)
\]

The Calibration Equation is the equation of a fitted line, which may be expressed in the following way for calibration purposes:

\[
T = \left(\frac{1}{M}\right)R - \left(\frac{B}{M}\right) \quad (5.15)
\]
5.2.3 Comparison of Heating and Cooling TR Experiments

This section will present a detailed comparison between single experimental repeats of heating and cooling temperature profiles and their effect on the temperature-resistance relationship. This will be realised by analysing the statistical parameters examined earlier.

Two experimental repeats performed on a TSF sample N10046S1 were selected for comparison purposes. Here N10046S1 stands for "sample number one (S1) of 46 inlayed structures having a sensing element of 100 micron Nickel wire". The results are presented in Figure 5.1 to Figure 5.10 and in Table 5-1.

5.2.3.1 Temperature Profiles

Heating and cooling temperature profiles of rig components i.e. the bottom Cu plate, the Temperature Sensing Fabric (TSF), and the top Cu plate are shown in Figure 5.1 and Figure 5.4. As mentioned in an earlier chapter; each Cu plate was monitored with four thermocouples. This means that the presented temperature profiles of the top and bottom Cu plates are actually the mean temperature profiles of their respective thermocouples. The temperature profile of the TSF is the mean of the top and bottom Cu plate temperature profiles.

When the heat is applied to the rig components in the form of a step input, the bottom Cu plate increased its temperature instantaneously whilst the top Cu plate responded slightly later, as shown in Figure 5.1. This created a thermal gradient of around 20 °C between the Cu plates in the initial phase of heating. This difference is shown in Figure 5.2 and Figure 5.3. Figure 5.2 shows that the temperature difference between the Cu plates was at a maximum after around 6 minutes of the start of test. At that time the TSF had already reached 35 °C as shown in Figure 5.3. However, after 40 minutes, the rig components attained an approximate steady state. Figure 5.4 shows the temperature profiles of the cooling test, which lasted for around 95 minutes. It is important to note here that in reality, the rig components would take lot longer than the time span described in the above tests in order to achieve a true steady state condition. Since the recording of extra hours of experimental data would not have a substantial effect on the TR relationship, the test was stopped when the rig components achieved an approximate...
steady state (i.e. a condition when the rate of change of temperature with respect to time becomes insignificant).

Figure 5.4 illustrates that the thermal gradient between the Cu plates reduces rapidly in the initial phase of cooling (first 20 min) and then approaches zero.

5.2.3.2 Residuals

Figure 5.2 and Figure 5.5 also present the temperature residuals of the heating and cooling test, with respect to time. Residuals were calculated from the difference between “experimental temperature data” and “fitted temperature data” at the corresponding resistance. Usually in regression analysis, residuals are expressed on the y-axis of the graph. However, for ease of understanding, residuals have been presented in terms of temperature rather than of resistance. The majority of the residual values belonging to the heating test lie between -0.3 and 0.1. Cooling test residuals are well within the range of ±0.06.

Residuals can also be represented with respect to the average Cu plate temperature as shown in Figure 5.3 and Figure 5.6. From Figure 5.3 it can be inferred that the majority of temperature data values arose when the test rig tried to reach equilibrium i.e. they lie between 40 and 50 °C. The concentration of residuals of the cooling curve is different from the heating curve. In the cooling curve, most values were recorded between 35°C and 25°C of the temperature range, as shown in Figure 5.6.

A slightly high residual range in the heating test can be related to the sudden initial phase of heating. During the initial phase of heating, there were some large residual values, which have the potential to be considered as outliers as shown in Figure 5.2. The outliers are responsible for the skewing of the regression curve.

From Figure 5.3 it can be seen that these outliers are not large in number in comparison with the rest of residuals. Therefore all data points were taken into consideration during the generation of the TR equation. As the rig components approached steady state, the residuals started decreasing.
Figure 5.1: Heating Temperature Profiles of Cu Plates and Temperature Sensing Fabric (N10046S1)

Figure 5.2: Profile of temperature difference of Cu Plates & temperature residuals of fitted curve (N10046S1, Heating test, with respect to time)

Figure 5.3: Profile of temperature difference of Cu Plates & temperature residuals of fitted curve (N10046S1, Heating test, with respect to temperature)
Figure 5.4: Cooling Temperature Profiles of Cu Plates and Temperature Sensing Fabric (N10046S1)

Figure 5.5: Profile of temperature difference of Cu Plates & temperature residuals of fitted curve (N10046S1, Cooling Test, with respect to time)

Figure 5.6: Profile of temperature difference of Cu Plates & temperature residuals of fitted curve (N10046S1, Cooling Test, with respect to temperature)
5.2.3.3 Temperature-Resistance curves

A full range of heating and cooling temperature-resistance curves is presented along with their respective fitted lines in Figure 5.7 and Figure 5.8. It can be seen that both curves seemed to be identical. However, because of the sudden temperature change during the initial phase of heating (around 20 °C) phase, a slight deviation of experimental values was observed on the curve. Figure 5.9 and Figure 5.10 show magnified views of the temperature-resistance curves around the region of 35°C. Moreover, the 95% confidence interval of uncertainty in resistance is also presented along with the subsequent confidence interval of uncertainty in temperature values at 35 °C. Table 5-1 presents the comparative descriptions of the heating and cooling curves in terms of the statistical parameters discussed earlier.

The quality of the fitted line and its associated uncertainty can be represented in terms of standard errors and confidence deviation of resistance, slope, and intercepts. However for ease of understanding and for purposes of comparison, it was more appropriate to estimate the uncertainties of the regression line in terms of global parameters. The 95% confidence deviation of temperature uncertainty (CDT\(_{95%}\)) at 35 °C is one such global parameter and shows that in the case of use of particular regression line for calibration purposes, 95% of the measured temperature values would lie within certain margins of uncertainty.

Table 5-1 shows that parameters related to error and confidence deviation belonging to the heating curve are higher than for the cooling curve. For example the 95% confidence deviation of temperature (CDT\(_{95%}\)) of a heating curve is around ±0.3 °C; almost ten times more than its cooling counterpart. This may be more easily visualised in Figure 5.9 and Figure 5.10.

Another global parameter which describes the quality of fitted line is the \(r^2\)-value (the coefficient of determination). In accordance with other errors parameters, the \(r^2\)-value of the heating curve was found to be slightly less (0.9995) than for its cooling counterpart (0.999993).

The experimental sensitivity (slope) of the heating TR curve was found to be marginally higher than that of the cooling TR curve. The same trend has been observed in alpha (\(a_0\) and \(a_{20}\)) and resistance ratio (\(RR_{(20–50)}\)) values. However, the intercept of the heating curve was found to be slightly lower than that of the cooling curve intercept. It is important to understand that the
slope is an absolute parameter and depends not only upon the type and formulation of the metal of the sensing element but on its diameter and inlay density as well. However, the alpha value \( \alpha \) and the Resistance Ratio \( RR \) are only related to the type of metal of the sensing element. This implies that TSF samples made with a sensing element of the same metal type (irrespective of their diameter and inlay density) would have the same \( \alpha \) and \( RR \) values. Therefore \( \alpha \) and \( RR \) may also be considered as global parameters while comparing the TSF samples made with sensing elements of the same metal type.

Apart from the global parameters, all remaining parameters listed in Table 5-1 are specific to particular experimental repeats or TSF samples.

![Figure 5.7: Experimental and fitted Temperature Resistance curves (Heating, N10046S1)](image1)

![Figure 5.8: Experimental and fitted Temperature Resistance curves (Cooling, N10046S1)](image2)
Figure 5.9: Uncertainty in Temperature-Resistance relationship at 35 °C (Heating, N10046S1)

Figure 5.10: Uncertainty in Temperature-Resistance relationship at 35 °C (Cooling, N10046S1)
Table 5-1  Key differences among HEATING and COOLING TR Curves (N10046S1)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Abbreviation</th>
<th>Unit</th>
<th>Heating TR Curve</th>
<th>Cooling TR Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR Equation</td>
<td>$R = MT + B$</td>
<td></td>
<td>$R = 0.224T + 42.435$</td>
<td>$R = 0.222T + 42.584$</td>
</tr>
<tr>
<td>Calibration Equation</td>
<td>$T = \left( \frac{1}{M} \right) R - \left( \frac{B}{M} \right)$</td>
<td></td>
<td>$T = 4.458R - 189.18$</td>
<td>$T = 4.515R - 192.25$</td>
</tr>
<tr>
<td>Test Duration</td>
<td>min</td>
<td></td>
<td>40</td>
<td>95</td>
</tr>
<tr>
<td>t-value</td>
<td>$(t - value)$</td>
<td></td>
<td>1.97</td>
<td>1.96</td>
</tr>
<tr>
<td>r-square value</td>
<td>$r^2$</td>
<td></td>
<td>0.999537</td>
<td>0.999993</td>
</tr>
<tr>
<td>Temperature Coefficient of Resistivity at 0 °C</td>
<td>$\alpha_0$</td>
<td>1/ °C</td>
<td>0.0053</td>
<td>0.0052</td>
</tr>
<tr>
<td>Temperature Coefficient of Resistivity at 20 °C</td>
<td>$\alpha_{20}$</td>
<td>1/ °C</td>
<td>0.0048</td>
<td>0.0047</td>
</tr>
<tr>
<td>Resistance Ratio (20-50 °C)</td>
<td>$RR_{(20-50)}$</td>
<td></td>
<td>1.143</td>
<td>1.41</td>
</tr>
<tr>
<td>Slope (Sensitivity)</td>
<td>$M$</td>
<td>Ω/ °C</td>
<td>0.224</td>
<td>0.222</td>
</tr>
<tr>
<td>Slope Error</td>
<td>$SE_M$</td>
<td>Ω/ °C</td>
<td>0.0003</td>
<td>0.00002</td>
</tr>
<tr>
<td>95% Confidence Interval of Slope</td>
<td>$M \pm CD_{M,95%}$</td>
<td>Ω/ °C</td>
<td>$0.224 \pm 0.0006$</td>
<td>$0.224 \pm 0.0005$</td>
</tr>
<tr>
<td>Nominal Resistance</td>
<td>$R_{20}$</td>
<td>Ω</td>
<td>46.92</td>
<td>47.01</td>
</tr>
<tr>
<td>Resistance at 35 °C</td>
<td>$R_{35}$</td>
<td>Ω</td>
<td>50.28</td>
<td>50.34</td>
</tr>
<tr>
<td>Intercept (Resistance at 0 °C)</td>
<td>$B, R_0$</td>
<td>Ω</td>
<td>42.435</td>
<td>42.584</td>
</tr>
<tr>
<td>Intercept Error</td>
<td>$SE_B$</td>
<td>Ω</td>
<td>0.013</td>
<td>0.0007</td>
</tr>
<tr>
<td>95% Confidence Interval of Intercept</td>
<td>$B \pm CD_{B,95%}$</td>
<td>Ω</td>
<td>$42.435 \pm 0.025$</td>
<td>$42.584 \pm 0.0015$</td>
</tr>
<tr>
<td>Standard error in Resistance</td>
<td>$SE_{B_T}$</td>
<td>Ω</td>
<td>0.034</td>
<td>0.003</td>
</tr>
<tr>
<td>95% Confidence Interval of Resistance at 35 °C</td>
<td>$R_{35} \pm CD_{R,95%}$</td>
<td>Ω</td>
<td>$50.28 \pm 0.067$</td>
<td>$50.34 \pm 0.007$</td>
</tr>
<tr>
<td>95% Confidence Interval of Temperature at 35 °C</td>
<td>$35 \pm CD_{T,95%}$</td>
<td>°C</td>
<td>$35 \pm 0.30$</td>
<td>$35 \pm 0.03$</td>
</tr>
</tbody>
</table>
5.3 Regression Uncertainty

This section will first investigate the “uncertainties within repeats” and then will compare the TSF samples. First, the effect of temperature profile will be discussed in detail in terms of the global variables such as the $r^2$-value and $CD_{T,95\%}$. Under this heading, there will also be further discussion of the effects of the sensing element and inlay density on regression uncertainty in terms of $CD_{T,95\%}$. Moreover, the effects of inlay density on the experimental coefficient of temperature resistivity will also be highlighted.

5.3.1 Effect of Temperature Profile

Differences between a single Heating and Cooling TR repeat have already been discussed in detail. Now, differences will be generalised over all Heating and Cooling TR repeat tests by comparing them in terms of the global parameters such as the $r^2$-value and $CD_{T,95\%}$.

Figure 5.11 presents the dispersion of $CD_{T,95\%}$ between the Heating and Cooling TR repeats in the form of a box and whisker plot. This plotting method is a convenient way to visualise the data in terms of a five number summary i.e. the smallest value, the largest value, the lower quartile, the upper quartile and the median. Furthermore, it also indicates if any value may be considered as an outlier. For example, in Figure 5.11, the red line inside the box shows the position of the median value of the data set of $CD_{T,95\%}$. The ends of the blue box indicate the positions of the upper and lower quartiles; The ends of the whiskers indicate the maximum and minimum values. The red + sign indicates the potential outliers.

It is evident from Figure 5.11 that not only the mean of the $CD_{T,95\%}$ values of Heating TR repeats is more, but that the dispersion is also greater in comparison with the Cooling TR repeats. Few outliers can also be seen in the Cooling and Heating TR repeats. The graphical display of the TR curves of the few outliers is shown in Figure 5.15.

Figure 5.12 presents the dispersion in respect of the $r^2$ value of the same data set of experimental repeats in the form of a box and whisker plot. The dispersion and the mean of the $r^2$ value almost follow the same trend (in the opposite direction) as was discussed in the case of $CD_{T,95\%}$. 
It may also be noted that there is an inverse relationship between the $r^2$ value and $CD_T, 95\%$ which can be represented in the form of a second degree polynomial as shown in Figure 5.13. It can be seen that the relationship between the $r^2$ value and $CD_T, 95\%$ of the Cooling TR repeats is more predictable than in the case of their Heating counterparts.

![Graph showing the comparison of Heating and Cooling TR repeats](image.png)

**Figure 5.11:** Comparison of Heating and Cooling TR repeats (95% Confidence Deviation of Temperature uncertainty)

![Graph showing the comparison of Heating and Cooling TR repeats ($r^2$-value)](image.png)

**Figure 5.12:** Comparison of Heating and Cooling TR repeats ($r^2$-value)

![Graph showing the comparison of Heating and Cooling TR repeats (Relationship between $r^2$-value and $CD_T, 95\%$)](image.png)

**Figure 5.13:** Comparison of Heating and Cooling TR repeats (Relationship between $r^2$-value and $CD_T, 95\%$)
5.3.2 Effect of Sensing Element

Samples of TSF were manufactured using ten different kinds of sensing element as mentioned in Chapter 3. The TSF samples can be grouped into three ranges of reference resistance as stated in Table 5-2.

Table 5-2: Classification of TSF in terms of Reference Resistance

<table>
<thead>
<tr>
<th>Reference Resistance (Ω)</th>
<th>Sensitivity mΩ/ °C</th>
<th>Sensing Elements Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low 3 to 7</td>
<td>Low 14 to 27</td>
<td>NC127, NC125, C150, EC150, BEC150 coarse diameter Cu based sensing elements</td>
</tr>
<tr>
<td>Medium 32 to 47</td>
<td>Medium 130 to 230</td>
<td>W80, N100 and N90 medium diameter Ni and W sensing elements</td>
</tr>
<tr>
<td>High 91 to 126</td>
<td>High 310 to 550</td>
<td>W50 and BE61 fine diameter Ni and W sensing elements</td>
</tr>
</tbody>
</table>

Figure 5.14 presents the effect of sensing elements on the regression uncertainty (in terms of CDₜ,95%). The CDₜ,95% of experimental repeats of all kinds of sample were individually calculated and then grouped according to their sensing elements. The solid bar presents the mean values of CDₜ,95% while the error bar presents the standard uncertainty in the corresponding group of data. The regression uncertainties in the experimental repeats of TSF samples having high and medium ranges of nominal resistance were found to be less than ± 0.13 °C, while in the case of the Cu based TSF samples, the uncertainties exceeded ± 0.18 °C, as shown in Figure 5.14. This marginal difference can be related to the accuracy of the multimeter.

Figure 5.14: Effect of Sensing Element on Regression uncertainty
The Agilent Multimeter employed to measure resistance data was not specifically designed for the measurement of tiny variations in resistance with high accuracy. According to the user guide of the multimeter, measurements will always be subject to a minimum error of ±4 mΩ. For Cu based TSF samples, a ±4 mΩ uncertainty in resistance may contribute an error as large as ± 0.3 °C. This was also evident from the graphical display of some TR repeats of Cu based TSF samples as shown in Figure 5.15. Because of the higher reference resistance values, the TSF samples embedded with a sensing element of Ni and W were not found to be affected by a ±4 mΩ and displayed the low regression uncertainty as shown in Figure 5.14.

The only exception to the above guideline is the behaviour of W50. Although W50 has the highest reference resistance of all the sensing elements, it still showed high regression errors. This may be related to the quality of the inlaying of the sensing element during manufacture. It was discussed earlier that TSF samples made of W50 were most difficult to manufacture because W50 demonstrated poor handling and poor bending behaviour along the edges. In some of the W50 samples, wire protruded from the surface of the samples and may have made contact with the Cu plate during TR testing. It can be inferred that these abnormalities in W50 samples were responsible for relatively high regression errors.

**Figure 5.15:** Few unusual repeats of TSF samples inlaid with Cu based sensing elements

**AXES:** x-axis – Temperature (°C), y-axis – Resistance (Ω),  
**LEGENDS:** blue line – Experimental data, red line – Fitted data
The regression errors can be grouped in terms of following combinations.

Table 5-3: Mean regression errors in various settings

<table>
<thead>
<tr>
<th>Group Category</th>
<th>Mean Regression Errors (± °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Repeats</td>
<td>0.16</td>
</tr>
<tr>
<td>Heating repeats</td>
<td>0.24</td>
</tr>
<tr>
<td>Cooling repeats</td>
<td>0.07</td>
</tr>
<tr>
<td>Repeats of 46 inlay TSF</td>
<td>0.15</td>
</tr>
<tr>
<td>Repeats of 34 inlay TSF</td>
<td>0.17</td>
</tr>
<tr>
<td>Heating repeats of 46 inlay TSF</td>
<td>0.22</td>
</tr>
<tr>
<td>Cooling repeats of 46 inlay TSF</td>
<td>0.07</td>
</tr>
<tr>
<td>Heating repeats of 34 inlay TSF</td>
<td>0.26</td>
</tr>
<tr>
<td>Cooling repeats of 34 inlay TSF</td>
<td>0.07</td>
</tr>
</tbody>
</table>

5.3.3 Effect of Inlay Density

The TSF samples were manufactured with either 46 inlays or with 34 inlays in the sensing area of 8 x 8 cm². Figure 5.16 compares the experimental values of temperature coefficient of resistivity (α₂₀) of the 46 and 34 inlay samples within their respective categories of sensing element. It is evident from Figure 5.16 that the α₂₀ results of the 34 inlay samples were found to be marginally lower than the α₂₀ results of the 46 inlay samples.

This may be related to the exposure of an 8 cm length of sensing element to the ambient environment during TR testing. The extra length of sensing element was required to make a connection with the Four-Wire-Connector. Therefore at the corresponding temperature of the Cu plates, the corresponding resistance would be marginally less than actual value. This leads to a slight decrease in the experimental sensitivity (slope) and the experimental value of α₂₀.

Irrespective of the number of inlays, this 8 cm length was constant for all TSF samples. In the case of the 46 inlay samples, the 8 cm equates to 2.1% of the total length of sensing element. The equivalent percentage of length in the case of the 34 inlay samples is around 2.8%. This means that the effect of the ambient environment on the sensing element of a 34 inlay TSF would be marginally more than that for the sensing element of a 46 inlay TSF. In terms of
errors in temperature at 35 °C, it will be less than 0.1 °C. However, this is a systematic error and would be the same for all the test procedures.

5.4 Repeatability Uncertainty

The variations within each individual experimental repeat have been discussed in detail in earlier sections. In this section, uncertainties among repeats of tests on the same sample will be discussed. This will address the repeatability of the experimental TR equation and the sources of uncertainty in respect of repeatability. At first, experimental repeats belonging to one sample will be analysed in terms of the parameters listed earlier. Then a method to formulate the uncertainty among repeats will be devised in terms of “Temperature Uncertainty”. Afterwards, the analysis methodology will be extended to the full range of TSF samples.

5.4.1 Analysis Criteria

The TR experiment on each sample was repeated at least 6 times. Various parameters (as mentioned earlier) can be used to compare the experimental repeats of the same samples and the uncertainties-among-repeats can be estimated by the calculating the 95% Confidence Deviation of these parameters. For ease of understanding and for comparison, it was important to present the uncertainties-among-repeats in terms of temperature rather than as part of any
resistance related parameter. However, prior to that it was prerequisite to define the overall uncertainties-among-repeats in terms of resistance values across the length of the TR Curve.

The temperature points of 20, 35 and 50°C were selected for the purpose of comparison. The resistance values at these temperature points i.e. $R_{20}$, $R_{35}$ and $R_{50}$ of each experimental repeat were calculated from the slope and intercept of their respective TR equations. The variations within $R_{20}, R_{35}$ and $R_{50}$ were first converted into 95% confidence deviations of uncertainty in resistance ($CD_{R_{20},95%}$, $CD_{R_{35},95%}$, $CD_{R_{50},95%}$) and then into 95% confidence deviation in temperature by dividing the $CD_{R_{20},95%}$, $CD_{R_{35},95%}$, and $CD_{R_{50},95%}$ by the mean sensitivity value of each particular sample.

Table 5-4 presents the methodology used to estimate the variations among repeats of a sample in terms of “Temperature Uncertainty”. This table is divided into three sections as highlighted by the red borders.

Section A of Table 5-4 compares the ten experimental repeats (five Heating and five Cooling cycles) of the TSF sample N10046S1 in terms of the $r^2$-value, the sensitivity, the intercept ($R_0$), temperature coefficient of resistivity ($\alpha_{20}$), the resistance ratio ($RR_{20-50}$), the reference resistances ($R_{20}$), $R_{35}$ and $R_{50}$. Uncertainties within each repeat are also presented in Table 5-4 in terms of the 95% Confidence Deviation of resistance ($CD_{R, 95%}$), and the temperature ($CD_{T, 95%}$). In order to emphasise and visualise the differences within the parameter’s values; each cell of the table was highlighted in terms of colour coded data bars.

