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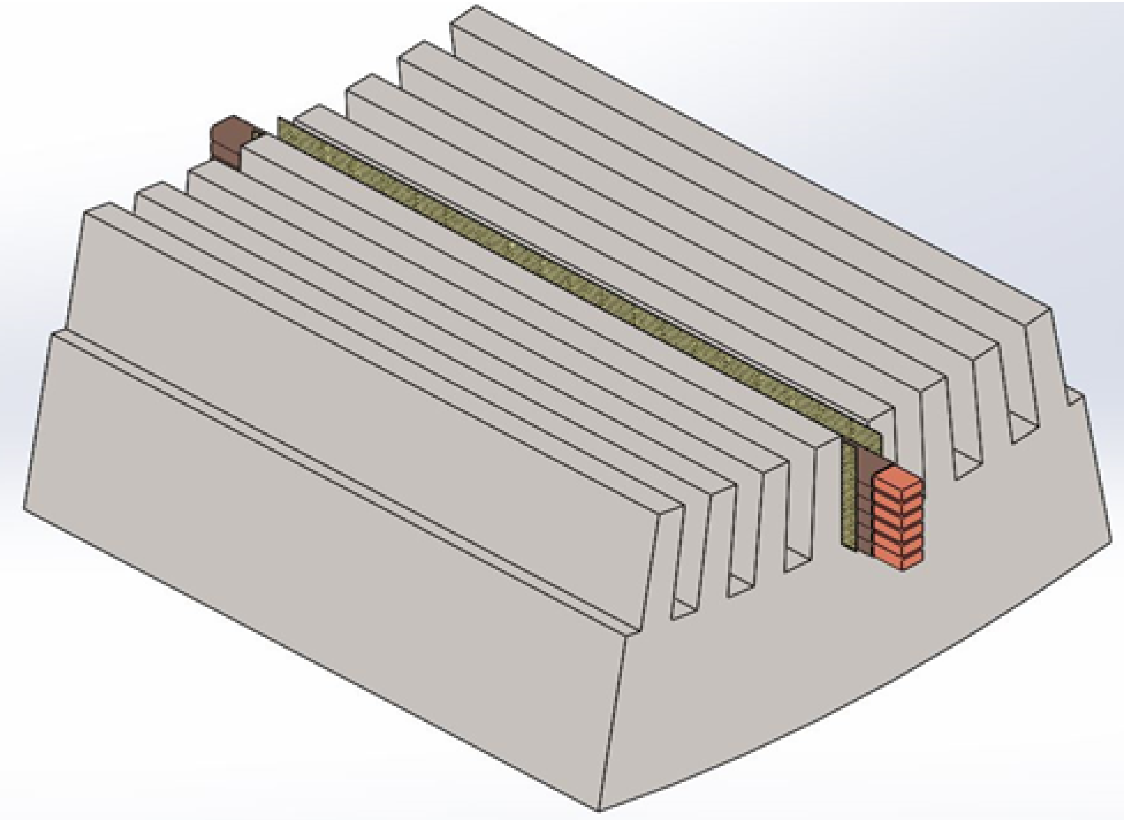

Thermal testing and thermal modelling of electrical insulation system in electric machines

Master's thesis in Electrical Engineering

CHETANKUMAR VEERAYYA SALIMATH

DEPARTMENT OF ELECTRICAL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
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Thermal testing and thermal modelling of electrical insulation system in electric machines

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This report contains the evaluation and method of thermal testing and modelling of electrical insulation system to obtain thermal properties in electric machines.
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Cover: A part of the stator constituting all the elements that form the stator assembly otherwise known as motorette.

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Abstract

The electric machines that are part of propulsion completely or partially based on full electrification or hybrid applications are also known as traction electric machines. Permanent Magnet Synchronous Machines (PMSM) are one of the most popular A/C synchronous motors available today [1]. These machines generate considerable amount of heat during operation and the performance is often limited to avoid excessive heating. Cooling systems are thus introduced to assure these machines are running in designed operational temperatures for extended periods and on peak performance. The cooling system design is based on the the thermal properties of the materials used in these motors. Thus with advancement in material science, defining the thermal properties is important to understand and promote designing appropriate cooling systems around the components.