The values deriving from each parameter of experimental repeats were further analysed statistically in terms of their standard deviation, standard uncertainty and 95% confidence deviation in section B of Table 5-4. The 95% Confidence Deviation of $R_{20}, R_{35}$ and $R_{50}$ i.e. ±(0.029, 0.023 and 0.025) Ω were converted into 95% Confidence Deviations in temperature by dividing them by the experimental mean value i.e. 0.223 Ω/ °C, as highlighted in yellow in section C of Table 5-4.

The 95% Confidence Deviation in temperature among the repeats, covering the temperature range of 20 to 50 °C, may be represented by one value i.e. ±0.12 °C (by taking an average of ±(0.13, 0.10 and 0.11) °C as demonstrated in section C of Table 5-4.
Figure 5.17 presents the TR curves of experimental repeats for sample N10046S1 as mentioned in Table 5-4. Heating and Cooling TR repeats are drawn in red and blue respectively.

![TR curves of experimental repeats of TSF sample N10046S1](image)

**Figure 5.17:** TR curves of experimental repeats of TSF sample N10046S1

Table 5-5 compares all the experimental repeats for sample W8034S2 and estimates the uncertainty among the repeats according to the analysis criteria discussed earlier. The 95% Confidence Deviation of temperature uncertainty among all repeats was calculated to be ±0.83 °C.
<table>
<thead>
<tr>
<th>Test Tag</th>
<th>( r^2 )-Value</th>
<th>Slope (Sensitivity) ( \Omega/°C )</th>
<th>Intercept ( (R_0) ) ( \Omega )</th>
<th>( \alpha_{20} ) 1/°C</th>
<th>RR(_{(20-50)})</th>
<th>( R_{20} ) ( \Omega )</th>
<th>( R_{35} ) ( \Omega )</th>
<th>( R_{50} ) ( \Omega )</th>
<th>CD(_R), 95% ±Ω</th>
<th>CD(_R), 95% ±°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>N10046S1-1H</td>
<td>0.9996</td>
<td>0.224</td>
<td>42.436</td>
<td>0.00478</td>
<td>1.143</td>
<td>46.92</td>
<td>50.29</td>
<td>53.65</td>
<td>±0.052</td>
<td>±0.23</td>
</tr>
<tr>
<td>N10046S1-1C</td>
<td>1.0000</td>
<td>0.222</td>
<td>42.564</td>
<td>0.00472</td>
<td>1.142</td>
<td>47.00</td>
<td>50.34</td>
<td>53.67</td>
<td>±0.009</td>
<td>±0.04</td>
</tr>
<tr>
<td>N10046S1-2H</td>
<td>0.9995</td>
<td>0.224</td>
<td>42.434</td>
<td>0.00478</td>
<td>1.143</td>
<td>46.92</td>
<td>50.29</td>
<td>53.65</td>
<td>±0.067</td>
<td>±0.30</td>
</tr>
<tr>
<td>N10046S1-2C</td>
<td>1.0000</td>
<td>0.221</td>
<td>42.584</td>
<td>0.00471</td>
<td>1.141</td>
<td>47.01</td>
<td>50.34</td>
<td>53.66</td>
<td>±0.007</td>
<td>±0.03</td>
</tr>
<tr>
<td>N10046S1-3H</td>
<td>0.9996</td>
<td>0.226</td>
<td>42.447</td>
<td>0.00480</td>
<td>1.144</td>
<td>46.96</td>
<td>50.34</td>
<td>53.73</td>
<td>±0.056</td>
<td>±0.25</td>
</tr>
<tr>
<td>N10046S1-3C</td>
<td>1.0000</td>
<td>0.223</td>
<td>42.565</td>
<td>0.00475</td>
<td>1.143</td>
<td>47.03</td>
<td>50.39</td>
<td>53.74</td>
<td>±0.010</td>
<td>±0.04</td>
</tr>
<tr>
<td>N10046S1-4H</td>
<td>0.9998</td>
<td>0.221</td>
<td>42.575</td>
<td>0.00471</td>
<td>1.141</td>
<td>47.00</td>
<td>50.33</td>
<td>53.65</td>
<td>±0.044</td>
<td>±0.20</td>
</tr>
<tr>
<td>N10046S1-4C</td>
<td>1.0000</td>
<td>0.223</td>
<td>42.534</td>
<td>0.00474</td>
<td>1.142</td>
<td>46.99</td>
<td>50.32</td>
<td>53.66</td>
<td>±0.010</td>
<td>±0.04</td>
</tr>
<tr>
<td>N10046S1-5H</td>
<td>0.9997</td>
<td>0.224</td>
<td>42.453</td>
<td>0.00477</td>
<td>1.143</td>
<td>46.93</td>
<td>50.28</td>
<td>53.64</td>
<td>±0.037</td>
<td>±0.17</td>
</tr>
<tr>
<td>N10046S1-5C</td>
<td>1.0000</td>
<td>0.223</td>
<td>42.532</td>
<td>0.00473</td>
<td>1.142</td>
<td>46.97</td>
<td>50.31</td>
<td>53.64</td>
<td>±0.009</td>
<td>±0.04</td>
</tr>
</tbody>
</table>

**A**

| Mean         | 0.2231          | 42.512                         | 0.005                | 1.142          | 46.975          | 50.321          | 53.668          | ±0.030         | ±0.133         |
| Sample standard deviation | 0.001          | 0.062                         | 0.000                | 0.001          | 0.041           | 0.032           | 0.035           | 0.024          | 0.105          |
| Sample size  | 10              | 10                           | 10                   | 10             | 10             | 10             | 10             | 10             | 10             |
| Standard uncertainty | 0.0004        | 0.0197                        | 0.0000               | 0.0003         | 0.0130          | 0.0101          | 0.0111          | 0.0074         | 0.0331         |
| Degrees of freedom | 9              | 9                             | 9                    | 9              | 9              | 9              | 9              | 9              | 9              |

**B**

| 95% t-value   | 2.262           | 2.262                         | 2.262                | 2.262          | 2.262           | 2.262           | 2.262           | 2.262          | 2.262          |
| 95% Confidence deviation | 0.001        | 0.045                         | 2.3E-05              | 0.001          | 0.029           | 0.023           | 0.025           | 0.017          | 0.075          |
| 95% Confidence interval (min) | 0.222        | 42.468                        | 0.00473              | 1.142          | 46.945          | 50.298          | 53.643          | 0.013          | 0.059          |
| 95% Confidence interval (max) | 0.224        | 42.557                        | 0.00477              | 1.143          | 47.004          | 50.344          | 53.993          | 0.047          | 0.208          |

**C**

<table>
<thead>
<tr>
<th>95% Confidence Deviation of temperature uncertainty among all repeats</th>
<th>±0.13 °C</th>
<th>±0.10 °C</th>
<th>±0.11 °C</th>
<th>at 20, 35 and 50 °C</th>
<th>Average</th>
</tr>
</thead>
</table>

Table 5-4: Comparison and estimation of uncertainty amongst experimental repeats of TSF sample N10046S1
### Table 5-5: Comparison and estimation of uncertainty amongst experimental repeats of TSF sample W8034S2

<table>
<thead>
<tr>
<th>Test Tag</th>
<th>r²-Value</th>
<th>Slope (Sensitivity) Ω/°C</th>
<th>Intercept (R₀) Ω</th>
<th>α₂₀ 1/°C</th>
<th>RR₁₀⁻₂₀ Ω</th>
<th>R₂₀ Ω</th>
<th>R₃₅ Ω</th>
<th>R₅₀ Ω</th>
<th>CD₉₅% ±Ω</th>
<th>CD₉₅% ±°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>W8034S2-1H</td>
<td>0.9995</td>
<td>0.130</td>
<td>32.572</td>
<td>0.00369</td>
<td>1.111</td>
<td>35.17</td>
<td>37.12</td>
<td>39.07</td>
<td>0.052</td>
<td>0.40</td>
</tr>
<tr>
<td>W8034S2-1C</td>
<td>0.9999</td>
<td>0.130</td>
<td>32.550</td>
<td>0.00370</td>
<td>1.111</td>
<td>35.15</td>
<td>37.10</td>
<td>39.05</td>
<td>0.009</td>
<td>0.07</td>
</tr>
<tr>
<td>W8034S2-2H</td>
<td>0.9996</td>
<td>0.129</td>
<td>32.536</td>
<td>0.00368</td>
<td>1.111</td>
<td>35.12</td>
<td>37.06</td>
<td>39.00</td>
<td>0.067</td>
<td>0.51</td>
</tr>
<tr>
<td>W8034S2-2C</td>
<td>0.9999</td>
<td>0.130</td>
<td>32.598</td>
<td>0.00368</td>
<td>1.110</td>
<td>35.19</td>
<td>37.13</td>
<td>39.07</td>
<td>0.007</td>
<td>0.05</td>
</tr>
<tr>
<td>W8034S2-3H</td>
<td>0.9998</td>
<td>0.131</td>
<td>32.711</td>
<td>0.00371</td>
<td>1.111</td>
<td>35.33</td>
<td>37.30</td>
<td>39.26</td>
<td>0.056</td>
<td>0.42</td>
</tr>
<tr>
<td>W8034S2-3C</td>
<td>0.9999</td>
<td>0.130</td>
<td>32.631</td>
<td>0.00368</td>
<td>1.110</td>
<td>35.22</td>
<td>37.17</td>
<td>39.11</td>
<td>0.010</td>
<td>0.08</td>
</tr>
<tr>
<td>W8034S2-4H</td>
<td>0.9999</td>
<td>0.130</td>
<td>32.475</td>
<td>0.00370</td>
<td>1.111</td>
<td>35.07</td>
<td>37.02</td>
<td>38.96</td>
<td>0.044</td>
<td>0.34</td>
</tr>
<tr>
<td>W8034S2-4C</td>
<td>0.9999</td>
<td>0.129</td>
<td>32.321</td>
<td>0.00370</td>
<td>1.111</td>
<td>34.91</td>
<td>36.85</td>
<td>38.79</td>
<td>0.010</td>
<td>0.07</td>
</tr>
</tbody>
</table>

#### A
- **Mean**: 0.1298, 32.549, 0.004, 1.111, 35.145, 37.092, 39.039, 0.032, 0.243
- **Sample standard deviation**: 0.001, 0.116, 0.000, 0.000, 0.123, 0.129, 0.135, 0.025, 0.194
- **Sample size**: 8, 8, 8, 8, 8, 8, 8, 8, 8
- **Standard uncertainty**: 0.0002, 0.0409, 0.0000, 0.0001, 0.0435, 0.0455, 0.0476, 0.0089, 0.0687
- **Degrees of freedom**: 7, 7, 7, 7, 7, 7, 7, 7, 7
- **95% t-value**: 2.365, 2.365, 2.365, 2.365, 2.365, 2.365, 2.365, 2.365, 2.365
- **95% Confidence deviation**: 0.000, 0.097, 9.1E-06, 0.000, 0.103, 0.108, 0.113, 0.021, 0.163
- **95% Confidence interval (min)**: 0.129, 32.453, 0.00368, 1.111, 35.042, 36.984, 38.926, 0.010, 0.081
- **95% Confidence interval (max)**: 0.130, 32.646, 0.00370, 1.111, 35.248, 37.199, 39.151, 0.053, 0.406

**95% Confidence Deviation of temperature uncertainty among all repeats**: ±0.80 °C, ±0.83 °C, ±0.87 °C at 20, 35 and 50 °C

**Average**: ±0.83 °C
5.4.2 Comparison among all TSF Samples

The earlier mentioned analysis criterion (calculating uncertainty amongst the repeat cycles of sample in terms of temperature uncertainty) was applied to all TSF samples for comparison purpose. Some of the samples, such as W8034S2, showed quite high variations. The uncertainty-among-repeats of some of the samples were noted to be as high as ±1.5 °C.

The primary reason behind such large variations in some of the samples was thought to be the extra length of sensing element required to make connections to the Four-Wire-Screw-Connector as shown in Figure 5.18. Experimental repeats were performed on different days and required fresh connections to the Four-Wire-Connector every time. Although care was exercised in making the connections to the sensing element at the same position, it was believed that the connecting points were slightly different during each test. Variations of ±1 cm can generate high errors in temperature by shifting the reference resistance value slightly. Some of the TSF samples were fastened with a Four-Wire-Molex-Connector as shown in Figure 5.18 in which the connecting point was always the same. The TSF samples having a Molex connector (such as N10046S1) showed less uncertainty among their experimental repeats (< ±0.5 °C) than the TSF samples connected with screw connectors (such as W8034S2).

Figure 5.19 demonstrated the uncertainty among experimental repeats of all the TSF samples in terms of their temperature uncertainty along with their resistance values at 35 °C ($R_{35}$). The length of the bar indicates the temperature uncertainty while the position of the bar shows the resistance values at 35 °C. It is evident from Figure 5.19 that the majority of samples, exhibited temperature errors less than ±0.5 °C. The large variations in temperature as shown by some of
the TSF sensors were mainly because of the variations in connecting point to the screw connector as discussed earlier.

It can therefore be concluded that the repeatability uncertainty of TSF samples would not be more than ±0.5 °C, in case of using Molex connectors.

5.4.3 Average TR Equation

In order to best represent the TR behaviour of a particular sample; its average TR equation can be generated by considering the parameters related to the experimental repeats. The average TR equation may be defined in any of the following ways:

- by considering only the three data points i.e. the mean resistance values at 20, 35 and 50 °C;
- by considering all data points i.e. all resistance values at 20, 35 and 50 °C;
- by considering the mean of “slope” and “Intercept” of all experimental repeats.

The resultant equation would be the same irrespective of the method applied to calculate the average TR equation. e.g. in the case of the TSF sample N10046S1, the average TR equation was found to be \( R = 0.223T + 42.512 \), while in the case of W8034S2, it was \( R = 0.1298T + 32.549 \)
Figure 5.19: Repeatability Uncertainty – Comparison of all TSF Samples

<table>
<thead>
<tr>
<th>TSF Sample no.</th>
<th>Dia. In μm</th>
<th>Type of sensing element</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEC 150 46 S1</td>
<td></td>
<td>B - Braided</td>
</tr>
<tr>
<td>N9034S1</td>
<td></td>
<td>E - Enamelled</td>
</tr>
<tr>
<td>N9034S2</td>
<td></td>
<td>C - Copper</td>
</tr>
<tr>
<td>N9046S1</td>
<td></td>
<td>N - Nickel</td>
</tr>
<tr>
<td>N9046S2</td>
<td></td>
<td>W - Tungsten</td>
</tr>
<tr>
<td>N9046S3</td>
<td></td>
<td>NC - Nickel coated Copper</td>
</tr>
<tr>
<td>W5034S1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W5034S2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W5034S3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W5046S1</td>
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<td></td>
</tr>
<tr>
<td>W5046S2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W5046S3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC127-34S1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC127-34S2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC127-34S3</td>
<td></td>
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<td>NC127-44S3</td>
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<tr>
<td>NC125-34S1</td>
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<td>NC125-34S2</td>
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</tr>
<tr>
<td>NC125-46S10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.19: Repeatability Uncertainty – Comparison of all TSF Samples
5.5 Manufacturing Uncertainty

In earlier sections, the uncertainty within repeats (regression uncertainty) and the uncertainty among repeats of the same sample types (repeatability uncertainty) has been investigated thoroughly. This section will discuss the uncertainties among samples of same sample type (manufacturing uncertainty). The variations among the samples may be represented in terms of their nominal resistance, however, for ease of understanding and comparison, the nominal resistance was converted into a calculated length of sensing element. The length of the sensing element ($l_{\text{cal}}$) in each sample was calculated using:

$$l_{\text{cal}} = \frac{\pi d^2 R_{20}}{4\rho}$$  \hspace{1cm} (5.16)

Where $d$ and $\rho$ represent the diameters and electrical resistivity of the sensing element respectively, while $R_{20}$ stands for the experimental reference resistance of TSF at 20 °C. The calculated length of sensing element was also compared with the target length ($l_{\text{tar}}$) of sensing element defined as:

$$l_{\text{tar}} = (W_{\text{tsf}} n) + L_{\text{tsf}}$$  \hspace{1cm} (5.17)

Where $W_{\text{tsf}}$ and $L_{\text{tsf}}$ denotes the width and length of the sensing area of the TSF while $n$ stands for the number of inlays. After inserting the $8 \times 8$ cm$^2$ dimensions and the number of inlays into equation (2.1), the target length of the 34 and 46 inlay samples was calculated to be 2.88 and 3.84 metres, respectively.

Figure 5.20 and Figure 5.21 present the uncertainty amongst various sample types in terms of the calculated length of inlaid sensing element. Variations within the sample type are expressed by error bars of standard uncertainty.

It is evident from Figure 5.20 and Figure 5.21 that length variations exist not only within samples of the same-sample-type but also amongst the sample-types. In the case of the 46 inlay samples, the 95% Confidence Deviation of calculated length from its mean was found to be ±4 cm, which is marginally more than for the 34 inlay counterparts which were ±3 cm. In both
figures, it can be seen that the mean of the calculated lengths were found to be quite close to
the target length.

Figure 5.20:  Calculated length of Sensing Element (46 inlay TSF samples)

Figure 5.21:  Calculated length of Sensing Element (34 inlay TSF samples)
5.6 Summary and General Discussion

This chapter has investigated uncertainties in the Temperature-Resistance relationship in respect of the temperature-sensing fabrics. For ease of understanding and for purposes of comparison, uncertainties within repeats, among repeats and among samples were estimated statistically (95% Confidence Deviations) in terms of the temperature (\(\text{CD}_T,95\%\)), rather than the resistance (\(\text{CD}_R,95\%\)). Sometimes, global parameters were also employed to analyse results, such as the coefficient of determination \((r^2\) value), the temperature coefficient of resistivity \((\alpha_{20})\), and the inlaid length of sensing element \((l_{cai})\). The results have already been discussed in their relevant sections. This section presents a general discussion and a summary of the key findings.

5.6.1 Regression Uncertainty

“Uncertainties within repeats” were compared in terms of the effects of the temperature profile, sensing element and inlay density. In all the experimental repeats, the maximum uncertainties were found to be not more than \(\pm0.3\ °C\) (apart from a few outliers). Uncertainties in the Cooling TR equation showed considerably reduced values (\(\pm0.07\ °C\)) in comparison with the Heating TR equation (\(\pm0.24\ °C\)). This also indicates that the test rig could be utilised to test the temperature of a TSF in a dynamic thermal environment with an uncertainty of \(\pm0.3\ °C\) and without any lag in its response time.

Considering the multimeter measuring uncertainty (\(\pm4\ m\Omega\)) and the low sensitivity of Copper (because of its low resistivity and its low temperature coefficient), the TSF sample made with a Copper-based sensing element showed high regression uncertainty (> \(\pm0.18\ °C\)) in comparison to the TSF sample made with a Nickel and Tungsten sensing element (< \(\pm0.13\ °C\)). It may therefore be concluded that the TSF samples having a low nominal resistance, such as the copper-based TSF may not be the most suitable candidates for measuring temperature in the application environment, in comparison with the higher-resistance TSF samples.

5.6.2 Repeatability Uncertainty

Repeatability uncertainty describes the degree to which further measurements provide similar TR data. It is understood that minor differences amongst repeated experimental cycles on the
same TSF sample would exist due to variation in factors that are inherent in the TR experiment; testing methodology and measurement uncertainty of test rig instruments. Experiments were performed on different days and involved pre-test handling as well. This means that the environmental conditions (room temperature and humidity), the quality of thermal contact between the TSF and the copper plates, and the quality of electrical contact between the sensing element and the four-wire-connector would be slightly different each time.

The TSF samples were connected to the multimeter by two kinds of four-wire-connectors, namely a Screw connector or a miniature Molex connector. By using the screw connector, there was always the possibility of a slightly different connecting point being used in each experimental repeat, as discussed earlier. A slight change in the connecting point affected the overall length of the sensing element and hence its reference resistance. Therefore some of the TSF samples, connected with screw connectors during the TR experiments showed repeatability uncertainty in the range of ±0.5 °C to ±1.5 °C. However, the TSF samples connected with the miniature Molex connector; demonstrated the repeatability uncertainty in the range of ±0.1 °C to ±0.5 °C.

Apart from connector error, large uncertainties amongst the experiment repeats were not observed to be related to other factors; such as the inlay density, the sensing element and the temperature profile. By testing all the samples with a Molex connector and by increasing the number of experimental repeats, the repeatability uncertainty can be decreased to ±0.3 °C.

**5.6.3 Manufacturing Uncertainty & Interchange-ability**

Uncertainty amongst samples was estimated in terms of the calculated length of the sensing element. In all the TSF samples, the 95% Confidence Deviation of the calculated length from its mean was found to be less than ±4 cm; which is not substantial considering the tolerance of the manufacturing process of the TSF samples. However ±4 cm variations in the length of the sensing element will shift the reference resistance of a particular TSF sample. This means the TSF samples may not be used as interchangeable sensors; or, the calibration equation for one sample may not be applied to another sample. In order words, each individual sample should be calibrated before using it in an application environment.
New TSF samples may be calibrated in a test rig for the required temperature range. However, considering the time duration required for performing calibration in the test rig, new samples may be calibrated using a 1-point calibration method. In this method, TSF samples would be calibrated at a reference temperature value \( (R_{20}) \). Since the database of temperature coefficient of resistivity \( (\alpha_{20}) \) of all the sensing elements has already been made available, consequently, the TR equation i.e. \( R = R_{20}(1 + \alpha_{20}(T - 20)) \) could be utilised to develop the calibration equation of each TSF sample:

5.6.4 Sensing properties of Sensing Element

The sensing properties of wires of the same metal type (purchased from different sources) were found to be different from the standard documented metal properties which may be the consequence of the inclusion of impurities and the wire manufacturing process (such as work-hardening and heat treatments). For example nickel wires from three different sources were used in developing the TSF samples; all three of them exhibited different experimental values of resistivity and temperature coefficient of resistivity.

5.6.5 Statistical Parameters

Temperature resistance data derived from a full length TR experiment can be explained by various parameters as explained in section 5.2.2 and Table 5-1. However, for ease of understanding and comparison, the uncertainties were presented in terms of global parameters such as the \( r^2 \)-value and the 95% Confidence Deviation of uncertainty in temperature \( (CD_{T,95\%}) \). The \( CD_{T,95\%} \) helps to build an interval where there is a 95% chance that a new temperature uncertainty value will lie at a particular resistance.

In total, more than 60 TSF samples were manufactured. A minimum of three samples of each type were produced considering the inlay density and type of the sensing elements. Each sample was tested at least six times to estimate the repeatability uncertainty and to generate their TR equation. Uncertainties may be further reduced by increasing the sample size of data e.g. by increasing the number of experimental repeats or by manufacturing a higher number of TSF samples of each sample type. However, this was not really required as the temperature-resistance trend was quite predictable.
According to the NPL Guide for Uncertainty Measurement (Bell 1999), when the sample size is high and the experimental observations are assumed to be normally distributed, then the 95% Confidence Deviation of uncertainty in that measurement can be calculated by multiplying a coverage factor ($k = 2$) to the standard uncertainty. However, in this study, the 95% Confidence Deviation was calculated using the t-value instead of the constant value of coverage factor ($k = 2$). Since the t-value depends upon the sample size, the larger the sample size, the lower will be the t-value, and the smaller will be the margin of Confidence Deviation. That means that by increasing the sample size, uncertainties within repeats, among repeats and among samples may be reduced further.

5.7 Conclusion

- The TSF sample made of Ni and W wires showed regression uncertainty of $< \pm0.13\, ^\circ$C in comparison to the Cu based TSF samples ($> \pm0.18\, ^\circ$C).
- Among all the TSF samples, BEN61 samples showed least regression uncertainty i.e. $\pm0.1\, ^\circ$C.
- The repeatability uncertainty of all TSF samples was found to be less than $\pm0.5\, ^\circ$C;
- The manufacturing uncertainty of all TSF samples in terms of the length of sensing element was found to be $\pm 2\%$ from its mean.
Chapter 6  Thermal modelling of Rig Components & Temperature-Resistance Relationship

6.1 Introduction

Chapters 4 and 5 discussed the development and usage of a test rig to develop the experimental Temperature-Resistance (TR) relationship of a Temperature Sensing Fabric (TSF). Validation of experimental results by modelling was one of the prime objectives of this study. In this chapter, the TR relationship of TSF will be reproduced by the modelling of rig components in the thermal-electrical domain. The components of the rig which were employed in modelling were a hotplate, a lower copper plate, the TSF, an upper copper plate and the environment. Firstly, a mathematical model of the rig components was developed under steady state conditions, by the application of basic heat transfer principles. Later, a transient version of the model was developed in the Simscape environment which deals in the modelling of temperature profiles of rig components during heating and cooling. A conceptual model of the TSF in terms of its basic components i.e. air, textile material and the sensing element was also developed, and this was later utilised in transient modelling. Following this, the results are presented, analysed and discussed.

6.2 Steady State Model of rig Components (Mathematical)

This section describes the one-dimensional steady state model of the rig components in terms of the application of basic heat transfer principles, so that the unknown information relating to temperature and thermal properties (thermal conductivity, coefficient of heat transfer etc) of the rig components may be calculated. The steady state is a stable condition, when the temperature of rig components does not change over time. Figure 6.1 presents a schematic diagram showing the rig components, important parameters associated with thermal modelling and the direction of heat flow. The top surface of the upper copper plate was exposed to convective heat transfer while the rest of the components all exchanged heat by conduction.
6.2.1 Assumptions

In order to develop an understanding, a simple model was created, with few assumptions incorporated. It was assumed that the hotplate was generating a constant heat flux so that the temperature of all the components was steady over time, as illustrated in Figure 6.1. It was also assumed that the edges of the rig components were insulated so that heat was only allowed to flow from the hotplate to the environment through the rig components. In other words, there was no lateral heat transfer. All system components were assumed to be in perfect contact with each other, without any thermal contact resistance. The TSF was assumed to be a homogenous material and can be considered as one component.

![Figure 6.1: Schematic diagram of heat flow through experimental rig](image)

6.2.2 Parameters and Equations

List of the parameters and their description, used in the modelling are:

- **Q** → Heat flow rate,
- **$T_1$** → Temperature at the interface of hotplate and bottom Cu plate,
- **$T_2$** → Temperature at the interface of bottom Cu plate and TSF sample,
- **$T_3$** → Temperature at the interface of TSF and top Cu plate,
\[ T_4 \rightarrow \text{Temperature at the interface of top Cu plate and environment,} \]
\[ T_{hp} \rightarrow \text{Hotplate temperature,} \]
\[ T_{env} \rightarrow \text{Room temperature,} \]
\[ k_{hp}, k_{cp1}, k_{tsf}, k_{cp2} \rightarrow \text{Thermal conductivities of hotplate, bottom Cu plate, TSF and top Cu plate respectively,} \]
\[ R_{hp}, R_{cp1}, R_{tsf}, R_{cp2}, R_{env} \rightarrow \text{Thermal resistances of hotplate, bottom Cu plate, TSF, top Cu plate and environment respectively,} \]
\[ L_{cp1}, L_{tsf}, L_{cp2} \rightarrow \text{Thicknesses of bottom Cu plate, TSF and top Cu plate respectively,} \]
\[ h_{env} \rightarrow \text{Convective heat transfer coefficient between top Cu plate and environment and,} \]
\[ A \rightarrow \text{Surface area of Cu plates, TSF sample and hotplate.} \]

In order to develop expressions for unknown parameters, Fourier’s law was applied across each component and Newton’s law of cooling was applied at the interface of the top copper plate and the environment. Since all the components were in the steady state, they can be compared in terms of heat flow rate \( Q \) as:

\[
Q = \frac{\kappa_{cp1} A(T_1 - T_2)}{L_{cp1}} = \frac{\kappa_{tsf} A(T_2 - T_3)}{L_{tsf}} = \frac{\kappa_{cp2} A(T_3 - T_4)}{L_{cp2}} = h_{env} A(T_4 - T_{env}) \quad (6.1)
\]

The thermal resistance is the resistance of a material to the conduction or convection of thermal energy and is defined as:

\[
R = \frac{L}{kA} \quad \text{(For conduction)} \quad (6.2)
\]
\[
R_{env} = \frac{1}{h_{env} A} \quad \text{(For convection)} \quad (6.3)
\]

Expression (6.1) can also be expressed in terms of thermal resistance as:

\[
Q = \frac{(T_1 - T_2)}{R_{cp1}} = \frac{(T_2 - T_3)}{R_{tsf}} = \frac{(T_3 - T_4)}{R_{cp2}} = \frac{(T_4 - T_{env})}{R_{env}} \quad (6.4)
\]

Expression (6.4) can be rearranged as:

\[
Q = \frac{(T_1 - T_2)}{R_{cp1} + R_{tsf}} = \frac{(T_1 - T_3)}{R_{cp1} + R_{tsf} + R_{cp2}} = \frac{(T_1 - T_4)}{R_{cp1} + R_{tsf} + R_{cp2} + R_{env}} = \frac{(T_1 - T_{env})}{R_{cp1} + R_{tsf} + R_{cp2} + R_{env}} \quad (6.5)
\]
In equation (6.4), the values of parameters; \(T_1, T_4, T_{\text{env}}, Q, R_{cp1} \) and \(R_{cp2} \), were known. The rest of the parameters may be derived as below:

\[
R_{tsf} = \frac{[T_1 - T_4] - 2R_{cp1}Q}{Q} \tag{6.6}
\]

\[
T_3 = T_1 - Q(R_{cp1} + R_{tsf}) \tag{6.7}
\]

\[
T_2 = T_1 - (R_{cp1}Q) \tag{6.8}
\]

\[
R_{env} = \frac{[T_1 - T_{\text{env}}] - Q(2R_{cp1} + R_{tsf})}{Q} \tag{6.9}
\]

\[
h_{\text{env}} = \frac{1}{R_{env}A} \tag{6.10}
\]

\[
k_{tsf} = \frac{L_{tsf}}{R_{tsf}A} \tag{6.11}
\]

### 6.2.3 Known and unknown Parameters

Considering a hotplate that is generating a constant heat flow rate of 1.21 watts in order to maintain temperatures \(T_1 \) and \(T_4 \) at 49.25 °C and 41.20 °C respectively, such that the all the components of the test rig are in the steady state. And suppose that the environmental temperature is 21 °C.

The heat flow rate was calculated by measuring the power consumed by the hotplate in the steady state (see Appendix A for further details) and \(T_1 \) and \(T_4 \) were measured by thermocouples fastened within the copper plates. The environmental temperature was measured using a RS Hygro-Thermometer. The thickness and surface areas were measured using a vernier scale. The thermal conductivity of copper is a universal parameters and taken as standard.

The values of known parameters are:

\[T_1 = 49.25 \, ^\circ\text{C}; \quad T_4 = 41.20 \, ^\circ\text{C}; \quad T_{\text{env}} = 21 \, ^\circ\text{C};\]

\[L_{cp1} = L_{cp2} = 0.004 \, \text{m}; \quad L_{tsf} = 0.0035 \, \text{m};\]

\[A = 9 \times 9 \, \text{cm}^2 = 0.0081 \, \text{m}^2\]

\[k_{cp1} = k_{cp2} = 386 \, \text{W/m} \, ^\circ\text{C}\]
The rest of the information could be determined by inserting known parameters into equations (6.6) to (6.11)

\[ T_3 = 41.202 \, ^\circ C \]
\[ T_2 = 49.248 \, ^\circ C \]
\[ R_{tsf} = 0.054 \, \text{m}^2{\text{C}} / \text{W} \]
\[ K_{tsf} = 0.0650 \, \text{W/m \text{C}} \]
\[ R_{env} = 0.135 \, \text{m}^2{\text{C}} / \text{W} \]
\[ h_{env} = 7.34 \, \text{W/m}^2{\text{C}} \]

6.2.4 Estimation of Temperature of Sensing Element

Assuming that TSF is a homogenous material whose temperature changes with respect to its thickness \((T = f(x))\) as shown in Figure 6.2.

Applying Fourier’s law across the TSF, would yield:

\[ \frac{Q}{A} = -k \frac{dT}{dx} \quad (6.12) \]
\[ \frac{Q}{A} dx = -kdT \quad (6.13) \]

The minus sign indicates the decrease in temperature as heat flows towards the positive x-direction. Now, suppose that the temperature of the underside of the TSF is indicated by \(T_2\) when \(x = 0\). Similarly \(T_3\) represents the temperature of the upper side of the TSF when
\( x = L_{tsf} \). After integrating both sides of equation (6.13) with the limits of 
\[ x = 0 \rightarrow L_{tsf} \text{ and } T = T_2 \rightarrow T_3 \] the result is:

\[
\frac{Q}{A} = \frac{k}{L_{tsf}} (T_2 - T_3) \quad (6.14)
\]

Assuming that \( T \) is the temperature at a certain distance \( x \) from the underside of the TSF. After integrating equation (6.13) again between the limits of \( x = 0 \rightarrow L \text{ and } T = T_2 \rightarrow T \) the result is:

\[
\frac{Q}{A} = \frac{k}{L} (T_2 - T) \quad (6.15)
\]

Now comparing equations (6.14) and (6.15) and ruling out the factor of \((Q/A)\), the temperature \((T)\) of the TSF at a certain thickness \((L)\) can be expressed as:

\[
T = T_2 - \frac{L(T_2 - T_3)}{L_{tsf}} \quad (6.16)
\]

### 6.2.5 Results and Discussion

The temperature drops across the components: i.e. 0.02 °C across the lower copper plate, 0.02 °C across the upper copper plate, and 8.04 °C across the TSF, indicates that there was hardly any temperature difference across the copper plates. However, a large gradient of temperature was observed across the TSF. This can also relate with the low Biot number of the copper plates and high Biot number of the TSF. The **Biot number** is a dimensionless parameter, usually used to classify the component as lumped or not, and can be defined as:

\[
Bi = \frac{hL}{k} \quad (6.17)
\]

Where \( h \) and \( k \) represents the convective heat transfer coefficient at the surface of the component and its thermal conductivity. While \( L \) is the characteristic length of the component, defined as the ratio of volume and surface area of the component.

When the Biot number of a component is less than 0.1, then the inside component temperature will be the same and the dominant temperature difference will be at the surface. In this case the component may be considered as “Lumped” or “Thermally Thin”. On the contrary, a
component, having a Biot number greater than 0.1 may be considered as “Non-Lumped” or “Thermally Thick”. Because of the high thermal conductivity and small thickness, the Biot number of the copper plates was found to be much lower than 0.1. This was also evident from the temperature drop across the copper plates (<0.02 °C). This means that copper plates may be considered as being Lumped.

Equation (6.16) describes that the temperature between $T_2$ and $T_3$ varies linearly. This means that the temperature of the sensing element can be calculated by knowing its exact position within the TSF. Since the sensing element was inlaid exactly in the middle of a double layer TSF, its temperature value could be calculated ($T_{SE} = 45.225$ °C) by inserting half of the thickness ($L = 1.75$ mm) in equation (6.16). It is important to note here that this equation can only be applied on homogeneous material having uniform ($k$) value over its entire thickness. Now the modelled $T_{SE}$ value is almost the same as the experimental $T_{SE}$ value at a certain temperature of the upper and lower copper plates. This is because the assumption behind the modelling and the experimental estimate were the same i.e. the Temperature changes linearly across the thickness of the TSF.

The thermal conductivity of the TSF ($K_{TSF}$) and the convective coefficient ($h_{env}$) are quite reasonable values considering the assumption of the model. However it is more appropriate to measure $h_{env}$ and $k_{TSF}$ experimentally and then use them in this model for more accurate results.

### 6.2.6 Model Limitations

The expressions stated earlier can only be applied when:

- all components of the rig are in the steady state i.e. there is no change in temperature with respect to time;
- heat transfer occurs in only one direction;
- TSF is considered to be homogenous material.

However it was known that:
• the experimental TR relationship was developed in a transient environment (during heating and cooling);
• heat not only transfers in one direction, but flows outwardly from the edges to the environment;
• the TSF is not a homogenous material and is composed of several basic elements i.e. textiles, metal wire and air.

Considering the limitation of the simple steady state model, it could not be exploited to develop the modelled TR relationship. Because in order to validate the experimental TR relationship, it is necessary to compare it with the modelled TR relationship, by modelling the heating and cooling profiles of the temperature and the corresponding resistance within a temperature range of 20-50 °C.

### 6.3 Conceptual Model of Temperature Sensing Fabric

It was important to develop a conceptual model of a TSF before using it as a component in the transient modelling of the rig components in a Simscape environment. Development of a conceptual model is the same idea as the process of nodalisation (meshing) in finite element modelling.

The TSF is composed of textile material, a sensing element and air. The thermal properties of each element, the volume occupied by these element and their masses are different from each other. This implies that under transient heat transfer conditions, the rate of change of temperature in each element would be different from each other. Therefore it may not be advisable to consider the TSF as a lumped component as a whole.

As was explained in Chapter 3; the TSF is not a basic knitted structure. It is a double layer structure with a combination of different knitted and spacer courses. Literature in terms of the modelling of knitted structures was limited to only basic structures i.e. plain knit, rib knit etc. Considering the complex structure of the TSF; the basic knit model may not be applied to it. At the same time, stitch level modelling of the TSF was not entertained, as it was beyond the scope of this study.
However, the Lumped Capacitance Method (LCM) can be applied to resolve this issue in a simplified way. In this approach the TSF may be converted into small sub-components and solved by first arranging them in close approximation to the actual structure and by then applying basic heat transfer principles.

The concept of the LCM originated from the technique used to solve electrical circuit behaviour by placing the electrical components (resistance, capacitance and inductance) in series or parallel settings. This kind of electrical network can be solved by (assuming the components as “Lumped”) the application of Kirchhoff’s Law.

Similarly thermal systems may be represented in the form of a network of thermal resistors (a.k.a. a thermal resistance network) and can be solved by LCM in the same manner as the electrical systems. Thermal components can only be modelled accurately by LCM, when heat exchange within an object is much faster than the heat exchange across the boundary of a component. Which leads to the basic assumption of LCM i.e. the temperature within the component is completely uniform at certain times.

Another advantageous aspect of the Lumped Capacitance Method (LCM) is that any complex shaped component may be approximated by converting it into smaller components and arranging them in parallel or series networks. Once this component is reduced into a sufficient number of sub-components (Lumps); their Biot number will be reduced. Therefore basic heat transfer principles may be applied to calculate the missing variables.

With reference to the above context, it was decided to create a simplified structure of the TSF by exploiting the LCM approach. However the question was how to break down the TSF in terms of its basic elements and how to arrange these elements in order to have good approximation of the TSF?

Figure 6.3 presents the rig components with the various possible arrangements of the basic elements of the TSF in series and parallel networks, separately. The TSF elements are shown in colour coded sections i.e. the textile is represented by blue, air by yellow and the sensing element by red. In Figure 6.3, parallel combinations of the TSF elements are shown by
schematics P1, P2 and P3, whilst the series arrangements are represented by schematics S1 to S5. The arrows represent the direction of heat flow.

In the early stages of modelling, all these possible combinations were modelled and simulated in the Simscape environment. The simulation of basic series and parallel combinations were not found to be in accordance with the experimental results as these combinations do not depict the close approximation of the TSF. However, the series combinations of S4 and S5 showed better results because the sensing element was placed exactly in the middle of the TSF.

Usually, in all textile structures, air and textile elements are networked in both a parallel and a series way randomly as shown in schematic A of Figure 6.4. The actual representation of the TSF may be different from this conceptual schematic. This can be further simplified by: first considering the TSF as a double layer fabric; then embedding a sensing element in between the two layers; and finally breaking down each layer of fabric in terms of air and textile sub-components, as shown in schematic B of Figure 6.4. The air and textile sub-components were arranged in parallel with each other whilst in series with the sensing element. Once the mass and volume of each component has been calculated, basic heat transfer principles may be applied, to calculate the temperature drop across each element and to estimate the temperature of the sensing element.

It is important to note that sub-components of the TSF in schematic B are not shown in proportion to their actual masses or dimensions; because the focus was to give an idea of the arrangement of the sub-components rather than of their masses or dimensions. Primary assumptions of a conceptual model of the TSF are:

- sub-components of textiles and air are parallel to each other whilst in series with the sensing element;
- all sub-components of the TSF are lumped;
- the sensing element is laid exactly in the middle of the TSF;
- all subcomponents are in perfect contact with each other without any thermal contact resistance. So that means that the surface temperature of two components which are in contact would be exactly same.
Figure 6.3: Various arrangements of the basic elements (textile, air, wire) of the TSF
6.3.1 Dimensions and Mass of sub-components of TSF

In order to use the TSF conceptual model in the transient thermal modelling of rig components, it was pre-requisite to estimate the dimensions and mass of each small lumped component of the TSF. For that purpose it was necessary to have information about the overall volume and mass of the TSF basic elements i.e. the air, textiles and sensing element.

A step by step detailed description of this procedure, in the form of a MATLAB Script file, is presented in Appendix C. This section summarises these steps in order.

- The dimensions and masses of the TSF and the sensing element were known initially along with the densities of air, textile and the sensing element (as described in step-1 in Appendix C).
- From the known information; mass, width, length and thickness of each element were calculated by considering them to be in series with each other (Step 2 – Appendix C).
- Then the dimensions of each element were calculated by considering them to be in parallel with each other (Step 3 – Appendix C).

Figure 6.4: Process of simplification of the TSF basic elements into sub-components
A) Raw form   B) TSF model used in the modelling of rig-components.
Finally the required mass and dimension of each small lumped component were calculated (Step 5 – Appendix C) according to the number of air and textile lumped components across both sides of the sensing element (Step 4 – Appendix C).

The Simscape model of the TSF was created by using four sub components of air and textile across both sides of sensing element (Step 4 – Appendix C). In preliminary modelling work, it was observed that by increasing the number of sub components of air and textile, the modelled temperature of sensing element was found to be marginally more close to the experimental values. However this effect was not found to be pronounced at high number of sub components. The four component model was found to be an optimum solution in comparison with the simplicity of the model and its validation with the experimental results.

6.4 Transient Model of Rig Components (Simscape)

Up until now in this chapter, the mathematical modelling of rig components under steady state conditions has been considered by the application of basic heat transfer principles. A conceptual model of a TSF in terms of its basic elements i.e. air, textile, sensing wire has also been presented. Now the development of a transient model of rig components in Simscape environment will be discussed in detail. This advanced version of the model deals with the modelling of temperature profiles of rig components whilst heating and cooling, estimation of the temperature of the sensing element, and the development of a modelled temperature-resistance relationship. The Simscape modelling environment will be introduced first, followed by the explanation of modelling blocks, parameters, equations and variables. Then the working of the main model and key sub models will be discussed in detail.

The objectives of the thermal modelling of rig components are:

- to estimate the error between modelled and experimental temperatures of the TSF sensing element;
- to compare the experimental and modelled TR curves;
- to understand the behaviour of rig components by varying the boundary conditions and modelling parameters.
6.4.1 Modelling in the Simscape Environment – An Introduction

Simscape (MathWorks 2011a) is a MATLAB toolbox for the modelling of physical systems in the Simulink environment by employing a physical network approach (also known as acausal modelling). Although Simscape works in the Simulink environment, its modelling approach is different from Simulink’s input-output method (also known as causal modelling).

Physical systems are usually expressed in the form of sets of Differential Algebraic Equations (DAEs) that must be solved simultaneously. Using Simulink’s input-output method to model such physical systems have a number of drawbacks (Miller 2010): the way that components of a physical system are modelled, it is difficult to change and reuse them in other models; if each component needs to interact in multi-physics environment, such as thermal-electrical, mechanical-hydraulic domains, for example, it becomes even harder to model them; and finally, physical systems may not have an exact solution.

These issues can be addressed by employing acausal modelling; a physical network approach. In this modelling technique, it is much easier to create reusable models which can work in a multi-physics environment.

According to this approach, each component of a physical system can interact with any other component by exchanging energy flow through their ports. These ports act like a physical connection between the components and allow energy to flow in both directions. The energy flow can be described in terms of its system variables i.e. Through and Across variables. Each physical domain (e.g. electrical, thermal, pneumatic, rotational etc.) has its own Through and Across variables. For example, current and voltage are respectively the Through and Across variables of an electrical domain. Similarly “Heat Flow” and “Temperature” are the Through and Across variables of the thermal domain (MathWorks 2011a).

It was discussed earlier that thermal systems can be presented in the form of thermal resistance networks and can be solved in the same way as the electrical resistance networks by application of Kirchhoff’s voltage and current laws. According to Kirchhoff’s voltage law; the voltage on the ports of all those components which are attached to an electrical node will be the same. In terms of their thermal domain it means that the temperature of ports of all those thermal components, attached to same thermal node will be the same. According to Kirchhoff’s
current law, the sum of currents flowing towards an electrical node is equal to the sum of currents flowing away from that node. In terms of thermal domain it means that \textit{sum of heat flowing towards a thermal node is equal to the sum of heat flowing away from that node} (MathWorks 2011a).