The objective of this thesis is to evaluate thermal property, specially the thermal conductivity of different electrical insulation system (EIS) materials using an experimental method and then evaluating how different material properties influence the heat transfer. This experimental data is then used to set up the thermal model of the stator in COMSOL and evaluate the thermal conductivity on the materials using the extracted test data. Furthermore, material combinations are proposed which best suit the application.

Keywords: propulsion,thermal properties, temperature, performance,COMSOL.

Acknowledgements

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Chetankumar Veerayya Salimath, Gothenburg, July 2021

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Introduction

1.1 Background

The automotive industry today is changing faster than ever. New regulations have been coming up constantly in order to keep the emissions low as possible by the internal combustion engines. Alternatively, the industries are looking forward to hybridizing the currently complete IC engines and further completely electrifying the vehicles. Performance advantages of electrifying the transport solutions like constant torque from the start, elimination of multistage gearbox is also an advantage alongside eliminating emissions on-the-go.

The advantages of the electric vehicles are often limited by its thermal capabilities. Although electric machines have an efficiency of 85-95% [2] the peak performance of the machine can be attained as long as the machine is not crossing its operating temperature, this goes to say that the machines are quite often limited by its ability to dissipate the heat. The insulation is damaged due to thermal stress further leading to thermal problems in the electric machine. There are few ways to assure longer and best performance from the machine. Electrifying vehicles is comprehensive part of the sustainable transport solutions in the world of commercial vehicle technologies. Therefore in order to achieve high power density and best performance, materials with improved thermal conductivity plays an important role.

1.2 Problem Description

The thesis has the following goals:

- Design a test for comparing thermal conductivity of different insulation systems.
- Perform thermal measurements of the different insulation systems before and after thermal aging of the materials.
- Post process the thermal measurements to evaluate the thermal conductivity of the different insulation systems.
- Setup a model of the motorette in COMSOL.
- Evaluate the thermal properties of the material using the test data in the simulation environment.

1.3 Objective

Thermal conductivity of the electrical insulation system is one factor that limits the power density of the electric machine. This goes to say that lower thermal conductivity worsens the heat transfer. Within this thesis, an experimental method for evaluating thermal conductivity through different electrical insulation systems (different materials, thicknesses, impregnation compounds and these material combinations etc.) shall be developed. Using this same experimental data in the COMSOL environment, the thermal conductivity of different material combination is evaluated.

1.4 Assumptions and Limitations

The samples for design of the test for comparing thermal conductivity is prepared on motorette and not the whole stator. The manufacturing process influences the results. This is important as the Vacuum Pressure Impregnation (VPI) method is used for the impregnation to seal the voids between the slot and the other constituents.

2

Theory

2.1 Fourier's Law of Thermal Conduction

The transfer of Internal energy by the excitation of atoms and further causing vibration to the adjacent atoms otherwise known as lattice vibration in the material is called thermal conduction [3]. Fourier's Law help us to determine the rate of heat transfer ($\vec{q}$) as a function of temperature difference (ΔT), area of cross section of the body perpendicular to the heat transfer and the materials thermal conductivity is represented by (K), the thickness of the material is L. Mathematically, it is represented as follows,