The concept of applying the above laws as constraints on each node can be applied to different physical domains (electrical, thermal, hydraulic, mechanical, pneumatic etc.)

\textbf{6.4.2 Modelling Blocks, Parameters and Equations}

Blocks are the basic model building unit in Simscape environment. Each physical domain has a library of blocks which can be used to develop a model of any physical system. These building blocks can be connected to each other by their physical ports and signal flow lines. Table 6-1 to Table 6-4 enlist all the blocks, which were employed to develop the model of the rig components.

In addition to system \textit{Through} and \textit{Across} variables, parameters are another kind of variable, usually used for defining a component’s physical properties e.g. mass, specific heat, thermal conductivity etc. The system variables and parameters of particular blocks are related through its governing equation. It is important to note that in the Simscape environment, the equations of blocks are defined in an implicit form. Unlike the explicit form of equations (simply input/output relations), the implicit form of equations can be solved simultaneously. Table 6-1 to Table 6-4 also presents the governing equation of a particular block along with its brief description.

Once the model is created and defined by boundary conditions, variables, and parameters; it can be simulated. The defined solver will then generate and solve the differential algebraic equations; resulting in the simulation of temperature and heat flows.
Table 6-1: Key modelling blocks of Simscape Thermal Domain (MathWorks 2011a), employed in the development of the model

<table>
<thead>
<tr>
<th>Thermal Blocks</th>
<th>Schematic</th>
<th>Governing Equation and Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduction</td>
<td><img src="image" alt="Conduction Block" /></td>
<td>[ Q = \frac{kA}{L} (T_A - T_B) ] The Conductive Heat Transfer block symbolises heat transfer by conduction between two layers of the same component. The transfer is governed by the Fourier law. This block was employed in the thermal network to represent the conductive heat flow within all main and sub-components of a test rig; e.g. Cu plates, sensing element, subcomponents of air and textile.</td>
</tr>
</tbody>
</table>
| Convection     | ![Convection Block](image) | \[ Q = h_c A (T_A - T_B) \] The Convective Heat Transfer block symbolises heat transfer by convection between two bodies by means of fluid motion. The transfer is governed by Newton’s law of cooling. This block was employed in the thermal network to represent the convective heat flow from the:
- Top Cu plate to the environment (Axially); and
- Edges of rig components to the environment (Radially) |
| Radiation      | ![Radiation Block](image) | \[ Q = h_r A (T_A^4 - T_B^4) \] The Radiative Heat Transfer block symbolises heat transfer by radiation between two surfaces in such a way that the energy of the emitting body is completely absorbed by a receiving body. The transfer is governed by the Stefan-Boltzmann law. This block was employed in the thermal network to represent the radiative heat flow between:
- Top Cu plate and surroundings; and
- Edges of rig components and their surroundings |
| Thermal Mass   | ![Thermal Mass Block](image) | \[ Q = cm \frac{dT}{dt} \] The Thermal Mass block symbolises a thermal mass, which reflects the ability of a material or a combination of materials to store internal energy. The property is characterised by the mass of the material and its specific heat. This block was employed in the thermal network to represent the thermal masses of all main and sub-components of the test rig. E.g. Cu plates, sensing element, and sub-components of air and textile. |
| Thermal Reference | ![Thermal Reference Block](image) | The Thermal Reference block symbolises a thermal reference point, that is, a point with an absolute zero temperature, with respect to which all the temperatures in the system are determined. Since all temperature signals in the Simscape environment are in the Kelvin scale therefore the value of the thermal reference is absolute Zero. |
The Temperature Sensor block symbolises an ideal temperature sensor, that is, a device that measures the temperature of a component with respect to the thermal reference. This block was connected in parallel to all components and sub-components, exactly in their middle layer. So that it gives the approximate temperature value of that component. In a few instances it also connected before and after the components in order to ascertain the total temperature drop across that component.

The Heat Flow Sensor block symbolises an ideal heat flow meter, that is, a device that converts a heat flow passing through the meter into a control signal proportional to this flow. This block was connected in series:
- with all components and sub-components to measure conductive heat flow and;
- between the top Cu plate, the environment and the edges of the component & environment to measure the convective heat flow.

The Temperature Source block symbolises an ideal source of thermal energy that is powerful enough to maintain a specified temperature at its outlet regardless of the heat flow consumed by the system. The hotplate of the rig component was considered to be an ideal temperature source block. The experimental temperature profile (both heating and cooling) of the bottom Cu plate was used as an input to this block. This block was also employed to simulate the constant environmental temperature.

Table 6-2: Key modelling blocks of Simscape Electrical Domain (MathWorks 2011a), employed in the development of the model

<table>
<thead>
<tr>
<th>Electrical Blocks</th>
<th>Schematic</th>
<th>Governing Equation and Description</th>
</tr>
</thead>
</table>
| **Thermal Resistor** | ![Thermal Resistor Schematic](image) | \[ R_T = R_0(1 + \alpha(T - T_{ref})) \]  
This block represents an electrical resistor with a thermal port. The governing equation describes a linear relationship between resistance and temperature. This block was used to model the sensing element in an electrical domain. For further description, see “Modelled relationship between Temperature and Resistance”. |
| **DC Current Source** | ![DC Current Source Schematic](image) | The DC Current Source block represents an ideal current source that is powerful enough to maintain a specified current through it regardless of the voltage across the source. The 1mA of constant dc current was specified to power the sensing element in the model. |
| **Voltmeter** | ![Voltmeter Schematic](image) | The Voltage Sensor block represents an ideal voltage sensor, which converts voltage measured between two points of an electrical circuit into a physical signal proportional to the voltage. The voltmeter was connected in parallel to a sensing element to measure the variations in voltage because of a change in temperature. |
| **Electrical Reference** | ![Electrical Reference Schematic](image) | The Electrical Reference block represents an electrical ground. It was connected to the circuit of an electrical domain in the sub-model of the sensing element. |
Table 6-3: General Simscape blocks (MathWorks 2011a), employed in the development of the model

<table>
<thead>
<tr>
<th>General Simscape Blocks</th>
<th>Schematic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Converter (SPS)</td>
<td><img src="signal_converter_sps" alt="Schematic" /></td>
<td>The Simulink-PS Converter block converts the input Simulink signal into a physical signal. This block was used to convert the experimental data of the hotplate temperature profile from the Simulink environment to the Simscape environment.</td>
</tr>
<tr>
<td>Signal Converter (PSS)</td>
<td><img src="signal_converter_pss" alt="Schematic" /></td>
<td>The PS-Simulink Converter block converts a physical signal into a Simulink output signal. This block was used to convert the signals of heat flow rate, temperature and voltage from the Simscape environment to the Simulink environment. Each sensor output requires a dedicated PSS block so that the signal could be viewed in the output scope in the Simulink environment. From the Simulink environment, a signal can be exported to the Matlab environment for further processing and analysis.</td>
</tr>
<tr>
<td>Solver</td>
<td><img src="solver" alt="Schematic" /></td>
<td>Each physical network model in the Simscape environment needs a Solver Configuration Block in order to simulate the model in terms of its system variables. Depending upon the model, a solver can be chosen and its parameters can be defined in a Solver Configuration Block. In order to solve the specified model, the default solver i.e. ode15s-stiff/NDF (MathWorks 2011c) was employed.</td>
</tr>
<tr>
<td>Connection Port</td>
<td><img src="connection_port" alt="Schematic" /></td>
<td>The main model and sub-models exchange signals through connection port blocks. This block transfers both the conserving and the physical signal connections to the outside boundary of sub-models. Connection ports were created to manage the flow of signals such as heat flow, temperature, and resistance across the main model and sub-models.</td>
</tr>
</tbody>
</table>

Table 6-4: General Simulink blocks (MathWorks 2011b), employed in the development of the model

<table>
<thead>
<tr>
<th>Simulink Blocks</th>
<th>Schematic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Builder</td>
<td><img src="signal_builder" alt="Schematic" /></td>
<td>The Signal Builder block is used to create a required signal as an input to the model. This block was employed to create a constant signal of environment temperature.</td>
</tr>
<tr>
<td>Input data from File</td>
<td><img src="input_file" alt="Schematic" /></td>
<td>The Input Data from File block reads data from a MAT-file and outputs the data as a signal. The data is a sequence of samples, consists of a time stamp and an associated data value. This block was employed to acquire the experimental temperature profile (temperature against time) as an input to hotplate.</td>
</tr>
<tr>
<td>Scope</td>
<td><img src="scope" alt="Schematic" /></td>
<td>The Scope block displays the output signals with respect to simulation time. This block was used to display the profiles of temperature and heat flow and temperature-resistance curve.</td>
</tr>
</tbody>
</table>
6.4.2.1 Modelled relationship between Temperature and Resistance

As has been explained in Chapter 3, the TR relationship of a sensing element in terms of dimensions of the TSF and wire can be modelled as:

\[ R_T = \frac{4\rho_{20}[(L_n W_s D_c) + L_s]}{\pi d^2} (1 + \alpha_{20}(T - 20)) \]  \hspace{1cm} (6.18)

Where \( R_T \) is the resistance at temperature \( T \) of sensing element and:

- \( \rho_{20} \) - electrical resistivity at reference temperature of 20 °C,
- \( d \) - diameter of sensing element,
- \( L_s \) - length of TSF,
- \( W_s \) - width of TSF,
- \( D_l \) - inlay density of sensing element,
- \( \alpha_{20} \) - temperature coefficient of resistivity at reference temperature (20 °C).

The term \( \frac{4\rho_{20}[(L_n W_s D_c) + L_s]}{\pi d^2} \) actually describes the nominal resistance at 20 °C \( (R_{20}) \). Equation (6.18) can be expressed in a simplified form as:

\[ R_T = R_{20}(1 + \alpha_{20}(T - 20)) \]  \hspace{1cm} (6.19)

In equation (6.18), apart from temperature \( T \), the rest of the parameters were known or measured experimentally. These parameters can be considered to be constant depending upon the type of TSF sample properties. The relationship (6.18) could be mapped on an experimental curve once the exact temperature of the sensing element \( (T) \) of the TSF is known. This implies that the dynamic resistance of the sensing element \( R_T \) would only depend upon the dynamic temperature of the sensing element \( T \).

The power required to raise the temperature of the sensing element \( (mc \frac{dT}{dt}) \) depends upon the net heat transfer \( (Q_{net}) \) through it and the self heating \( (I^2 R_T) \), and may be expressed as:

\[ mc \frac{dT}{dt} = Q_{net} + I^2 R_T \]  \hspace{1cm} (6.20)
Where \( m \) and \( c \) are the mass and specific heat capacity of the sensing element and their product is known as “Thermal Capacitance”. \( dT/dt \) is the rate of change of the sensing element temperature with respect to time. \( I \) is the excitation current passing through the sensing element. The net heat transfer \( (Q_{net}) \) through the sensing element can be expressed as:

\[
Q_{net} = Q_{in,cd} - (Q_{out,cd} + Q_{out,cv}) \quad (6.21)
\]

Where

\( Q_{in,cd} \) - Heat entered by conduction from layer one of TSF

\( Q_{out,cd} \) - Heat escaped by conduction to layer two of TSF

\( Q_{out,cv} \) - Heat escaped from edges to environment by convection

After rearranging, equation \( (6.20) \) can be expressed as:

\[
\frac{dT}{dt} = \frac{Q_{net} + I^2 R_T}{mc} \quad (6.22)
\]

Equations \( (6.18) \) and \( (6.22) \) are cross domain equations. In order to determine the \( R_T \) and \( T \) with respect to time, the model would solve both equations simultaneously throughout the duration of the experiment, as the output of one equation depends upon the input of the other equation.

### 6.4.3 Description of Main and Sub Models

The complete model of the rig components comprises a main model and a number of sub-models. The sub-models were created to make the model schematics reader-friendly and for ease of trouble-shooting the model. Since the basics behind the creation of the model, the flow of signal and the attachment of sensors are the same. Only the main model and two key sub-models will be discussed. Figure 6.5 to Figure 6.7 present the schematics of the main model of the rig components and the sub-models of the TSF, and the sensing element respectively.

In all model schematics, the direction of heat flow is self explanatory. Heat flows in axial and radial directions as represented by black signal lines (without arrows). It was assumed in the
model that all components were in perfect thermal contact such that there was no thermal resistance at the interface of components. Arrowed lines denote the flow of signals in the Simulink environment whilst lines without arrows represent the flow of signals in the Simscape environment. SPS and PSS-Signal converter blocks were employed to convert signals between the Simscape and the Simulink environments of the model.

Ideal temperature sensors were attached in parallel to each component and sub-components of the test rig (such as in Figure 6.7) to determine the modelled heating and cooling temperature profiles. The modelled heat flow rate was measured with a heat flow meter connected in series with each component and sub-component (as shown in Figure 6.6)

<table>
<thead>
<tr>
<th>Inputs</th>
<th>A model, a solver, Temperature Boundary Conditions and Modelling Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outputs Main</td>
<td>Temperature and resistance of sensing element</td>
</tr>
<tr>
<td>Outputs Supporting</td>
<td>Heat flow rate and temperature drop across all components.</td>
</tr>
</tbody>
</table>

### 6.4.3.1 Main Model

Figure 6.5 presents the main model of the rig components, which are connected in a series network. From the hotplate to the upper copper plate, transfer of heat occurs only by conduction. From the surface of the upper copper plate to the environment, transfer of heat occurs by convection and radiation. Along the edges, heat transfer occurs only by convection. Radiation along the edges was assumed to be negligible. The environmental component further comprises of convective and radiative blocks which were attached in parallel to each other.

The SPS-Signal converter block was employed to convert signals from Simulink to the Simscape environment, as can be seen in two instances i.e. the conversion of experimental input data (extreme left side) and the conversion of constant room temperature (extreme right side).

The error block calculates the error between the experimental and the modelled temperatures of the sensing element. The scope block (model output) presents a graphical display of the
temperature profiles of all the test rig components, temperature error profile of sensing element and the modelled temperature-resistance curve.

In order to solve the model in terms of its system variables, the solver configuration block was connected to the main model by creating a branch point. The default solver, the standard solver ode15s-stiff/NDF (MathWorks 2011c) along with its default parameters was employed to solve the model. “The ode15s-stiff/NDF computes the model’s state at each time step using variable-order numerical differentiation formulae (NDFs). ode15s is a multistep solver, and thus generally needs the solutions at several preceding time points in order to compute the current solution. ode15s is efficient for stiff problems”.

6.4.3.2 Sub-Model of Temperature Sensing Fabric (TSF)

In order to map the nodal diagram of the TSF (explained earlier), the TSF component was modelled in terms of its basic elements i.e. air, textile and the sensing element as shown in Figure 6.6. The TSF comprises of three components i.e. the first textile layer, the sensing element and the second textile layer. Each textile layer is further divided into its basic textile and air sub-components.

The TSF model was connected with the main model through their connection ports as denoted in Figure 6.6 by blue hexagons. The TSF sub-model receives the heat flow signal from the lower copper plate at connection port 01 and (after processing), delivers it to the upper copper plate at port 2, and to the environment (from the edges) at port 3. Each component of the TSF sub-model was further divided into sub components. The temperature ports from 1 to 5 represent the temperature signals of the sub components of the TSF.

Three heat flow sensors are also shown in the model to measure the net heat flow across the TSF as a whole. In order to convert the heat flow signals from Simscape to the Simulink environment, PSS signal converters were employed.

6.4.3.3 Sub-Model of Sensing Element

Figure 6.7 presents the modelling diagram of the sensing element. For ease of understanding, it is shown in terms of its electrical and thermal domains.
The sensing element model was connected with the TSF sub-model through their connection ports as denoted by the blue hexagon. The sensing element sub-model receives the heat flow signal from the lower (first) textile layer at connection port 01 and after processing, delivers it to the upper (second) textile layer at port 2, and to the environment, from the edges, at port 3.

It was discussed earlier that in order to measure the temperature variations in the layers of component, it could be further broken down into several sub-components. Similarly, the sensing element was also broken down into two half sub-components as shown in the thermal domain of the model in Figure 7.7. In order to measure the temperature in the middle of the sensing element, the temperature sensor was connected in parallel.

Connection between the electrical and the thermal domains is represented by the bold orange signal line. The sensing element in the electrical domain acts as a dummy sensing element as its thermal mass is negligible.

Ideal sensors i.e. the voltmeter and the temperature sensors were employed in the electrical and the thermal domains respectively, to measure the voltage drop across the sensing element and its corresponding temperature. These Simscape signals were later converted to Simulink signals through the PSS signals converter.

In order to power the sensing element, a constant current source of 1 mA was also employed. Voltage signals were transformed to resistance by dividing them by the excitation current value.
Figure 6.5: Thermal Model of Rig Components created in Simscape
Figure 6.6: Thermal Model of TSF created in Simscape (the Sensing Element is placed in the middle of the two textile layers)
Figure 6.7: Thermal Model of the Sensing Element created in Simscape (the Electrical and Thermal domains are separated by dotted lines)
### 6.4.4 Parameters values as input to the model

Table 6-6 presents the list of parameters taken from one of the full length experimental repeats of sample W5046S2 (A TSF sample no. 2 made of 50 μm Tungsten wire with 46 inlays). The results and discussion presented in the next section also belong to the same input data as presented in Table 6-6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment Temperature (°C)</td>
<td>21</td>
</tr>
<tr>
<td>Test Duration (minutes)</td>
<td>160</td>
</tr>
<tr>
<td>Initial Temp of Rig Components (°C)</td>
<td>21.05</td>
</tr>
<tr>
<td>TSF Volume (cm³)</td>
<td>28.38</td>
</tr>
<tr>
<td>TSF Mass (g)</td>
<td>6.04</td>
</tr>
<tr>
<td>TSF Thickness (mm)</td>
<td>3.5</td>
</tr>
<tr>
<td>TSF Sensing Length (cm)</td>
<td>8</td>
</tr>
<tr>
<td>TSF Sensing Width (cm)</td>
<td>8.1</td>
</tr>
<tr>
<td>No. Of Inlays (of Sensing Element)</td>
<td>46</td>
</tr>
<tr>
<td>Sensing Element Resistivity (Ωm)</td>
<td>6.50E-08</td>
</tr>
<tr>
<td>Sensing Element Diameter (μm)</td>
<td>50</td>
</tr>
<tr>
<td>Reference Temp (°C)</td>
<td>20</td>
</tr>
<tr>
<td>Coefficient of Resistivity (1/°C)</td>
<td>0.0035</td>
</tr>
<tr>
<td>Top Cu Plate Emissivity</td>
<td>0.1</td>
</tr>
<tr>
<td>Radiation Constant (W/m²K⁴)</td>
<td>5.6703E-09</td>
</tr>
<tr>
<td>Overall Heat Transfer coefficient of Top Cu Plate (W/°C m²)</td>
<td>0.6375</td>
</tr>
<tr>
<td>Cu Plate Thermal Conductivity (W/(m°C))</td>
<td>400</td>
</tr>
<tr>
<td>Cu Plate Specific Heat (J/Kg/°C)</td>
<td>385</td>
</tr>
<tr>
<td>Cu Plate Thickness (mm)</td>
<td>4</td>
</tr>
<tr>
<td>Cu Plate Mass (g)</td>
<td>300</td>
</tr>
<tr>
<td>Air Thermal Conductivity (W/(m°C))</td>
<td>0.025</td>
</tr>
<tr>
<td>Air Specific Heat (J/Kg/°C)</td>
<td>1005</td>
</tr>
<tr>
<td>Air Volume (cm³)</td>
<td>24.17</td>
</tr>
<tr>
<td>Air Mass (g)</td>
<td>0.029</td>
</tr>
<tr>
<td>Air Density (g/cm³)</td>
<td>0.0012</td>
</tr>
<tr>
<td>Textile Thermal Conductivity [W/(m°C)]</td>
<td>0.17</td>
</tr>
<tr>
<td>Textile Specific Heat (J/Kg/°C)</td>
<td>1200</td>
</tr>
<tr>
<td>Textile Volume (cm³)</td>
<td>4.21</td>
</tr>
<tr>
<td>Textile Mass (g)</td>
<td>5.9</td>
</tr>
<tr>
<td>Textile Density (g/cm³)</td>
<td>1.4</td>
</tr>
<tr>
<td>Wire Thermal Conductivity [W/(m°C)]</td>
<td>173</td>
</tr>
<tr>
<td>Wire Specific Heat (J/Kg/°C)</td>
<td>133</td>
</tr>
<tr>
<td>Wire Volume (cm³)</td>
<td>0.0000073</td>
</tr>
<tr>
<td>Wire Mass (g)</td>
<td>0.14</td>
</tr>
<tr>
<td>Wire Density (g/cm³)</td>
<td>19300</td>
</tr>
</tbody>
</table>
6.5 Results & Analysis

6.5.1 Temperature Profiles

Figure 6.8 compares the experimental and modelled temperature profiles (both heating and cooling) of the rig components and presents the error in the experimental and modelled temperature profiles of the sensing element.

The “experimental” sub-plot presents the temperature profiles of the upper and lower copper plates; measured by the thermocouples fastened within the copper plates and the temperature of the sensing element was estimated by taking the average of the temperatures of the two copper plates. The hotplate was set to reach a temperature of 50°C before the start of each test. In order to achieve the set temperature, a sudden heat flow was generated at the start of the heating profile as shown in the “experimental” sub-plot. For a full description of the procedures adopted in the heating and cooling experiments, refer to section 5.2.

The “modelled” sub-plot presents the modelled temperature profiles of the sensing element, the upper copper plate and the TSF sub-components (air and textile) across both sides of the sensing element. In the “modelled” sub-plot, the experimental temperature profile of the lower copper plate was employed as an input to the model. It is important to note that the modelled temperature profiles of a component depend upon the placement of the “temperature sensor block” in the component. The temperature could be measured at the boundaries of or inside a component. For ease of comparison, temperature information of the middle of the components is presented only in the “modelled” sub-plot.

A small error of around 0.3 °C was noted between the air and textile components of the same layer of the TSF under steady state conditions. This could be due to the difference in size and mass of the air and textile components as well as their different thermal properties i.e. the thermal conductivity and specific heat.

The “error” sub-plot in Figure 6.8 presents the error in experimental and modelled temperature profiles of the sensing element. The error profile belongs to the initial phase of heating shows an error as large as 0.75 °C. However, as the rig components approached the steady state, the error profile also stabilised at 0.2 °C.
Figure 6.8: Comparison of Experimental and Modelled Temperature Profiles of Rig Components

Top: Modelled Temperature Profiles
Middle: Experimental Temperature Profiles
Bottom: Error between Experimental and Modelled Temperature Profiles of Sensing Element
Upon the onset of the cooling profile, the error further dropped down and approached zero. It is evident that apart from the error peak in the start of test, the majority of errors are well within the range of 0 to 0.2 °C.