$$\vec{q} = -K * \Delta T \tag{2.1}$$

$$q_x = -K * A * \frac{T_1 - T_2}{L} \tag{2.2}$$

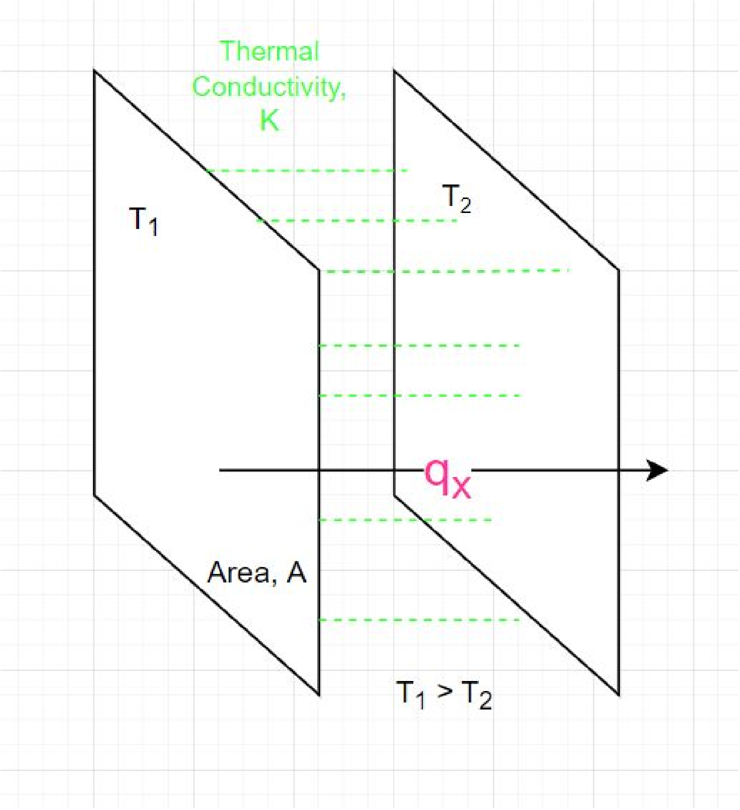

Figure 2.1: Fourier Law representation

2.1.1 Effective Thermal Conductivity

When two different slabs are connected in series to form a composite slab of different thickness L_1 and L_2 and are of different thermal conductivities K_1 and K_2 respectively, made of equal cross section area will result in an equivalent thermal conductivity. The figure 2.2 shows series combination of two different materials.

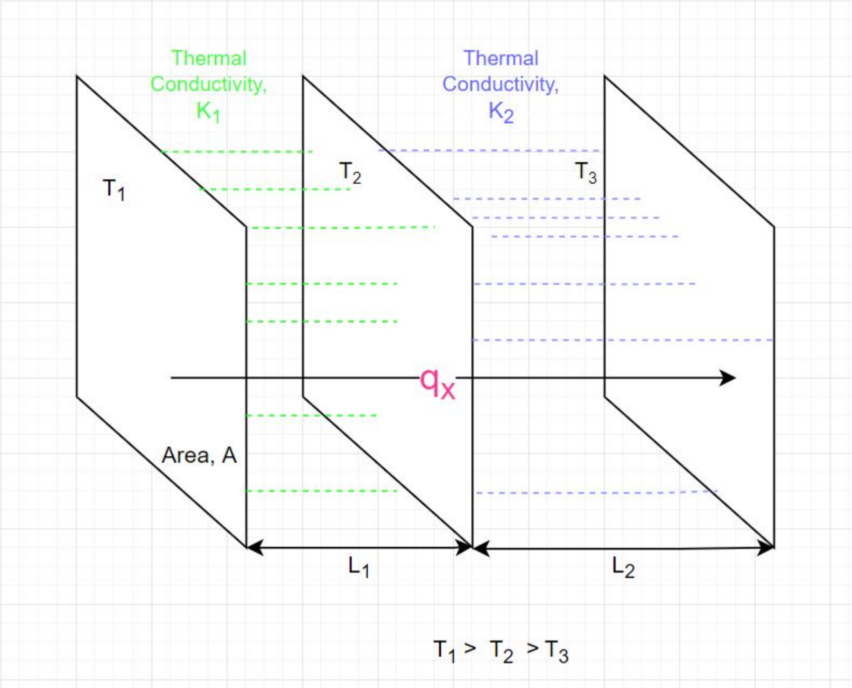

Figure 2.2: Different materials in series combination.

The equivalent thermal conductivity of the slab can be derived as follows using equation 2.1.
The rate of thermal conduction through the first slab is

$$q_1 = K_1 * A * \frac{T_2 - T_1}{L_1} \tag{2.3}$$

The rate of heat conduction through second slab is

$$q_2 = K_2 * A * \frac{T_3 - T_2}{L_2} \tag{2.4}$$

Since the slabs are connected end to end, the heat transfer between them is same.

$$q_x = q_1 = q_2 \tag{2.5}$$

Re-writing the above equation with effective thermal conductivity K_{eff} as follows:

$$K\_eff * A * \frac{T_3 - T_1}{L_1 + L_2} = K_1 * A * \frac{T_2 - T_1}{L_1} = K_2 * A * \frac{T_3 - T_2}{L_2} \tag{2.6}$$

Resolving the equations 2.4, 2.5, 2.6 and eliminating the temperature function in the equation , we get:

$$K\_eff = \frac{L_1 + L_2}{\frac{L_1}{K_1} + \frac{L_2}{K_2}} \tag{2.7}$$

2.2 Electric Machines

An electric machine converts electrical power to mechanical power (or vice-versa) using the electromagnetic forces. Permanent Magnet Synchronous Machines (PMSM) is one of the variant that is most used for wide range of applications. These electromechanical energy converters can be effectively described in mechanical terms constituting of two major components. The rotating part of the machine called **rotor** and the stationary part of the machine called the **stator**. [4]

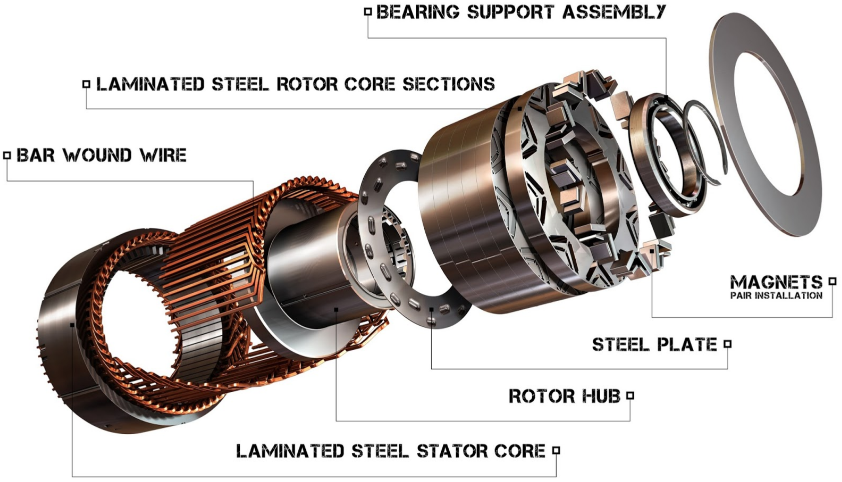

Figure 2.3: Electric motor constituents [5]

The stator consists of three main components, the laminated stator core, the electrical insulation system (EIS) and the copper conductors. The current carrying copper conductors will generate the rotating magnetic field which guides the rotor to rotate around the axis. The important role of the electrical insulation system is to isolate the environment forming a barrier between the windings and between ground and winding. It is a passive component and it helps avoid short circuits between the potential and ground. [6]

2.2.1 Motorette

A small segment of the stator that represents the stator as a whole and includes all the main components that the stator assembly is motorette. It has copper conductors, electrical insulation system, this includes both slot liner, impregnation and insulation layer on the copper conductors and the stator.

This small segment otherwise known as motorette is generally very simple, quick and economically viable to prepare large test segments with variety of combinations to and test the electrical insulation system properties.