At steady state, the temperature drop across the copper plates was calculated to be less than 0.001 °C. The temperature drop across the sensing element was virtually zero. This means that the textile and air components were mainly responsible for the overall 8 °C temperature drop across the TSF.

### 6.5.2 Heat Flow Rate Profiles

Figure 6.9 presents the modelled heat flow balance at each component of the rig. In the mathematical modelling, a steady heat flow rate was used as a known parameter which was calculated by using the power meter as described in Appendix A. However, there was uncertainty about the heat flow rate across different components of the test rig during transient conditions (heating and cooling). The voltage and current are the key variables of the electrical domain and are important in the analysis of any electrical network. Similarly, the heat flow rate is one of the most important variables of the thermal system along with the temperature. Heat flow information can be related to the temperature drop across components and their thermal resistances and subsequently used for further analysis of test rig behaviour.

Each subplot of Figure 6.9 shows the entrance and escape of heat by various transfer heat mechanisms i.e. conduction, convection and radiation. Since all components were assumed to be in perfect thermal contact with each other, only conduction was considered as the primary mode of heat transfer between the components through their surfaces. Since the edges were not insulated, heat escaped from the edges to the environment by convection. That implies that heat entered into the component by conduction (axially) and escaped to the next component by conduction (axially) and escaped to the environment by convection (at the edges). The “environment” sub-plot of Figure 6.9 shows the total transfer of heat from the surface of the upper copper plate to the environment, in terms of convection and radiation. Radiation heat transfer to the environment from the edges was assumed negligible, because of its lower weighting.
As discussed earlier in this Chapter, in order to achieve the set temperature, the hotplate generated a sudden flow of heat (almost 11 watts) for a short period of time in the initial heating stage. This effect could be seen in the heat flow profiles of subsequent components, in a diffused way. As the hotplate achieved its set temperature value, it maintained the heat flow rate resulting in the steady temperature profiles of all components. With the onset of the cooling profile, the heat flow rate dropped suddenly and approached zero as the rig components attained room temperature. Due to the escape of heat energy to the environment from the edges, the heat that entered the component was always greater than the heat transferred to the next component. This trend can be seen in all sub-plots except the sensing element.

Due to its extremely small mass and high thermal conductivity, the temperature drop across the sensing element was found to be almost zero. Due to the extreme fineness of the sensing element component, the heat transfer to the environment from its edges was practically zero. This is evident from the “sensing element” sub-plot as the heat flow profiles of the input and output were almost superimposed, leaving virtually zero heat flow to the environment.

The axial heat flow output shown in the “top Cu plate” sub-plot was further analysed in the “environment” sub-plot in terms of its convective and radiative proportions. It can be seen that convection was found to be the primary mode of heat transfer comprising 86% of the total heat loss to the environment.

The effect of convective heat flow from the edges can also be seen on the steady heat rate of the subsequent component. Steady heat flow rate gradually reduced from 1.02 watt (lower copper plate) to 0.72 (upper copper plate) as presented in Table 6-7. It can be observed from the table that out of the total heat energy which entered into the component, 92% flows into the next component by conduction while 8% flows out by convection to the environment. Overall, 1.02 watts entered the lower copper plate from the hot plate, 0.29 watt escaped from the edges and 0.73 watt escaped from the surface of the upper copper plate to the environment by convection.
Heat enters into the component by conduction (Axially)
Heat escapes from the component by conduction (Axially)
Heat escapes from the component by convection (Edges)

Figure 6.9: Heat Flow Rate through the Components of the Test Rig
Table 6-7: Heat flow rate balance at the rig components at steady state

<table>
<thead>
<tr>
<th>Rig Components</th>
<th>Heat entered (watt)</th>
<th>Heat escaped axially (watt)</th>
<th>Heat escaped radially (watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Copper Plate</td>
<td>1.02</td>
<td>0.94</td>
<td>0.08</td>
</tr>
<tr>
<td>TSF Layer 01</td>
<td>0.94</td>
<td>0.86</td>
<td>0.08</td>
</tr>
<tr>
<td>Sensing Element</td>
<td>0.86</td>
<td>0.86</td>
<td>0</td>
</tr>
<tr>
<td>TSF Layer 02</td>
<td>0.86</td>
<td>0.79</td>
<td>0.07</td>
</tr>
<tr>
<td>Upper Copper Plate</td>
<td>0.79</td>
<td>0.73</td>
<td>0.06</td>
</tr>
<tr>
<td>Environment</td>
<td>0.72 (total)</td>
<td>0.62 (convective)</td>
<td>0.1 (radiative)</td>
</tr>
</tbody>
</table>

6.5.3 Temperature-Resistance Relationship

Figure 6.10 and Figure 6.11 present a magnified view of the experimental and modelled temperature-resistance curves around the region of 35 °C. Moreover, the 95% confidence interval of their fitted lines along with their subsequent 95% temperature confidence interval at 35 °C is also presented. It can be seen that both curves seem to be identical due to the insignificant differences in their slopes, intercepts and r-square values. Experimental resistance at 35 °C was found to be 135.35 ± 0.02 Ω as shown in Figure 6.10.

Because of the presence of a small error (<0.2 °C) in between the experimental and the modelled temperatures of the sensing element, the modelled resistance at 35°C was found to be slightly lower (i.e.135.30 ± 0.00 Ω) than its experimental counterpart as shown in Figure 6.11.

Figure 6.11 demonstrates that the modelled temperature-resistance curve is a perfectly straight line without any associated uncertainties in either the slope or the intercept. This was predicted, since the modelled resistance was simulated from the following linear relationship:

\[
R_T = \frac{4\rho_{20}[(L_s W_s D_c) + L_s]}{\pi d^2} (1 + \alpha_{20}(T - 20))
\]  

(6.23)

Furthermore, the virtual sensors employed to measure the voltage across the sensing element, were ideal and free from instrumentation error. In practice, a perfect linear straight line would never be possible because of random measurement errors.

Considering the insignificant differences between the experimental and the modelled temperature-resistance curves, it could be concluded that the temperature of the sensing
element may be estimated by taking the mean of the upper and lower copper plate temperatures.

Figure 6.10: Experimental and fitted Temperature Resistance curves (Cooling+Heating, W5046S2)

Figure 6.11: Modelled and fitted Temperature Resistance curves (Cooling+Heating, W5046S2)
6.6 Discussion

6.6.1 Thermal Contact Resistance

In mathematical and Simscape modelling, it was assumed that all rig components and sub-components were in perfect contact with each other and there was no temperature drop at the boundaries. In practice this would never happen. Even highly polished metal contact surfaces suffer some temperature drop.

Thermal contact resistance depends upon contact pressure, interstitial materials and surface roughness, waviness, flatness, deformations, and cleanliness (Cengel 2003). Contact pressure plays an important role in reducing the thermal resistance. The higher the contact pressure, the larger will be the contact area between the two surfaces. This would lead to increased contact conductance and decreased thermal resistance. This means that the 8 °C of temperature drop at steady state across the TSF was not entirely due to the TSF thermal resistance but is the result, to some extent, of contact thermal resistance between the copper plates and the TSF.

For instance, at a hotplate temperature of 55 °C, in the absence of the TSF, the temperature drop between the copper plates was found to be around 0.6 °C; mainly because of contact thermal resistance. The contact thermal resistance between the TSF and the copper plates would be even higher. However, whatever the contact thermal resistance presents between the copper plates and the TSF, it would not affect the approach to estimate the temperature of the sensing element. Since the contact thermal resistance of the couplings between the lower copper plate and the TSF, and between the TSF and the lower copper plate would be the same, it would therefore cancel out their effects when estimating the temperature of the sensing element.

6.6.2 Nodalisation of the TSF

The TSF is composed of textile material, a sensing element and air. The thermal properties of each element, the volume occupied by these elements and their masses are different from each other. Therefore a conceptual model of the TSF was created by considering the mass and volume of the sub-components corresponding to the basic elements of the TSF i.e. air, textile and the sensing element. This conceptual model of the TSF could be adapted for any double
layer fabric for thermal modelling purposes (irrespective of their structure), provided the dimensions or mass of the sub-components are known.

At an earlier stage of transient modelling of the rig components, the TSF was considered as one component. The error between "modelled" and “experimental” wire temperature at steady state was calculated to be 0.4 °C. This is almost twice as much as when the TSF was considered as a composite product. This further proved that considering the TSF as a composite instead of one component helped to estimate the temperature of the sensing element more accurately.

### 6.6.3 Heat transfer through the TSF

Heat transfer through textiles is a very complex phenomenon. In reality, the overall heat transfer through a textile specimen is the sum of the heat transfer through the fibre plus the heat transfer through the air gaps, which may involve various transport mechanisms including conduction, radiation and convection (Li and Zhu 2003). Considering the domain of this thesis, only conductive heat transfer was modelled through the TSF because heat transfer coefficients associated with convective and radiative mechanisms were not known. Determination of these coefficients was beyond the scope of this thesis as this requires exact information of fabric structure, yarn structure and air gaps.

### 6.6.4 Excitation Current

Excitation current is an important parameter of the electrical domain of the modelling. High excitation currents may affect the temperature profile of the sensing element and ultimately the corresponding resistance. The multimeter employed in the test rig used a 1 mA current rating to measure the resistance of the TSF. Therefore the same rating was employed in the modelling. In order to see the effect of self heating on the temperature profiles of rig components, a model was also run on increased current ratings. It was concluded that a maximum current of 10 mA could be used to power the sensing element without any significant variations in the temperature-resistance curve. Similarly, it would not be suggested to use a TSF in a practical environment with an excitation current of over 10 mA.
6.6.5 Boundary conditions

The boundary conditions of the model include the temperature profile of the lower copper plate, the environmental temperature, and the initial temperature of the rig components. Although the temperature profile of the lower copper plate is the primary boundary condition, the room temperature and the initial temperature of the rig components may also have significant effects on the modelled temperature profiles of the rig components. In order to map the modelled temperature profiles on the experimental ones, both these conditions are quite important.

Experiments were performed over the duration of a couple of years. It was not possible to maintain the temperature of the laboratory over this entire time period. However efforts were made to maintain the temperature in between the range of 18-22 °C. Usually along the length of one test, variation in room temperature was well within ±0.5 °C. Room temperatures were also recorded during the test. In the case of modelling of particular experiments, the recorded room temperature was used as an input to the model.

Before the run of simulations, it was necessary to describe the initial temperature information of all the rig components, which could be different from the environmental temperature. Sometimes the starting value of the experimental temperature of the lower copper plate was noted to be slightly higher than the room temperature. This usually happened with the second or third test of the day. The second or third test of the day was usually started without waiting for the rig components to achieve room temperature as this could take several hours. Therefore the lowest value of the lower copper plate temperature at the start of an experiment was considered to be the initial temperature value of all the components of the rig for modelling purposes.

6.6.6 Generalisation of Results to all data

Although the results and discussion are limited only to a single full length test and its modelled counterpart, the same trends have been observed in the remaining repeats. It is important to note that for development of modelled data of a particular test repeat, the associated sample parameters and boundary conditions of the model have to be changed according to the experimental and sample data i.e.
• **Sample Parameters**
  - Properties of sensing element \((\alpha_{20}, \rho_{20}, \text{density}, \text{mass}, \text{length})\)
  - Sensing element inlay density
  - Dimensions of TSF
  - Mass of TSF

• **Boundary Conditions**
  - Room temperature
  - Initial temperature of all components
  - Input temperature profile of lower copper plate.

### 6.6.7 Comparisons of Mathematical and Simscape Modelling

This section compares the Mathematical and Simscape models in terms of heat flow rate, TSF thermal conductivity and the heat transfer coefficient between the upper copper plate and the environment.

The thermal conductivity of the TSF can be estimated using Fourier’s law, once the information about the TSF thickness, surface area, heat flow rate and temperature drop are known.

\[
k = \frac{QL}{A\Delta T}
\]

Apart from the heat flow rate, the rest of the parameters are the same in both the Mathematical and Simscape models. This implies that the thermal conductivity of the TSF depends only on the heat flow rate passing through the TSF, in a direct manner.

\[
k \propto Q \quad (6.24)
\]

Similarly, the heat transfer coefficient between the upper copper plate and the environment can be estimated using Newton’s law of cooling once the information about the copper plate surface area, heat flow rate and temperature drop are known.

\[
h = \frac{Q}{A\Delta T}
\]
Apart from the heat flow rate, the rest of the parameters are the same in both the Mathematical and Simscape models. This implies that the heat transfer coefficient between the upper copper plate and the environment directly relates to the heat flow rate between the upper copper plate and the environment.

\[ h \propto Q \quad \text{(6.25)} \]

### 6.6.7.1 Heat Flow rate

In the Mathematical model, the edges were assumed to be insulated. This implies that the heat flow rate across each piece of the rig was the same:

\[ Q_{hp} = Q_{cp1} = Q_{tsf} = Q_{cp2} = Q_{env} \]

In order to approximate the actual testing scenario, in the Simscape model, the edges were not insulated. Therefore heat was also lost to the environment through the edges in such a way that the heat energy passing through each proceeding component would always be less than the earlier component.

\[ Q_{hp} > Q_{cp1} > Q_{tsf} > Q_{cp2} > Q_{env} \]

This disparity has been explained graphically in Figure 6.12 along with its effect on calculated values of the TSF thermal conductivity \( k_{u/f} \) and the heat transfer coefficient between the upper copper plate and the environment \( h_{env} \).

### 6.6.7.2 TSF Thermal Conductivity

In the Mathematical model, 1.21 watts of heat was flowing through the TSF. In the Simscape model, the same parameter was estimated to be around 0.86 watt (average of input and output of axial heat flow rate through the TSF as mentioned in Table 6-7). According to equation (6.24), the heat flow rate and the thermal conductivity are directly related. Therefore the thermal conductivity, calculated in the Mathematical model \( (k_{tsf-mm}) \), was higher in value than the thermal conductivity calculated in the Simscape model \( (k_{tsf-ssc}) \) as shown in Figure 6.12.
In the actual experimental set-up, the edges were not insulated, therefore the thermal conductivity value estimated using the Simscape model \( (k_{tsf-ssc}) \) was closer to reality. This can further be validated when comparing \( k_{tsf-ssc} \), with the TSF thermal conductivity values measured by experiment \( (k_{tsf-exp}) \). The TSF thermal conductivity measured using the Alambeta instrument was found to be in the range of 0.043 to 0.044 W/m°C. The process of measurement of experimental thermal conductivity is explained in detail in Appendix B.

\[
Q_{tsf-mm} = 1.21 \text{ w} \\
k_{tsf-mm} = 0.065 \text{ w/m°C} \\
Q_{env-mm} = 1.21 \text{ w} \\
h_{env-mm} = 7.34 \text{ w/m²°C} \\
Q_{tsf-ssc} = 0.86 \text{ w} \\
k_{tsf-ssc} = 0.046 \text{ w/m°C} \\
Q_{env-ssc} = 0.72 \text{ w} \\
h_{env-ssc} = 4.44 \text{ w/m²°C} \\
\]

Figure 6.12: Comparison of Heat Flow rates, Thermal conductivity of TSF and Heat Transfer Coefficient (Mathematical Model vs. Simscape Model)

6.6.7.3 Coefficient of heat transfer

In the Mathematical model, 1.21 watts of heat was lost to the environment from the surface of the upper copper plate. In the Simscape model, the same parameter was estimated to be around 0.72 watt (sum of radiative and convective heat flow rates as mentioned in Table 6-7). According to equation (6.25), the heat flow rate and the heat transfer coefficient are directly
related. Therefore the heat transfer coefficient, calculated in the Mathematical model \( h_{env-mm} \), was higher in value than the heat transfer coefficient calculated in the Simscape model \( h_{env-ssc} \) as shown in Figure 6.12.

The modelled heat transfer values could not be verified by experimentation as the experimental measurement of heat transfer coefficient was beyond the scope of this study. However, modelled heat transfer coefficient values \( h_{env-mm} \) and \( h_{env-ssc} \) are well within the typical range of heat transfer coefficient in a free convection environment i.e. \( 2-25 \, \frac{w}{m^2\cdot ^\circ C} \) (Cengel 2003).

### 6.7 Conclusion

- Considering the insignificant differences between experimental and modelled temperature-resistance curves (<0.2 °C), it could be concluded that the temperature of the sensing element could be estimated by taking a mean of the upper and lower copper plate temperatures.
- It was concluded from the Simscape modelling, that a maximum of 10 mA current could be used to power the sensing element without any significant variations in the temperature-resistance curve. Similarly it would not be advised to use the TSF in a practical environment with an excitation current of over 10 mA.
- This conceptual model of the TSF could be adapted for any double layer fabric for thermal modelling purposes (irrespective of its structure), provided the dimensions or mass of the sub-components are known. Similarly the SSC Model could also be used to closely estimate the thermal conductivity of any textile structure.
Chapter 7  
Thermal Time Constant, Effect of Humidity and Strain

7.1 Introduction

In earlier chapters, the effect of temperature on TSF performance was investigated. In those experiments, temperature was considered as an independent variable while resistance was a dependent variable. However, there are other independent variables, which may affect the TSF performance (by affecting the dependent variable i.e. resistance) such as humidity and strain. It was also discussed in the literature review that external parameters such as strain and humidity may influence the sensing performance of Resistance Thermometers (RTDs).

In the case of using a TSF in a practical environment, due to body movement and in close proximity to the humid skin environment, TSF performance may deteriorate. Before using a TSF for skin temperature measurement, it was therefore important to investigate the effect of strain and humidity on TSF performance in the laboratory environment. This chapter also includes the comparison of the thermal time constant (thermal response) of TSF samples, which is one of the important base line specifications of any temperature sensor.

7.2 Effect of Strain

7.2.1 Introduction

It was important to study the effect of different mechanical effects (such as tensile force and bending) on the TSF sensing performance because mechanical loads on a TSF can disturb the inlaid wire, resulting in resistance variations because of either wire-to-wire contact along the edges of the TSF, or change in resistivity of the metallic wire by permanent deformation of its molecular lattice. Under extreme load conditions, a TSF may fail to perform because of wire breakage. This section presents the effect of strain on the performance of TSF. Two kinds of strain test i.e. tensile and bending were performed on a purpose-designed test rig.
7.2.2 Methods and Materials

Since, there was no standard available to be used as a benchmark to design the strain test, a specifically-designed test rig was developed.

The test rig (strain rig) was designed by considering the requirements:

- it should provide standard repeatable testing conditions (such as different levels of extension and bending of TSF); and
- it should facilitate the strain and resistance measurement process.

The strain-rig was made with a pair of jaws, one of which was moveable, guided by parallel tracks fastened on a wooden board as shown in Figure 7.1. The clips were mounted on both jaws to hold the TSF fabric by its non-sensing area. One of the jaws was fixed while the other jaw was allowed to move to produce the required stretch or bend in the fabric. Tensile and bending tests were performed on the strain-rig by the displacing the movable jaw from its initial position. Moving the moveable jaw away from the fixed jaw produced extension in fabric, while bringing it towards the fixed jaw produced a bend in the fabric. In order to measure the length of a TSF fabric during a tensile test, a length measurement scale was also marked beside the tracks.

In order to see the effect of any independent variable on other dependent variables, it is important that remaining independent variables should be uniform during the test. Similarly, in order to quantify the strain-dependent resistance, the TSF temperature should be constant throughout the test, otherwise it would add error to the measurement. Since the setting of the jaw position involved manual handling which may increase the TSF temperature because of transfer of heat from the human body to the TSF, a five minute pause was allowed between each new setting of the jaw position so that the TSF could regain thermal equilibrium with the room.

An Agilent 34401A multimeter along with a four-wire resistance measurement connector was employed to measure the TSF resistance during the strain testing.

7.2.2.1 Tensile Test Procedure

The tensile test was performed by exerting the tensile forces on a non-sensing area of the TSF (by moving the adjustable jaw away from the fixed jaw) as shown in Figure 7.1 and by
manually measuring the extension of the TSF fabric along with the corresponding resistance. The extension of the TSF sample was calculated by considering the initial ($L_i$) and final ($L_f$) lengths of the TSF (distance between the clamps):

$$\text{Extension} \% = \left( \frac{L_f - L_i}{L_i} \right) \times 100$$  \hspace{1cm} (7.1)

**Figure 7.1:** Tensile strain testing on strain-rig

**Figure 7.2:** Bending strain testing on strain-rig
7.2.2.2  Bending Test Procedure

The bending test was performed by producing a bend in the sensing area of the TSF by moving
the adjustable jaw towards the fixed jaw as shown in Figure 7.2 and by manually measuring the
bending height of the TSF fabric along with the corresponding resistance. Image A of Figure
7.2 shows the various levels of bending test. The height of bending curvature (as shown in
image B of Figure 7.2) can be related to the bending stresses experienced by the TSF. The
height of bending curvature was calculated from the neutral position when the TSF was in a
relaxed condition before the test.

7.2.3  Result and Discussion

Figure 7.3 and Figure 7.4 present the TSF performance during extension and bending,
respectively. For ease of understanding and comparison, the resistance values acquired during
the strain tests were converted into temperature by making use of the calibration equation for
the respective TSF sample.

From the results of both bending and tensile testing, it can be seen that TSF samples made with
bare wire sensing elements (such as nickel, tungsten and nickel-coated copper) showed more
variation in their resistance in comparison with the insulated sensing elements (such as
braided, enamelled copper and nickel). These variations can be attributed to the wire-to-wire
contact at the edges due to the unsatisfactory bending of the sensing element during TSF
manufacturing as shown in Figure 7.5. When the fabric is strained, the bending region along
the edges may induce errors by making or losing wire-to-wire contact. It is important to note
that wire-to-wire shorting problems were only observed along the edges. If the sensing
element touches itself in the main sensing area, then a large variation in resistance would
occur.

The variations in the TSF sample made of insulated copper may be related to its low nominal
resistance and sensitivity values as discussed in detail in Chapter 5. TSF samples inlaid by
insulated sensing elements and specified by high sensitivity (such as braided, enamelled Ni 61)
did not show any significant variation.
Figure 7.3:  TSF performance during a tensile test

Figure 7.4: TSF performance during a bending test
7.2.4 Conclusion

The TSF samples made of insulated sensing wire were found to be unaffected by strain-dependent resistance errors, it may thus be a better option to incorporate them in the practical environment, in preference to the TSF sample made with bare sensing wires.