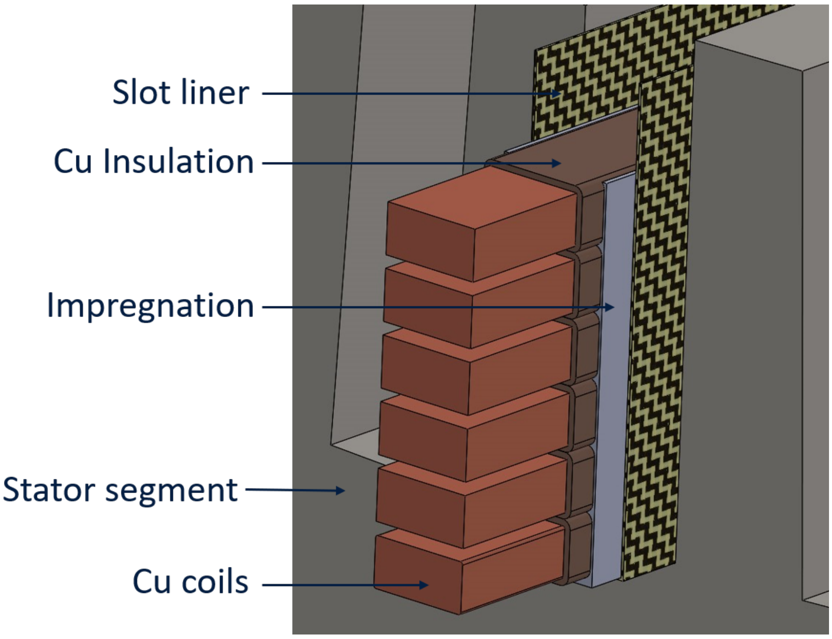

Figure 2.4: Constituents of a motorette

2.2.1.1 Slot Liner

Slot liners are the integral part of the insulation material which isolate the stator core from the copper coils (winding). Slot liners prevent partial discharges and further shorting the copper conductors and the stator. [7]

2.2.1.2 Cu Insulation

Often the Cu conductors in the same slot are connected in different combinations of series and parallel thereby it becomes necessary to insulate each conductors in order to carry the current independent of each other and thereby it becomes necessary to insulate the Cu conductors and aid the current to flow in the desired direction.

2.2.1.3 Impregnation

Impregnation is a process of filling the voids in the electric machine between the stator slots and the Cu conductors with an insulating material. This assures all the Cu conductors are not dangling in the slots due to vibration, alongside the polymer aids in carrying the heat away from the Cu coils. and also provides electrical insulation. [8]

2.3 Partial Discharge

When an insulating material is subjected to high voltage stress, there will be localised partial bridges between the conductors as the result of breakdown of the insulating material causing the partial discharges. All the insulating materials encounter this phenomenon when the applied voltage is greater than the dielectric strength of the material. [9]

2.4 Degradation in Electric Machines

The performance of the electrical insulation system deteriorates over time due to several stresses that the material is subjected to. The four main stresses it is subjected to are called as MATE. These stresses are Mechanical, Ambient, Thermal, and Electrical stresses. Thermal stresses is a key interest in our study. Due to continuous thermal loading of the electric machine while operating, it becomes important to observe the behavioural pattern of the thermal properties of EIS over the time. The materials undergo change in their chemical composition most likely due to oxygen (oxidation) or any other chemicals (coolant oils etc) coming in contact with them. This process causes material deterioration making them brittle and even causing de-lamination especially on the conductor insulation.

2.5 Accelerated Aging Technique

The ideal way to actually study the behaviour of the material properties after aging is to run the vehicle in its normal condition and wait for 10-15 years to be able to undergo the real aging effect on the insulation materials. This is really not feasible solution during the design phase and selecting the material. This can be overcome by accelerating the aging process by increasing the thermal stresses that it is subjected to in the real-time but for shorter period. This gives the ballpark values quickly to study the degradation of the material properties due to aging effect.