7.3 Effect of Humidity

7.3.1 Introduction

During the TR testing, the humidity of the environment was maintained within the range of 40% ± 5% R.H. However, the intended application of the TSF is for the measurement of human skin temperature. Due to evaporation of sweat from the skin of the human body, the relative humidity next to the skin tends to be higher than the relative humidity in the environment, as discussed in the literature review. The presence of high humidity near the skin may increase the moisture content of the TSF and affect the sensing characteristics of the TSF. Therefore this section studies the influence of high humidity on the sensing performance of TSF.

7.3.2 Methods and Materials

Instruments employed in this experiment were: a multimeter (for the measurement of TSF Resistance); an Oregon Scientific Weather Station (For measurement of room temperature and humidity); and a digital balance (for measurement of the TSF mass).
All experiments were performed in a conditioned laboratory (equipped with Mitsubishi Mr. Slim air conditioner and Hygromatik hygrometer) in which a thermal environment of 30 to 90% Relative Humidity (RH) was created at a room temperature of 20 °C. The initial laboratory RH level of 65% was raised to 90% by adjusting the Hygrometer settings. After the laboratory achieved the 90% RH and maintained it for an hour, the environment temperature and the mass & resistance of the TSF were noted. After that Hygrometer was turned off, allowing the RH level of the lab to drop gradually to 30%. This whole procedure took more than 15 hours. The environment temperature and the mass & resistance of the TSF were noted at various humidity levels between 90% and 30% of RH. The temperature of the lab during the whole duration of test was measured to be in between the range of 20 to 22 °C.

7.3.3 Result and Discussion

Figure 7.6 presents the effect of relative humidity on the relative increment of the TSF mass due to the increase in moisture. The relative mass of the TSF was calculated with 32% RH as the base value. It can be seen from Figure 7.6 that the relative mass of the TSF is directly related to the relative humidity in an exponential manner. This relationship was more pronounced at high humidity levels. At 65% RH, the average relative increment of mass of all TSF samples was found to be somewhere between 0.2 and 0.3% which is low in comparison to the documented moisture regain of polyester i.e. 0.4% at 20 °C and 65% RH (Sekhri 2011). This error can be related to the initial RH value (32%) used to calculate the relative increment of the TSF mass. Once the completely dry weight of the TSF is known, the above-mentioned error may be reduced further.

Figure 7.7 presents the effect of RH on the sensing performance of the TSF (in terms of error in temperature measurement). In order to understand and compare the effect of air humidity on TSF performance, resistance values of TSF acquired at various humidity levels were converted to the corresponding temperature values by making use of their respective calibration equation. The temperature values measured by the TSF were then compared with the temperature values noted by the Oregon Scientific Weather Station. The difference between the two temperature values was plotted against the relative humidity in Figure 7.7. It can be seen from the plot, that the relative humidity did not affect the TSF performance significantly. The temperature error was found to be in the range of ±0.15 °C and random in nature. The error of ±0.15 °C may be considered as acceptable considering the uncertainties associated with the: uniformity of the
thermal environment, the measurement of temperature by the room hygrometer and the measurement of temperature by the TSF (calibration error and resistance measurement error).

![Relative Humidity and TSF Mass](image1)

**Figure 7.6:** Moisture Regain of TSF at various humidity levels

![Relative Humidity and TSF Performance](image2)

**Figure 7.7:** Effect of Relative Humidity on TSF Performance

One of the possible reasons for the insignificant effect of humidity on the TSF performance may be related to the extremely low moisture regain of polyester. The moisture regain of cotton is 7% under standard conditions (20 °C and 65% RH), which is much higher than polyester (Sekhri 2011). In the case of using cotton as a base material, the TSF might have experienced large measurement errors in different humidity environments because due to the high moisture content of the cotton insulation, the inter-wire resistance would reduce and leak the excitation current during measurement. This would measure artificially low resistance values and
eventually show a lower temperature than in reality. From the above-mentioned results and discussion, it can be seen that choosing polyester over cotton as the base material of the TSF was a sound decision.

7.3.4 Conclusion

- The moisture content of the TSF increased exponentially, with an increase of environmental humidity.
- The effect of relative humidity on TSF performance was found to be insignificant. The temperature error was random in nature and was well within the range of ±0.15 °C.
- TSF made with insulated wire as well as bare wire sensing elements could be used in a high humidity environment without any compromise in their sensing performance.

7.4 Thermal Time Constant

7.4.1 Introduction

The Thermal Time Constant (TTC) is one of the most important baseline specifications of a temperature sensor, especially when the measurement environment has a high frequency of temperature variation. It can be defined as the time required by the temperature sensor to reach 63% of the final temperature value. TTC describes the speed of dynamic response of a temperature sensor to an instantaneous step change in the thermal environment. Errors in temperature measurement may arise if the TTC of a sensor is greater than the frequency of temperature variation. Therefore it was important to know the TTC of a TSF before its employment in a practical environment. The objectives of the TTC experiment were to observe the effect of: the form of sensing element (bare, enamelled or textile-wrapped wire); the size, mass, and structure of the TSF; and the changes caused by the inlay density (the wire content in the TSF); on the TTC of TSF.

7.4.2 Methods and Materials

The standard methods to measure the TTC of the sensor are based on introducing a temperature sensor into a temperature controlled liquid or gaseous environment (BS EN 60751 2008). It was not possible to create a gaseous thermal environment on a laboratory scale. While a liquid environment did not seem to be a practical idea, considering the construction of the
TSF. However, similar to the test rig methodology, a thermal environment based on solid contacts may be developed to measure the TTC of a TSF. Therefore the thermal environment was created by sandwiching a TSF between two solid materials, at a higher temperature than the TSF.

The components employed in the experiment (along with their initial conditions) were:

- a hotplate - whose surface temperature was maintained at 50 °C;
- a ceramic slab - preheated (in an oven) at 50 °C;
- a multimeter – for TSF resistance measurement;
- TSF samples - conditioned at room temperature.

As the TSF was sandwiched between a hotplate (below) and a ceramic slab (above) as shown in Figure 7.8, it began receiving the heat energy in the form of a step input. The resistance data were recorded during this period until the TSF achieved steady state. Resistance profiles of all samples were measured in exactly the same way.

![Experiment to measure the thermal time constant of a TSF](image)

**Figure 7.8:** Experiment to measure the thermal time constant of a TSF

### 7.4.3 Result and Discussion

#### 7.4.3.1 Result

The dynamic resistance profiles of the TSF were converted into temperature profiles by making use of their respective calibration equations. In order to compare the TTC of different TSF samples, absolute temperature profiles were scaled (between 0 and 100) to normalise the temperature profiles. Figure 7.9 to Figure 7.11 present the thermal response profile (scale of 0
to 100) of various samples along with TTC values measured at 63% and 95% of the final temperature.

![Figure 7.9: Thermal Response profile of TSF (34 inlay samples)](image)

![Figure 7.10: Thermal Response profile of TSF (46 inlay samples)](image)

![Figure 7.11: Thermal Response profile of TSF (samples of different size)](image)
The thermal response of the 46 inlay samples was found to be marginally faster (lower TTC) than the 34 inlay samples as shown in Figure 7.9 and Figure 7.10. The thermal response of relatively large size samples was found to be marginally slower (higher TTC) than the smaller size samples as shown in Figure 7.11. The effect of the sensing element (metal type, mass, diameter) on the TTC was found to be insignificant.

7.4.3.2 Discussion

TTC is directly related to the thermal mass (product of mass and specific heat) of a material and inversely related to the surface area:

\[ \text{TTC} \propto mc \]

Table 7-1 lists the thermal masses of components of the TSF. It may be noted that although a great variation is present in the thermal masses amongst the various sensing elements used to develop the TSF, this difference was not evident in the thermal response profiles as presented in Figure 7.9 to Figure 7.11. It is also evident from Table 7-1 that the thermal mass of the textile component is much higher than the thermal masses of the air and the sensing element. This implies that only the thermal mass of the sensing element may not be used to get an idea of the TTC of the TSF; it is the textile component of the TSF which is the governing factor in defining the TTC of the TSF. The much higher mass of the textiles would make the overall TTC of the TSF much higher (slower in response) than the TTC of the sensing element (faster in response). On the basis of the experimental results and theoretical calculations, it can be concluded that the overall TTC of the TSF could be reduced by developing a thin TSF of small surface area (or small sized TSF).

Since the procedure to create a thermal environment based on solid contact, was not explained in the literature, a custom-made method was developed to measure the TTC of TSF. It is important to note here that the TTC measured by this method should not be compared with the TTC measured by standard methods. For example, the standard thermal environment for measuring the response time of RTDs are; flowing water with a velocity > 0.2 m/s; or flowing air with a velocity of 3 ± 0.3 m/s (BS EN 60751 2008). Therefore the TSF could not be compared to industrial temperature sensors in terms of TTC. However, the designed method could be used to compare the TSF samples in terms of size, thickness and mass of TSF.
Table 7-1: Thermal mass of TSF components i.e. textile, air and sensing element

<table>
<thead>
<tr>
<th>TSF Component</th>
<th>Specific Heat (J/Kg.K)</th>
<th>Mass (g)</th>
<th>Thermal Mass (J/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textile (in 46 Inlay TSF)</td>
<td>1200</td>
<td>5.90</td>
<td>7.080</td>
</tr>
<tr>
<td>Textile (in 34 Inlay TSF)</td>
<td>1200</td>
<td>6.43</td>
<td>7.716</td>
</tr>
<tr>
<td>Air</td>
<td>1005</td>
<td>0.03</td>
<td>0.030</td>
</tr>
<tr>
<td>127 µm Ni coated Cu (in 46 Inlay TSF)</td>
<td>385</td>
<td>0.45</td>
<td>0.172</td>
</tr>
<tr>
<td>127 µm Ni coated Cu (in 34 Inlay TSF)</td>
<td>385</td>
<td>0.34</td>
<td>0.131</td>
</tr>
<tr>
<td>125 µm Ni coated Cu (in 46 Inlay TSF)</td>
<td>385</td>
<td>0.43</td>
<td>0.167</td>
</tr>
<tr>
<td>125 µm Ni coated Cu (in 34 Inlay TSF)</td>
<td>385</td>
<td>0.33</td>
<td>0.126</td>
</tr>
<tr>
<td>100 µm Nickel (in 46 Inlay TSF)</td>
<td>460</td>
<td>0.38</td>
<td>0.177</td>
</tr>
<tr>
<td>100 µm Nickel (in 34 Inlay TSF)</td>
<td>460</td>
<td>0.28</td>
<td>0.127</td>
</tr>
<tr>
<td>90 µm Nickel (in 46 Inlay TSF)</td>
<td>460</td>
<td>0.22</td>
<td>0.100</td>
</tr>
<tr>
<td>90 µm Nickel (in 34 Inlay TSF)</td>
<td>460</td>
<td>0.16</td>
<td>0.075</td>
</tr>
<tr>
<td>80 µm Tungsten (in 46 Inlay TSF)</td>
<td>133</td>
<td>0.37</td>
<td>0.049</td>
</tr>
<tr>
<td>80 µm Tungsten (in 34 Inlay TSF)</td>
<td>133</td>
<td>0.28</td>
<td>0.037</td>
</tr>
<tr>
<td>50 µm Tungsten (in 46 Inlay TSF)</td>
<td>133</td>
<td>0.15</td>
<td>0.019</td>
</tr>
<tr>
<td>50 µm Tungsten (in 34 Inlay TSF)</td>
<td>133</td>
<td>0.11</td>
<td>0.014</td>
</tr>
</tbody>
</table>

7.4.4 Conclusion

- The bigger the dimensions of the TSF, the slower will be the response.
- The greater the mass of the TSF, the slower will be the response.
- The type of metal or size and mass of the sensing wire has an insignificant effect on a TTC. It is the textile component that plays a dominant role in increasing the TTC and making the TSF slow in response.
Chapter 8  Testing of Human Body Temperature

8.1 Introduction

Previously, laboratory scale experimental results of TSF, have been presented and discussed. In particular, the Temperature-Resistance relationship of all the TSF samples have been analysed statistically. This chapter provides information about TSF behaviour under actual working conditions, when used for extended periods of time and how its performance compares with the reference temperature sensor. The chapter begins by describing the preparation of TSF samples and the development of testing software for measurement of Human Body Temperature (HBT). Then, the performance of the TSF will be analysed by measuring the human body skin temperature under steady-state and dynamic conditions. The last section of this chapter will discuss the results in general.

8.2 Materials and Methods

8.2.1 Reference Temperature Measurement System

In order to assess the performance of TSF in a practical environment, it was necessary to employ a reference temperature measurement system. A foil RTD made with a platinum element was used as the reference temperature sensor as shown in Figure 8.1. This sensor is especially designed for surface temperature measurement. In order to acquire the RTD signals, a data logger especially designed for RTD (PT-104 by PicoTech) sensors was also employed. According to the specifications of the RTD sensor and the data logger, their combined accuracy, when close to 35 °C, was ±0.22 °C.

Figure 8.1: Reference Temperature Measurement System
A) A foil RTD with a platinum element  B) A PT-104 data logger for the foil RTD
8.2.2 TSF Temperature Measurement System

In order to acquire the temperature data from the TSF, an Agilent 34401 Multimeter was employed as a data-logger. It is the same instrument which was used to measure resistance during R-T testing. In operation, it acquired the resistance signals from the TSF and displayed them as temperatures after processing the calibration equation of a particular TSF sample.

The calibration equation of a TSF sample can be created by first generating the regression equation of Resistance(R) and Temperature (T) data acquired during rig testing (as explained in chapter 5) in the following form:

\[ R = MT + B \]  \hspace{1cm} (8.1)

and after rearranging the constants, converting the regression equation into a calibration equation as:

\[ T = \left( \frac{1}{M} \right) R - \left( \frac{B}{M} \right) \]
\[ T = PR - N \]  \hspace{1cm} (8.2)

where M and B are the slope and the intercept of the regression equation, whilst \((P = \frac{1}{M})\) and \((N = \frac{B}{M})\) are the constants of the calibration equation (8.2). Each TSF sample would have a different calibration constant, which should be calculated before using it in the application scenario.

8.2.3 TemPCorder (Temperature Recording Interface)

The computerised instruments used for measurement of the temperature of the TSF and the reference sensor have their own respective software suites for measuring and recording data. However, the requirement of this experiment was to visualise the temperature and resistance signals in one application.

The PT-104 data logger and Agilent Multimeter were also supplied with driver routines and a selection of examples of how to use these drivers with different languages such as C, C++, Visual Basic and LabVIEW. By calling and modifying the example LabVIEW files of both
instruments, a customised PC interface for the measurement and recording of TSF and RTD temperature data was developed in a LabVIEW environment.

The consequence of this development is the provision of a capability to visualise and record the temperature data along with a date and time stamp during the Human Body Test sequences.

![Figure 8.2: Temperature Recording interface (TemPCorder) created in the LabVIEW environment](image)

The Graphical User Interface (GUI) was styled to view the real time temperature data of the TSF and reference sensor (RTD) in various formats as shown in Figure 8.2. This customised interface was named the TemPCorder (Temperature Recorder).

**Operation of TemPCorder:** Initially, it was necessary to ensure that the PT-104 datalogger and the multimeter had been successfully connected with the PC and were switched ON. Step by step instructions to run the TempCorder interface are listed below.

- Open the TemPCorder interface.
- Set the Data Acquisition (DAQ) rate using the knob.
- Insert the calibration constants of the particular TSF sample in use.
• Run the program by pushing the START button. It displays a file dialogue box for initialisation of a text data file at the specified path. Type the file name and save.
• Straight away, measurement data are accepted along with a time stamp. Real time data can be viewed in tabular, graphical and indicator form.
• When the required length of test has come to an end, press the STOP button.
• Open the data file in Excel and analyse the data.

8.2.4 Preparation of Sample

In order to deploy the TSF samples for human body testing, the samples required some preparation. Figure 8.3 explains all the steps of the sample preparation process.

It was discussed in chapter 4 and 5 that a screw type four-wire-connector was employed for resistance measurement during Temperature-Resistance (TR) testing. However, using a screw type connector for human body testing was not an appropriate choice because of its size and shape. Moreover the connection point of the sensing element to the connector would always be different and may add an unavoidable offset in to the temperature measurement (see sections 4.4.2.2 and 5.6.3 for further details). In order to address this problem, it was decided to attach a tiny dedicated connector on the TSF, such as a Molex connector. This would not only provide the fixed connecting point but also offers an improvement in the measurement process in comparison to a screw connector.

Initially, the ends of the sensing element of each TSF sample were few centimetres apart (depending upon the dimensions of the TSF), as shown in image A of Figure 8.3. In order to connect the ends of the sensing element to the Molex connector, it was important to bring both ends of sensing element close to each other as shown in image B of Figure 8.3. Therefore both ends of the sensing element were routed towards the non-sensing area of the TSF by inlaying (using a sewing needle) the sensing element manually along the edges. Subsequently, the ends of the sensing element were soldered to the Molex connector (see image C of Figure 8.3), which was already bonded to the required position with polyacrylate cement.

The highly sensitive TSF samples made of insulated sensing element (i.e. BEN6146) were employed to assess the TSF performance in actual environment. BEN6146 samples were chosen because of their better performance in the laboratory TR experiments and the strain testing.
Figure 8.3: Various stages of sample preparation for human body testing.

A) TSF with ends of sensing element widely separated;
B) ends of sensing element routed together;
C) ends of sensing element soldered to Molex connector;
D) Velcro pads attached at non sensing area of TSF;
E) Velcro pads sewn to stretchable fabric belt;
F) TSF fastened to belt by Velcro.
In order to facilitate the measurement process of human body temperature and to maintain the TSF pressure on the skin, a stretchable fabric belt was prepared as shown in images D and E in Figure 8.3. In order to fasten the TSF sample on the fabric belt, Velcro pads were sewn on the non-sensing area of the TSF and on the belt as shown in images D and E in Figure 8.3.

### 8.3 TSF Performance in Steady State

After the preparation of the TSF samples and the development of the Temperature Recording Software (TemPCorder), various experiments to measure the human body skin temperature were performed. This section describes the TSF performance in a steady state by performing two types of experiment.

- The effect of “pressure applied by the TSF on skin” on “TSF temperature measurement”.
- Estimating the thermal conduction error in the TSF temperature measurement by comparing it with a standard temperature sensor (RTD).

In order to rule out any variations in pressure because of body movement (such as respiratory effort), limbs (arm and thigh) were chosen as a measurement site instead of the torso in the above mentioned experiments. During steady state testing, the subject was relaxed and comfortably seated.

#### 8.3.1 Effect of Pressure

##### 8.3.1.1 Introduction

The pressure applied to a human body by wearing a cloth is known as clothing pressure. Skin temperature registered by a TSF deployed on a human body depends upon the quality of its thermal contact with the skin of human body. This thermal contact may be enhanced by increasing the pressure applied by the TSF on the skin. Therefore knowledge of the TSF pressure is important while assessing its sensing performance.

##### 8.3.1.2 Method and Materials

Clothing pressure is usually measured by inserting a flexible pressure sensor (such as an air pack) into the region between the skin and the clothing (Kobayashi, Oi et al. 2011) (Hyewon,
Pressure may be applied by stretching the fabric or by applying pressure circumferentially (such as by using a blood pressure measurement cuff).

Experiments were performed by considering the arm and thigh as measurement sites. A pressure cuff, used for blood pressure measurement was exploited to apply the required pressure circumferentially around the limb as shown in Figure 8.4. The Oxford Pressure Monitor (OPM MK II) was employed to measure the pressure applied by the TSF on the skin. The Oxford Pressure Monitor is an electro-pneumatic interface pressure measuring device with a 20 × 20 mm inflatable sensor.

First the pressure sensor was affixed to the specified body part. Then the TSF-attached-fabric-belt was wrapped around the limb and kept in place with the Velcro. Then the cuff was wrapped on top of the fabric belt. A rubber bulb (attached to the cuff by a tube) was used to inflate the cuff by blowing air into it as shown in Figure 8.4. The inflated cuff increased the TSF pressure on the Skin.

Tests were performed at various pressure settings in the range of 0 KPa and 4 KPa. During each pressure setting a pause was introduced to allow the temperature readings to become steady. When the temperature readings were stable, the pressure was increased. During pressure testing, the subject was relaxed and comfortably seated, but was aware of the increasing pressure and tightening at the experimental location.

### 8.3.1.3 Results and Discussion

Figure 8.5 and 8.6 present the relationship between the temperatures registered by the TSF in response to its pressure on the skin. It can be seen that pressure applied by the TSF on the skin improved the thermal contact and hence registered an increased TSF temperature. The number of temperature readings taken at set pressure values can be related to the time required to achieve thermal equilibrium. The time required to achieve thermal equilibrium at low pressure values was greater than at high pressure values. Another important observation can be made, that the TSF temperature increased more rapidly up to a defined pressure range (2-2.5 Pa). At higher pressure, very little temperature increase was observed. It can be concluded that clothing pressure plays an important role in the estimation of skin temperature.
In the literature review, it was discussed that in order to measure the temperature of any surface, the thermal contact of a temperature sensor with the surface should be as good as possible. Similarly, for skin temperature measurement, the TSF must have good thermal contact with the skin, which can be improved by applying adequate clothing pressure.
However, clothing pressure is not a constant quantity and is different at different regions of the body and also varies with respect to time due to body movement. The factors upon which clothing pressure depends are: clothing design, fabric structure, fabric material, size and shape of the body, and body movements (Hyewon, See-Jo et al. 2007). Additionally, air movement can also affect clothing pressure considerably.

Considering the above-mentioned factors, it may not be possible to have constant clothing pressure at specific body positions during different body movements. This implies that the quality of thermal contact between the TSF and the skin would not always be constant. Due to this irregular thermal contact, the temperature registered by the TSF would also possess movement artifacts.

8.3.2 Thermal Conduction Error

8.3.2.1 Introduction

It was discussed earlier that the sensing element is inlaid exactly in the middle of a 3.5 mm thick TSF. Which means the sensing element will never be in contact with the skin, even if the TSF is completely affixed to the skin with some sort of adhesive.

Depending upon the overall thermal resistance between the sensing element and the skin, there will always be temperature drop from the skin to the sensing element of the TSF, which can be termed thermal conduction error. This terminology can be related to the stem conduction error related to the RTD and thermocouple probes.

This experiment will estimate the thermal conduction error in the TSF temperature measurement by comparing it with a standard temperature sensor (RTD) in a steady state environment under standard conditions.

8.3.2.2 Materials and Methods

In order to rule out any artifacts generated by respiratory efforts, the thigh area was selected as the measurement site, as mentioned in respect of the earlier experiment. A constant pressure of about 1 KPa was applied and maintained by the blood pressure cuff in order to rule out any variation in thermal contact between the TSF and the skin.
The first reference temperature sensor was attached on the thigh region. Then the TSF-attached fabric-belt was wrapped around the thigh and kept in place with Velcro. Then the cuff was wrapped on top of the fabric belt and inflated to maintain a constant pressure of 1kPa. Both the RTD and the TSF were in full contact with the skin in this experimental situation. After achieving thermal equilibrium, the temperature of both the TSF and the RTD were measured for few minutes. After a while, the RTD position was changed. The newly-positioned RTD was between the TSF and the Belt. In this phase of the test, the RTD was not in contact with the skin whilst the TSF was in full contact with the skin. During testing, the subject was relaxed and comfortably seated.

8.3.2.3 Results and Discussion

Figure 8.7 presents the temperature profiles of the TSF and the RTD in both phases of the experiment. In the first phase the TSF showed a thermal conduction error of 1.3 °C in comparison to the RTD. The drop in TSF temperature can be attributed to the overall thermal resistance between the TSF sensing element and the skin. After changing the position of the RTD sensor, in the second phase of the experiment, the RTD temperature dropped from 31 to 28.5 °C. Considering the new position of the RTD, its temperature drop can be attributed to the overall thermal resistance of the TSF.

It can also be seen in Figure 8.7, that the new position of the RTD disturbed the thermal equilibrium between the TSF and the skin for a short time, as witnessed by a brief downward peak. Apart from that, the TSF temperature profile remained constant throughout the test with a conduction error of 1.3 °C.
Figure 8.7: TSF performance in steady state
(TSF sample of high Nominal Resistance – BEN6146)

Heat Flow Direction in both phases of the test
Phase 01: [Skin → RTD → TSF → Belt → Cuff → Environment]
Phase 02: [Skin → TSF → RTD → Belt → Cuff → Environment]

Figure 8.8: TSF performance in steady state
(TSF sample of low Nominal Resistance – BEC15046)

Heat Flow Direction in both phases of the test
Phase 01: [Skin → TSF → RTD → Belt → Cuff → Environment]
Phase 02: [Skin → RTD → TSF → Belt → Cuff → Environment]
Figure 8.8 presents the same experiment, but this time the order of positioning of the RTD was changed. In the first phase of the experiment, the RTD was sandwiched between the TSF and the fabric belt. While in the second phase, the RTD was placed in between the TSF and the skin. The drop in temperature in both experiments was found to be more or less the same.

The only noticeable difference between Figure 8.7 and Figure 8.8 is the quality of the temperature reading registered by the TSF. The temperature profile of the TSF in Figure 8.7 is smoother than in Figure 8.8 which may be related to the nominal resistance and sensitivity of the TSF samples employed in these tests. In the first test, a TSF sample of nominal resistance of 110 Ω was used (see Figure 8.7). However, a low TSF sample (about 4 Ω) was used in the second test (see Figure 8.8). This observation can also be related to the results of laboratory testing in which TSF samples of high nominal resistance showed less regression uncertainty in comparison to the TSF samples of low nominal resistance.
8.4 TSF Performance in the Dynamic State

8.4.1 Introduction

In the previous section, TSF performance in the steady state was discussed during which the subject was sitting comfortably, relaxed and stationary. In order to avoid the effect of respiratory effort, the limbs (arm and thigh) were chosen as measurement sites. Furthermore, no change in the external thermal environment of the TSF was made, and apart from the fabric TSF and belt, no extra layers of clothing were worn. This section presents the TSF performance in a dynamic state by considering the effects of factors such as body movement, respiratory chest movement, clothing layers, and the external environment.

8.4.2 Materials and Methods

The chest area, beneath the arm was selected as a measurement site because it not only provided a broad surface to place the TSF but it was also less prone to respiratory movements in comparison with other possible sites on the torso. Figure 8.9 shows the TSF placed on the lateral chest wall along the mid-axillary line, just below the armpit. Another advantage of the measurement site is that the external environment of the TSF area can be changed by forcing the arm to contact the lateral chest wall or be stretched out as shown in Figure 8.11.

Figure 8.9: TSF placement on lateral chest wall of torso for skin temperature measurement

The first reference temperature sensor (RTD) was attached at the measurement site, as described above. Then the TSF-attached fabric belt was worn around the chest and kept in place with Velcro as shown in image A of Figure 8.11.
8.4.3 Results and Discussion

8.4.3.1 Test 01

In this test, the subject wore only a TSF-attached belt. The subject was stationary and sitting comfortably on the chair. However, the subject was allowed to move his arm, between the relaxed and extended positions as shown in images A and B of Figure 8.11. The temperatures profiles from this test are shown in Figure 8.10.

As discussed earlier, the TSF temperature is prone to thermal conduction error and will register lower temperatures than the actual skin temperature. This can be further verified by examining the temperature profiles of the TSF and RTD in Figure 8.10. However, the most important observation to be noted here is that the reference and TSF sensor both followed exactly the same trend and experience the same quality of movement artifacts.

Although the subject was seated on a chair, nonetheless, respiratory efforts and arm movement affected the temperature profile. The major abnormalities in both temperature profiles, as highlighted by the dotted circles, were related to the arm movements. Sometimes the arm was in full contact with the lateral chest wall, sometimes in half contact, and sometimes in the outstretched position. Arm movement not only disturbed the thermal contact between the sensors and the skin, but also influences the external thermal environment near the measurement site.
Figure 8.10: TSF performance in dynamic environment (Test 01)

Heat Flow Direction

[Skin → RTD → TSF → Belt → Environment] with arm movement

Figure 8.11: Subject arm movement while wearing different layers of clothing
8.4.3.2 Test 02

This experiment was performed to investigate the effect of clothing and arm position on the performance of the TSF in comparison with the reference temperature sensor (RTD). The temperatures profiles deriving from this test are shown in Figure 8.12, along with indications of the three phases of the test.

<table>
<thead>
<tr>
<th>Test Phase</th>
<th>Heat Flow Direction</th>
<th>Subject</th>
<th>Duration (Minutes)</th>
<th>Temp Profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>[Chest → RTD → TSF → Belt ↔ Arm]</td>
<td>Sitting relaxed</td>
<td>10</td>
<td>Smooth Diff: ±0.2 °C</td>
</tr>
<tr>
<td>B</td>
<td>[Chest → RTD → TSF → Belt → Shirt ↔ Arm]</td>
<td>Sitting relaxed</td>
<td>23</td>
<td>Smooth, Diff: ±0.2 °C</td>
</tr>
<tr>
<td>C</td>
<td>[Chest → RTD → TSF → Belt → Shirt → Jacket ↔ Arm]</td>
<td>Sitting relaxed</td>
<td>10</td>
<td>uneven Diff: ±0.2 °C</td>
</tr>
</tbody>
</table>

As can be seen from the above settings, the only difference between the phases of the test is the extra clothing worn by the subject during the test. In phase B the subject wore the T-shirt on top of the fabric belt, whilst in phase C, the subject wore a (wind-breaker) Jacket in addition to the fabric belt and T-shirt as shown in Figure 8.11.

According to Figure 8.12, the difference between the TSF and RTD temperatures throughout the test were not as significant as in earlier experiments, which may be related to the position of the subject’s arm which, throughout the full length of the test, was rested straight in parallel to the lateral chest wall as shown in images A, C and E of Figure 8.11. This arm position not only reduced the effects of environmental temperature on the temperature profile of the sensors but also provided an additional heating and pressure source to help bring the temperature of the sensors closer to the skin temperature.

The layers of clothing helped to reduce the difference between the TSF and RTD temperatures by reducing the effect of the environmental temperature and improving the isothermal conditions near the measurement site. With each added clothing layer, the thermal equilibrium point was increased slightly. Almost a 2 °C increment in temperature was observed with additional clothing. However it is important to note that the arm was pressed against the body...
all the time. In the case of other body measuring sites such as the front chest wall, the equilibrium point would be different.

It can be seen from Figure 8.12 that both temperature profiles experienced a few abnormalities as highlighted by the dotted green circles. The explanations of these abnormalities are:

- the subject wore the T-shirt from around the 11th minute of the test;
- between minutes 22 and 28, the subject stretched out his arm from its resting position for few minutes (see image D of Figure 8.11) and then returned it to the normal position;
- the subject wore the Jacket from around the 40th minute of the test.

As a consequence of having to put on the extra clothing, the subject’s arm was displaced from its resting position. This reduced the thermal contact of the TSF and the skin and disturbed the thermal equilibrium in the proximity of the TSF resulting in the lowering of the TSF temperature.

8.4.3.3 Test 03

This experiment was performed to investigate the effect of clothing and body movement on the performance of the TSF in comparison to the reference temperature sensor (RTD). The
Temperature profiles from this test are shown in Figure 8.13 along with the marking of the five phases of the test. The five phases of the test are explained in the following table.

<table>
<thead>
<tr>
<th>Test Phase</th>
<th>Heat Flow direction</th>
<th>Subject</th>
<th>Duration (Minutes)</th>
<th>Temp Profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Chest ↔ RTD ↔ TSF ↔ Belt ↔ Shirt ↔ Jacket ↔ Arm</td>
<td>Sitting relaxed</td>
<td>3</td>
<td>Smooth</td>
</tr>
<tr>
<td>B</td>
<td>Chest ↔ RTD ↔ TSF ↔ Belt ↔ Shirt ↔ Jacket</td>
<td>Sitting relaxed</td>
<td>2</td>
<td>Smooth, slightly drop (0.2 °C)</td>
</tr>
<tr>
<td>C</td>
<td>Chest ↔ RTD ↔ TSF ↔ Belt ↔ Shirt ↔ Jacket</td>
<td>Standing and random body movement</td>
<td>3</td>
<td>Uneven, slightly drop (0.3 °C)</td>
</tr>
<tr>
<td>D</td>
<td>Chest ↔ RTD ↔ TSF ↔ Belt ↔ Shirt</td>
<td>Standing and random body movement</td>
<td>9</td>
<td>Uneven, extensive drop (1 °C)</td>
</tr>
<tr>
<td>E</td>
<td>Chest ↔ RTD ↔ TSF ↔ Belt</td>
<td>Standing and random body movement</td>
<td>5</td>
<td>Uneven, extensive drop (1.6 °C)</td>
</tr>
</tbody>
</table>

It is evident from Figure 8.13 that Phase A in which the subject was wearing a shirt and jacket, and was sitting relaxed with his arm pressed against the lateral chest wall, is the most stable among all phases of the experiment. As the subject started to remove the layers of clothing and started executing random movements, the temperature profiles of both sensors became irregular and fell in comparison with the temperature values at the start of the test. Figure 8.14 presents some photographs of phase C of test 03 when the subject was making random body movements while standing.
Figure 8.13: TSF performance in a dynamic environment (Test 03)

Figure 8.14: Images of phase C of test 03 while the subject made random body movements
8.5 Discussion

8.5.1 Comparison of TSF and Reference Temperature Sensor (RTD)

It is evident from all steady state and dynamic experiments that choice of measurement site, movement of subject, layer of clothings, TSF pressure on skin and external environment affected not only the performance of TSF but also the reference temperature sensor. Even a RTD sensor of ±0.001 °C accuracy would also experience the dynamics of the application environment while measuring the skin temperature. However, the encouraging sign is that, in each of the test, apart from conduction error, TSF and reference sensor followed the same trend in general.

8.5.2 Errors associated with the Skin Temperature Measurement

In standard conditions, temperature registered by TSF would always be less than the skin temperature because of the:

- Thermal contact error (depends on the thermal contact resistance between TSF and skin);
- Thermal conduction error (depends on the thermal resistance presents between the skin and sensing element (mainly half of the thickness of TSF) and the temperature of outer side of TSF).

Once the values of these errors are known, it can be added into the TSF temperature to estimate the human body skin temperature. Figure 8.15 presents the general scenario of temperature drop between core body temperature and environment as highlighted by yellow marker. It can be seen that the temperature registered by the sensing element of TSF depends upon the environment temperature, thermal contact error, and thermal conduction error. Thermal contact error can be reduced by making a firm contact between TSF and the skin. Thermal conduction error may be reduced by bringing the sensing element (within the TSF) more close to the skin (possibly by producing thin TSF). Environmental effects can be reduced by using extra layers of clothing’s.

However as discussed in detail in literature review, that skin temperature of human body is affected by the dynamic interaction of the parameters of Human Thermal Environment (HTE)
i.e. air temperature, radiant temperature, air velocity, air humidity, layers of clothing, body movement and metabolic heat generation. That means the TSF (or any other temperature sensor) deployed to measure skin temperature would also be affected by the above mentioned parameters. In addition to that the values of the TSF “thermal contact” and “thermal conduction” error would also be changed and may no longer be valid for estimating the skin temperature. It was not possible to assess the TSF performance by varying all HTE factors as it was beyond the scope of this thesis. Probably another PhD study is required to fully assess the TSF performance in practical environment by varying the HTE factors.

This problem is not only limited to the TSF; as any textile based sensor used to measured human body vital sign such as ECG and respiration would also experience movement artifacts in practical applications. These movement artifacts are sometimes even stronger than the weak signal of vital sign. This is probably the main factor which limits the broad applications of the textile based health monitoring systems (Changzhi and Jenshan 2008).

8.5.3 Estimating Core body Temperature by TSF

The Arm pit is an ideal place for measurement of core body temperature as it provides the isothermal environment. However, taking into account of the size and construction of TSF, it would not be appropriate to consider arm pit as a measurement site. First of all its not possible to have uniform thermal contact between TSF and arm pit skin. Secondly arm movement would produce strain to the sensing element and may damage it by frequent movements. Core body temperature can be estimated by measuring skin temperature and heat loss from the body

Figure 8.15: Error scenario while estimating human body skin temperature
and knowing the thermal resistances of skin tissue and clothing layers and using an appropriate algorithm designed to be used in various thermal environments.

### 8.5.4 Proposed Sensing Board

According to the nominal resistance and sensitivity data of the TSF discussed in Chapter 5, it can be asserted that the TSF is a very low resistance transducer. For a large change in temperature, a TSF generates very little change in resistance. Therefore, even a small error in the resistance measurement may contribute a large error in the temperature measurement. As high excitation current should not be used because of the problem of self-heating, only very small changes in resistance are being measured, so it is important to employ the four-wire-Wheatstone-bridge, as used in RTD circuitry.

During TSF testing in a practical environment, a multimeter and connecting wires were employed to acquire the resistance signals which were later converted into temperature readings after applying the calibration equation appropriate for the respective TSF. For TSF testing in various dynamic environments, it is essential to have a dedicated wearable sensing system, connected wirelessly to a PC. Considering the time frame of the study, it was not possible to develop a dedicated sensing system for the TSF. However, the concept of this sensing system has been presented in Figure 8.16 and this includes the TSF, circuit board and temperature display units.

The sensing element of the TSF would sense the temperature and its resistance would change accordingly. The modification of the resistance would be converted into voltage signals by the four-wire Wheatstone bridge circuitry.

A low-pass filter would smooth out the voltage response by removing any unnecessary high frequency noise components. Before converting the signals from analogue to digital, the voltage signal would be amplified using an operational amplifier. Then the signal would be fed to the ADC (Analogue to Digital Converter) of the micro-controller which uses the voltage signals to reveal the resistance of the TSF. After this, the measured temperature can be calculated by using the TSF calibration equation, which was already programmed into the microcontroller. Finally, digital data would be sent out through its SCI (Serial
Communications Interface) to a suitable digital display such as an LCD or could be wirelessly transferred to a PC database or cell phone.

The need for a low excitation current minimises the TSF output voltages, increases the proportion of signal noise and limits the resolution of the temperature signal. However, the avoidance of excessive sensing current may be addressed in another way; by programming the microcontroller to power the TSF in an episodic fashion instead of continuously. Pulsing the sensing element would allow higher currents to be used for a short time. Hence the average current would be reduced, thus minimising the self-heating errors and simultaneously, a higher interrogation current could be used, which would allow more accurate voltage and therefore temperature readings to be extracted.

**8.5.5 Clinical investigation of TSF for Human body temperature measurement**

In order to assess the clinical performance of the TSF and to make it a commercialised product, the following standards need to be considered. The (Draft ISO 80100 2006) standard specifies the requirements and the test procedures for the validation of clinical accuracy for electrical clinical thermometers. The (ISO 14155 2011) standard deals with good clinical practice for the design, conduction, recording and reporting of clinical studies performed on human subjects to evaluate the safety and performance of medical instruments for regulatory purposes. Considering the scope of this standard, it was not possible to perform the above-mentioned task; this may be considered to be relevant future work.
Chapter 9  Conclusions and Future Work

9.1 General Summary & Conclusion

The aim of the study was to develop Temperature Sensing Fabric (TSF) for continuous temperature measurement in healthcare applications. Human body temperature is an important indicator of physical performance and physical condition in terms of comfort, heat or cold stresses. The study covers the development and manufacture of Temperature Sensing Fabric and its performance testing in the laboratory and in an application environment.

Relatively little research has taken place on this topic, therefore apart from statistical analysis of Temperature-Resistance data of the TSF, the work is largely exploratory in nature. The focus of this study was on gaining insights into this new area so that the work may form a firm foundation for further investigations in future.

9.1.1.1 TSF Design and Fabrication

From the review of most common contact temperature sensors, it was demonstrated that the design and measurement principles of the Resistance Thermometers (RTD) can be applied in the development of a Temperature Sensing Fabric (TSF). The review was conducted with emphasis on their design, construction, measurement principles, baseline specifications and application scenarios and especially from the point of view of their integration into textiles.

The design of the TSF was based on the principle (as used in RTD designs) of inlaying a fine metal wire (as a sensing element) within the knitted fibrous structure. The measurement principle of the TSF is based on the inherent property of metal wire to change its electrical resistance with change in temperature.

TSF was fabricated on a 10 gauge Shima Seiki computerised flat-bed knitting machine. Shima Seiki Knit Paint software was employed to design the TSF structure, which is a double layer knitted structure comprised of knit courses, spacer courses and metal inlays with a sensing area of 8 x 8 cm². The knitting machine was not designed to inlay metals; therefore some modifications were made in the feeding of the sensing element in order to embed it smoothly exactly in the middle of the TSF.
From the review, various types of metal used in sensing elements were identified and compared in conjunction with the selection criteria. Ten different types of sensing element were employed to make the TSF samples; either in bare or insulated form, with numerous diameters (from 50 µm to 150 µm) and metals (nickel, copper, tungsten and nickel-coated copper). In terms of inlay density, two types of TSF were developed i.e. 4.7 inlays/cm (low inlay density) and 6.4 inlays/cm (high inlay density). High density TSF has 46 courses of metal inlay whilst low density TSF has 34 inlays. In total more than 60 TSF samples were developed with combinations of ten different sensing elements and two inlay densities.

Highly textured polyester yarn was employed as the base material of the TSF, because of its extremely low moisture regain, high tensile strength, and better wicking properties in comparison to cotton. Moreover, the textured characteristics of the yarn increased the fabric bulkiness and provided better cover of the sensing element.

9.1.1.2 A Modified Temperature-Resistance Relationship

A modified Temperature-Resistance relationship for the TSF in terms of its dimensional parameters was also established which could be used to optimise the dimensions of a TSF patch for a required reference resistance. That will facilitate the specification and visualisation of the sensor characteristics.

9.1.1.3 Manufacturing Uncertainty

The manufacturing uncertainty of the TSF, in terms of the calculated length of the sensing element inlaid in the TSF, was found to be ± 2% from its mean. Considering the tolerance of the knitting process, ± 2% variation in length may not be considered as substantial; however it will produce an uncertainty in reference resistance of same type of the TSF samples. Therefore the TSF samples could not be used as interchangeable sensors i.e. the calibration equation for one sample may not be applied to another sample.

9.1.1.4 Test Rig Development, Modelling and Methodology Error

In order to generate the Temperature-Resistance (TR) relationship of the TSF sample for calibration purposes, a customised test rig apparatus (based on a simplified version of a standard
parallel hotplate method for measurement of thermal resistance of textiles -BS 4745 2005), was
developed. The designed rig employed a constant temperature hotplate with four K-type
thermocouples in order to maintain the TSF fabric at the required temperature. A 4-wire
resistance measurement system was set up to measure and record the minute changes in
electrical resistance. Special software was created in the LabVIEW environment, in order to
record and visualise the temperature and resistance signals side by side.

The experimental T-R relationship of the TSF was validated by the modelling of rig
components (in the thermo-electrical domain) in steady and transient states. A mathematical
model of the rig components was developed under steady state conditions, by the application of
basic heat transfer principles. A transient version of the model was developed in the Simscape
environment which deals in the modelling of temperature profiles of rig components during
heating and cooling.

A maximum error of 0.2 °C was found between the experimental and modelled T-R
relationship which justified that methodology used to estimate the temperature of the sensing
element by taking a mean of the upper and lower copper plate temperatures.

The Simscape model was run with different excitation currents to power the sensing element,
and it was concluded, that a maximum of 10 mA current could be used to power the sensing
element without significant variations in the temperature-resistance curve.

A conceptual model of the TSF in terms of its basic components i.e. air, textile material and the
sensing element was also developed, and this was later utilised in transient modelling in the
Simscape environment. This conceptual model of the TSF could be adapted for any double
layer fabric either for thermal modelling purposes (irrespective of its structure), provided the
dimensions or mass of the subcomponents are known.

9.1.1.5 Thermal Conductivity

The TSF thermal conductivity measured using the Alambeta instrument and calculated in the
Simscape transient environment were found to be in good agreement in the range of 0.043-

\[ 0.046 \text{ W/m°C}. \]
9.1.6 Strain Effects

The effect of tensile and bending strain on the performance of the TSF was also studied on a purpose-made test rig. TSF samples made with bare wire sensing elements showed slight variations in their resistance during strain tests which can be attributed to the wire-to-wire contact at the edges due to the unsatisfactory bending of the sensing element during TSF manufacturing. The TSF sample made with an insulated sensing element did not show any strain-dependent-resistance error.

9.1.7 Humidity Effect

The effect of Relative Humidity (RH) on the performance of a TSF was also studied in the range of 30 to 90% RH. The random temperature error of $< \pm 0.15 \, ^\circ C$ showed that the effect of RH on TSF performance was not significant. TSF made with an insulated sensing element could be used in an environment as high as 90% RH, without any compromise in the sensing performance. One of the possible reasons for the insignificant effect of humidity on TSF performance may be related to the extremely low moisture regain of polyester (0.4% at 65% RH). The moisture content in TSF increases exponentially, with an increase in environmental humidity. The measured moisture content of TSF samples was found to be in close agreement to the documented moisture regain of polyester.

9.1.8 Thermal Time Constant

The Thermal Time Constant (thermal response) of TSF samples was measured using the customised solid contact method. This test was performed to observe the effect on the thermal response of TSF of: the form of the sensing element (bare, enameled or textile wrapped wire); the size, mass, and structure of the TSF; and the inlay density (wire content in the TSF). The effect of metal type, diameter, mass or insulation on the overall thermal response of a TSF was found to be insignificant. However the size of the TSF affected the thermal response of the TSF. The bigger the dimensions and the greater the mass of the TSF, the slower was the thermal response and vice versa.
9.1.1.9  **T-R Relationship**

In-depth statistical analysis of the Temperature-Resistance (TR) relationship of TSF samples was performed by taking into consideration the uncertainties within experimental repeats (regression uncertainty), amongst repeats of the same sample types (repeatability uncertainty), and amongst samples of the same sample type (manufacturing uncertainty).

9.1.1.10  **Regression Uncertainty**

The TSF sample made with a copper-based sensing element showed high regression uncertainty (> ±0.18 °C) in comparison with the TSF sample made with a nickel and tungsten sensing element (< ±0.13 °C). This can be attributed to the multimeter measuring uncertainty (±4 mΩ) and the low sensitivity of copper (<25 mΩ/1 °C). Regression uncertainty in the T-R equation of all cooling tests showed considerably reduced values (±0.07 °C) in comparison with the T-R equation of all heating tests (±0.24 °C). The high uncertainty of heating tests was related to errors in the dynamic thermal environment of the test and the presence of a large thermal gradient across the TSF.

9.1.1.11  **Repeatability Uncertainty**

Repeatability uncertainty describes the degree to which further measurements of the same TSF sample provide similar T-R data. The TSF samples demonstrated the repeatability uncertainty in the range of ±0.1 °C to ±0.5 °C. This minor difference among experimental repeats can be attributed to the variation in factors that are inherent in the T-R experiment such as testing methodology, handling, and measurement uncertainty of the test rig instruments. Factors like inlay density and the sensing element of the TSF were not found to be related to the repeatability uncertainty.

9.1.1.12  **Calibration of new TSF samples**

Since TSF samples are not interchangeable, each individual sample should be calibrated before using it in an application environment. New TSF samples may be calibrated using a 1-point calibration method. In this method, the resistance of the TSF samples would be measured at a reference temperature value \( R_{20} \). Since the database of the temperature coefficient of resistivity \( \alpha_{20} \) of all the sensing elements has already been made available, consequently, the
standard Resistance-Temperature relationship \[ R = R_{20}(1 + \alpha_{20}(T - 20)) \] could be utilised to develop the calibration equation of each TSF sample.

### 9.1.1.13 Comparison of TSF in terms of bare and insulated Sensing Element

In general, the TSF samples made with an insulated sensing element were found to be relatively easy to manufacture (because of their increased tensile strength) and exhibited better sensing performance (because of their insulating properties) in comparison with the TSF samples made with bare wire. The benefits of using an insulated sensing element over a bare sensing element may be usefully summarised.

- **Better Manufacturing**: Ease of handling of wire; Less breakage of wire during knitting; Reduced manufacturing time; No wire-to-wire contact in the TSF; Improved textile character; Possibility of reducing the thickness of the TSF; Possibility of increasing the inlay density
- **Better TSF Performance**: Achieving higher nominal resistance and sensitivity with a small sensing patch (by using a short length of very fine metallic wire); Reduced influence of external parameters i.e. moisture, sweat, strain, corrosion etc; More precise, accurate, and stable temperature measurement; Increased durability and reliability

### 9.1.1.14 Human Body Testing

TSF behaviour over extended periods of time in a practical application and its comparison with the reference temperature sensor was also investigated. The performance of the TSF was analysed by measuring the human body skin temperature under steady-state and dynamic conditions.

In all the human body tests, the reference and TSF sensors both followed exactly the same trends and experienced the same type of movement artifacts. Layers of clothing worn by the subject helped to reduce the difference between the TSF and the reference temperature sensor by reducing the effect of the environmental temperature and improving the isothermal conditions near the measurement site.
The quality of the TSF thermal contact with the skin is the most important parameter in respect of estimating the skin temperature. Thermal contact was found to be improved by increasing the clothing pressure on the skin and was varied by movement of the subject.

9.2 TSF Application Areas

A TSF can be deployed for continuous measurement of body temperature in non-clinical settings e.g. sports, military, general healthcare, firefighting situations and studies related to biorhythms and assessment of thermal strain in extreme environments.

Considering the temperature measurement uncertainly of TSF, it may not be suitable to use in those medical applications in which small difference in temperature (such as ±0.1 °C) are clinically significant. However, it can be used for screening purposes. Once a subject’s TSF temperature profiles have been found to be abnormal, then further investigation may be performed with a more accurate sensor.

The rate of acquisition of temperature signals from TSF depends upon the application environment. Unlike ECG and respiration signals, which are required to be monitored continuously, temperature signals may be acquired periodically e.g. after every few seconds, few minutes or an hour. The only requirement the TSF should fulfil is the achieving of thermal equilibrium so that it can accurately measure the temperature of the measurement body site.

9.2.1.1 Circadian Rhythms

Circadian rhythms are biological rhythms of the human body which are controlled by the biological clock. Most of the biological activities of the human body such as hormone production, cell regeneration, and brainwave activity can be linked to these daily rhythms. Tracking of these biological rhythms can be used to understand the thermoregulatory process and to optimise the disease management process. Core and skin body temperatures are important parameters for studying these rhythms. Recording of skin temperature by TSF at different body sites might be useful for the research related to circadian rhythms.
9.2.1.2 Studies related to the Human Thermal Environment

Research related to the Human Thermal Environment may be considered as potential application areas for TSF. Because the skin temperature and especially the rate of change of the skin temperature has its particular importance in studies related to “Human Comfort” and “Performance Assessment” in different thermal environments especially in Heat and Cold stresses.

9.2.1.3 Heat Flow Measurement

A pair of TSF devices integrated into the internal and external layers of clothing may be used to estimate heat flow by application of Fourier’s law as discussed in the literature review.

9.2.1.4 High Temperature Environments

TSF can also be deployed to measure environmental temperatures in extreme conditions such as below 0 °C and over 100 °C in fire-fighting conditions. For that the TSF needs to be calibrated for the desired temperature range. For high temperature applications, the basal fabric of the TSF also needs to be replaced by fire resistant material such as Nomex.

9.2.1.5 Cooling and Heating Blankets

Hyperthermia and hypothermia are non-invasive treatments, given in the clinical environment to alter the core body temperature. These treatments are usually performed by blankets (cooling or heating) which work both as a thermal medium and as a sensing platform to maintain the required body temperature for extended period of times. A TSF can be integrated into such blankets to measure human body temperature during the treatment.

9.2.1.6 TSF as a Heating Element

A TSF can also be used as a heating element to provide localised warming of the skin. In such circumstances, a high level of excitation current could be employed and would utilise significant energy to provide the heat to the surface.
9.2.1.7 **TSF as an Anemometer**

TSF can be used as a hot-wire anemometer. The hot wire anemometer is the most common type of anemometer, and measures the velocity of fluid by recording the heat transferred away by the fluid. The TSF might act as constant heat anemometer or constant temperature anemometer. The constant heat anemometer measures the change in wire temperature under constant current to obtain the heat lost. Similarly, the constant temperature anemometer measures the current required to maintain the wire temperature to obtain the heat lost. The heat lost can then be used to measure the fluid velocity in accordance with the theory of convective heat transfer.

9.2.1.8 **TSF as a Wet Bulb Thermometer**

A wet TSF could be employed as a *wet bulb thermometer* to measure the wet bulb temperature of an environment. Wet bulb temperatures are usually measured by using a thermometer with the bulb wrapped in damp cloth. The evaporation of water from the thermometer will have cooling effect; therefore the temperature shown by the wet bulb thermometer will always be lower than a dry bulb temperature, except in the case of 100% Relative Humidity when both wet and dry bulb thermometer readings will be identical.

9.2.1.9 **Temperature Measurement of Large Bodies**

Usually standard temperature sensors are small in size. In the case of temperature measurement of large bodies, an array of thermocouples or RTDs is deployed over the surface. However, measuring temperature using a TSF is advantageous in this case because a TSF sample can be fabricated as large as required.

9.2.1.10 **Other non Clinical Applications**

Other possible textile items, into which TSF may be integrated, are electric blankets, bed sheets, mattress, car seats or carpets etc.
9.3 Future Work

- Investigations into the solutions for increasing the quality of thermal contact between the TSF and the skin, to reduce the movement artifacts and to minimise the effects of the environment.

- Improve the robustness of electrical contacts between the sensing element and the lead wire to improve the overall TSF performance in the practical environment.

- Investigation into the performance of TSF to estimate true skin temperature in various thermal environments (by changing parameters such as air temperature, radiant temperature, layers of clothing and air velocity, in order to estimate the thermal conduction error and movement artifacts.

- Investigation into the effect of machine washing cycles on TSF performance.

- Effect of increased moisture (greater than regain) on TSF performance and exploration into the employment of TSF for measurement of wet bulb temperatures.

- Development of new TSF samples based on insulated sensing-elements with decreased thickness and increased inlay density without compromising its textile character. These alterations would produce a small sized TSF patch with high nominal resistance. Thin TSF would also exhibit low thermal conduction errors while measuring the temperature of any surface.

- Development of a “Smart Shirt” using whole garment technology with exact positioning of TSF patches and connecting wires by intarsia technology.

- Development of a dedicated TSF sensing system board along with wireless integration into a standard PC or using a “credit-card-sized” processor.

- Exploring TSF for new application areas such as heating elements, heat flow measurements and for use as an anemometer.
References


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APPENDICES

Appendix A: Hotplate Power Rating

The heat flow rate was calculated by measuring the power consumed by the hotplate at steady state; a power meter was employed for this purpose. The power consumed was measured by plugging the Power Meter into the mains socket and then plugging the Hotplate into the Power Meter. The hotplate employed in the rig was a constant temperature hotplate which tries to maintain its set temperature by switching its heating elements, on or off, automatically. Therefore it was important to measure the power for a known duration and take an average by dividing “the sum of all power values” for the “duration of the test”. The average power required by the hotplate to maintain the rig components at steady state was found to be 3.68 watts. The average power (in watts) can be considered as the heat flow rate. The surface area of the hotplate and the copper plates were 240.25 cm$^2$ and 81 cm$^2$ respectively. This implies that the fraction of the hotplate area covered by the copper plate is only 33%. Therefore, the heat flow passing through the rig components was calculated by multiplying the total heat flow of the hotplate by 33% i.e. 1.21 watts
Appendix B: Experimental Measurement of Thermal Conductivity

In order to gain further understanding between the experimental temperature drop and heat flow rate across the TSF, and the modelled temperature drop and heat flow rate across the TSF, thermal conductivity was also measured experimentally using the Alambeta instrument, which is based on the hot plate method.

Method

Initially, the TSF sample was placed on the bottom copper plate; which was kept at room temperature. While the top plate (positioned at 10 cm distance from the bottom plate) was allowed to heat to achieve a pre-determined constant temperature. Then the top plate was suddenly brought into contact with the TSF sample. Simultaneous contact of the TSF with the hot and cold plates created a temperature difference across the TSF.

The temperatures of both plates were monitored until they achieved a steady state. At this point, the heat flow rate was recorded. The thickness of the TSF sample was also measured according to the position of the top plate. All measurements were measured and recorded using the Alambeta instrument automatically.

Once the temperature information across the TSF, thickness and steady heat flow rate were known, Fourier’s law could be applied to measure the thermal conductivity of the TSF.

Results and Discussion

Since textile fabric is a not a homogenous medium and consists of fibres and air, thermal conductivity does not have its typical specific meaning in textiles. In practice, conduction is the primary mode of heat transfer; however, heat can also be transferred by radiation or convection. In order to calculate the thermal conductivity of the textile material using Fourier’s law, the measured heat flow rate (using the Alambeta instrument) was therefore the overall transfer of heat by conduction, radiation and convection (BS 4745 2005).
The average thermal conductivity of the 34 inlay samples ($0.0441 \text{ W m}^{-1} \text{C}^{-1}$) was found to be slightly higher than the 46 inlay samples ($0.0432 \text{ W m}^{-1} \text{C}^{-1}$). This could be related to the density of the TSF, as the 34 inlay sample possesses almost 9% more mass than the 46, due to the extra spacer yarns in it.

The sensing element has the highest thermal conductivity (over $100 \text{ W m}^{-1} \text{C}^{-1}$), however, because of its extremely low mass and volume, its effect on the overall thermal conductivity of the TSF was found to be insignificant. The governing factors of overall TSF thermal conductivity are the thermal conductivities of textile material and air and their relevant volumes in the TSF. The thermal conductivities of air and textile (Polyester) are $0.025 \text{ W m}^{-1} \text{C}^{-1}$ and $0.17 \text{ W m}^{-1} \text{C}^{-1}$ respectively (James E. Mark 2007). However, because of the high proportion (85%) of air volume in the TSF, the overall thermal conductivity of the TSF was found to be very close to that of air.
Appendix C: Calculation of Dimension and Mass of Sub-components of TSF

%% Description
% This is a script file which breaks the elements of TSF i.e. air, textile and wire into further sub-components, according to the
% conceptual model of TSF. The output of this file will be the input of the rig components model created in Simscape environment.
% The defined sub-components can be considered as 1) Series to each other 2) Parallel to each other 3) in combination of Series
% and Parallel. All parameters which are related to SERIES setting have _ser with their name. Similarly which are related with
% PARALLEL setting have _par with their name.

%% CALCULATION STEPS
% STEP-1: Define Known Parameters
% STEP-2: Calculate thickness of each TSF component in Series
% STEP-3: By Keeping wire in series, calculate THICKNESS, WIDTH and AREA of Air and Textile (as Parallel components)
% STEP-4: Define input of "No. of part system".
% 2 part system means;
% 2 components on Top (1 Textile, and 1 Air)
% 2 components on Bottom(1 Textile, and 1 Air)
% similarly we can define, 4-parts, 6-part, and 8-part systems
% STEP-5: Calculate New THICKNESS, AREA and MASS of Air and Textile components (according to no. of part system)

%% STEP-1: KNOWN PARAMETERS
% cm, Thickness of Temperature Sensing Fabric
% cm, Width of Temperature Sensing Fabric
% cm, Width of Temperature Sensing Fabric
% cm^2, area of Temperature Sensing Fabric
% gram, Measure it by experimentation
% gram, depends upon wire type, wire mass/length, inlay density
% g/cm^3 depends upon wire type
% gram
% g/cm^3 depends upon TSF basal fabric. if possible measure it by experimentation.

%% STEP-2: Calculate THICKNESS of TSF components in SERIES (from mass, Density and TSF dimensions)
% cm, Thickness of TSF wire component as series
% cm, Thickness of TSF textile component as series
% cm, Thickness of TSF air component as series
Calculate Mass of Air

\[
\text{air}\_\text{density} = 0.0012; \quad \text{g/cm}^2, \text{Density of air}
\]

\[
\text{air}\_\text{mass} = \text{air}\_\text{density}\times\text{tsf}\_\text{area}\times\text{air}\_\text{thickness}\_\text{ser}; \quad \text{g}, \text{Depends on air density and thickness of air component in series}
\]

\% STEP-3: Calculate THICKNESS, and AREA of Air and Textile in PARALLEL Setting

\[
\text{air}\_\text{thickness}\_\text{par} = \{(\text{tsf}\_\text{thickness}) - \text{wire}\_\text{thickness}\_\text{ser}\}; \quad \text{cm}, \text{Thickness of TSF air component as Parallel}
\]

\[
\text{textile}\_\text{thickness}\_\text{par} = \text{air}\_\text{thickness}\_\text{par}; \quad \text{cm}, \text{Thickness of TSF textile component as parallel}
\]

\[
\text{air}\_\text{width}\_\text{par} = \{(\text{tsf}\_\text{width} \times \text{air}\_\text{thickness}\_\text{ser})/\text{air}\_\text{thickness}\_\text{par}\}; \quad \text{cm}, \text{Width of TSF air component as parallel}
\]

\[
\text{textile}\_\text{width}\_\text{par} = \{(\text{tsf}\_\text{width} \times \text{textile}\_\text{thickness}\_\text{ser})/\text{textile}\_\text{thickness}\_\text{par}\}; \quad \text{cm}, \text{Width of TSF textile component as parallel}
\]

\[
\text{wire}\_\text{area} = \text{tsf}\_\text{area}; \quad \text{cm}^2, \text{Area of TSF wire as series (its same as tsf\_area)}
\]

\[
\text{air}\_\text{area}\_\text{par} = \text{air}\_\text{width}\_\text{par}\times\text{tsf}\_\text{length}; \quad \text{cm}^2, \text{Area of TSF air as parallel}
\]

\[
\text{textile}\_\text{area}\_\text{par} = \text{textile}\_\text{width}\_\text{par}\times\text{tsf}\_\text{length}; \quad \text{cm}^2, \text{Area of TSF textile as parallel}
\]

\% STEP-4: Define no. of Parts System

\[
\text{no}\_\text{part}\_\text{system} = 4; \quad \% \text{No. of part system. It will define new WIDTH and AREA of Air and Textile components}
\]

\[
n = \text{no}\_\text{part}\_\text{system}/2;
\]

\% STEP-5: Calculate New THICKNESS, AREA and MASS of Air and Textile components in Parallel(according to no. of part system)

\[
\text{air}\_\text{thickness}\_\text{par2} = \text{air}\_\text{thickness}\_\text{par}/2; \quad \% \text{Thickness of air component as Parallel(Minimum 2-part system)}
\]

\[
\text{textile}\_\text{thickness}\_\text{par2} = \text{air}\_\text{thickness}\_\text{par}/2; \quad \% \text{Thickness of textile component as parallel (Minimum 2-part system)}
\]

\[
\text{air}\_\text{width}\_\text{par2} = \text{air}\_\text{width}\_\text{par}/n; \quad \% \text{New Width of air component as parallel}
\]

\[
\text{textile}\_\text{width}\_\text{par2} = \text{textile}\_\text{width}\_\text{par}/n; \quad \% \text{New Width of textile component as parallel}
\]

\[
\text{air}\_\text{area}\_\text{par2} = \text{air}\_\text{area}\_\text{par}/n; \quad \% \text{New Area of air component as parallel}
\]

\[
\text{textile}\_\text{area}\_\text{par2} = \text{textile}\_\text{area}\_\text{par}/n; \quad \% \text{New Area of textile as parallel}
\]

\[
\text{air}\_\text{mass2} = (\text{air}\_\text{mass}/\text{no}\_\text{part}\_\text{system})\times2; \quad \% \text{New Mass of air component as parallel}
\]

\[
\text{textile}\_\text{mass2} = (\text{textile}\_\text{mass}/\text{no}\_\text{part}\_\text{system})\times2; \quad \% \text{New Mass of textile component as parallel}
\]

\% Calculate Sideways Surface area for each TSF components ( to use it in the convective elements along the edges).

\% This is minimum for 2 part system. One Air and one Textile has to be before wire and similarly one after. wire\_s\_area belongs % to the total wire sideways area. While textile\_s\_area belongs to the half of total textile surface area in the TSF that's why % we need to use two convective elements...one before wire and one after.

\[
\text{wire}\_\text{s}\_\text{area} = \text{tsf}\_\text{area}\times\text{wire}\_\text{thickness}\_\text{ser};
\]

\[
\text{textile}\_\text{s}\_\text{area} = (\text{textile}\_\text{width}\_\text{par}\times\text{textile}\_\text{thickness}\_\text{par2})\times2 + (\text{textile}\_\text{thickness}\_\text{par2}\times\text{tsf}\_\text{length});
\]

\[
\text{air}\_\text{s}\_\text{area} = (\text{air}\_\text{width}\_\text{par}\times\text{air}\_\text{thickness}\_\text{par2})\times2 + (\text{air}\_\text{thickness}\_\text{par2}\times\text{tsf}\_\text{length});
\]

\% RUN Script file

```
rig_mod_var
```
Appendix D: T-RYZER (Interface to analyze T-R data)

T-RYZER is a customized program to analyze the experimental and modelled data, created in a MATLAB. This program imports the data file generated by LabVIEW, load the modelling data, convert the primary variables into secondary variables, rename variables according to the test tag, curve fit the experimental T-R curve, generate the fitted and modelled Resistance Ratio, and finally plot the data in four different ways as shown in next page, by just few clicks of the mouse. T-RYZER is capable of analysing one data file at a time.

Plot 1 of the T-RYZER output shows the comparison the experimental and fitted curve and comparison to its modelled counterpart. Modelled and fitted resistance ratio curves are compared in Plot 2. Resistance ratio (RR) is calculated by dividing the fitted resistance $R_T$ at temperature $T$ by its nominal resistance $R_b$ at base temperature $T_b$.

Using RR instead of $R_T$ has several advantages. KTS samples with quite different values of $R_b$ can be compared because they should have similar values of RR. Plot 3 is the histogram of temperature data values and describes the quantity of data values taken during the length of test at different temperatures. Temperature profiles of top Cu plate, bottom Cu plate and TSF are presented in Plot 4. Each plot is tagged with its unique test ID as explained in previous section.
Experimental, Fitted & Modeled T-R curves of TSF: N10341D1A.txt

- Temperature (Degree Centigrade)
- Resistance (Ohm)
  - Experimental
  - Modelled
  - Fitted

Fitted and Modeled Resistance Ratios of TSF: N10341D1A.txt

- Temperature (Degree Centigrade)
- Resistance Ratio
  - Fitted Resistance ratio
  - Modelled Resistance ratio

Histogram of Cu plates and TSF Temperature values: N10341D1A.txt

- Temperature (Degree Centigrade)
- No. of data values
  - TSF
  - Bottom Cu plate
  - Top Cu plate

Temperature profile of copper plates & TSF: N10341D1A.txt

- Temperature (Degree Centigrade)
- Time (Minutes)
  - Bottom Cu plate
  - Top Cu plate
  - TSF

Graphical output of T-RYZER
Appendix E: Thesis Media Files

This appendix contains the thesis media files on a Compact Disc (CD). Media files include the customized LabVIEW interfaces, the Simscape Model and the TSF machine program. A brief summary of the usage of these media files is also included in the disc.