The accelerated ageing technique given by Arrhenius equation that co-relates reaction rates to temperatures. To put it into perspective, every 10 °C gives $2X$ faster aging. The Arrhenius equation is given by [10] as follows,

$$Time(Life) = A * e^{\frac{-Ea}{k*T}} \tag{2.8}$$

where,
A = constant determined by test
e = the base of the natural algorithm
Ea = Activation Energy (eV) which varies by failure mechanism
k = Boltzman's constant = $8.62 * 10^{-5}\ eV/K$
T = Temperature in degrees Kelvin (°K)

3

Material Synopses

3.1 Material Information and Designation

Table 3.1: Material Information and its designation

Type	**Material**	**Thickness [µm]**	**Designation**	**Comment**
Copper Insulation	PEEK	230	A1	THICK
	PEEK	130	A2	THIN
Slot Insulation	B1	160	B1	
	B2	270	B2	
	B3	160	B3	
	B4	210	B4	
	B5	210	B5	
	B6	200	B6	
	B7	250	B7	
	B8	230	B8	
	B9	127	B9	
	B10	508	B10	
Impregnation	Standalone Polyester		C1	
	Epoxy + Particles for high heat conduction		C2	
	Polyester + Particles for high heat conduction		C3	

As seen from the table 3.1, there are two variants of the Copper Insulation with 130μm referred as thin PEEK and the 230μm reffered as thick PEEK. There are ten different variants of the slot liners available which are made of different materials and are of different thickness. The primary interest of the study was for B1, B2, B3, B4, B5, B6. There were also three different impregnation material available, which are Standalone Polyester, Epoxy with particles for high heat conduction and the Polyester with the particles for high heat conduction. Using all these combinations different motorettes were imprenated with different material while each slot in every motorette were having a unique combination of the slot liner and the Copper insulation of different thickness as shown in the following table.

Table 3.2: Measurements made on motorettes and type of aging process.

Motorette	Unaged	Aged in Oil	Aged in Air
M1	✓	✓	
M2	✓		✓
M3	✓	✓	
M4	✓		✓
M5	✓	✓	
M6	✓		✓

Table 3.3: Motorette 1 and 2 Material Combination

Slot	Cu Insulation	Slot Insulation	Impregnation
S1			
S2	A1	B1	C1
S3	A2	B2	C1
S4	A2	B1	C1
S5	A1	B3	C1
S6	A1	B4	C1
S7	A1	B5	C1
S8	A1	B6	C1
S9			
S10	A1	B7	C1
S11	A1	B10	C1

Slot	Cu Insulation	Slot Insulation	Impregnation
S1			
S2	A1	B1	C1
S3	A2	B2	C1
S4	A2	B1	C1
S5	A1	B3	C1
S6	A1	B4	C1
S7	A1	B5	C1
S8	A1	B6	C1
S9			
S10			
S11			

Table 3.4: Motorette 3 and 4 Material Combination

Slot	Cu Insulation	Slot Insulation	Impregnation
S1			
S2	A1	B1	C2
S3	A2	B2	C2
S4	A2	B1	C2
S5	A1	B3	C2
S6	A1	B4	C2
S7	A1	B5	C2
S8	A1	B6	C2
S9			
S10		B8	
S11			

Slot	Cu Insulation	Slot Insulation	Impregnation
S1			
S2	A1	B1	C2
S3	A2	B2	C2
S4	A2	B1	C2
S5	A1	B3	C2
S6	A1	B4	C2
S7	A1	B5	C2
S8	A1	B6	C2
S9			
S10			
S11			

Table 3.5: Motorette 5 and 6 Material Combination

Slot	Cu Insulation	Slot Insulation	Impregnation
S1			
S2	A1	B1	C3
S3	A2	B2	C3
S4	A2	B1	C3
S5	A1	B3	C3
S6	A1	B4	C3
S7	A1	B5	C3
S8	A1	B6	C3
S9			
S10		B8	
S11		B9	

Slot	Cu Insulation	Slot Insulation	Impregnation
S1			
S2	A1	B1	C3
S3	A2	B2	C3
S4	A2	B1	C3
S5	A1	B3	C3
S6	A1	B4	C3
S7	A1	B5	C3
S8	A1	B6	C3
S9			
S10		B7	
S11		B9	

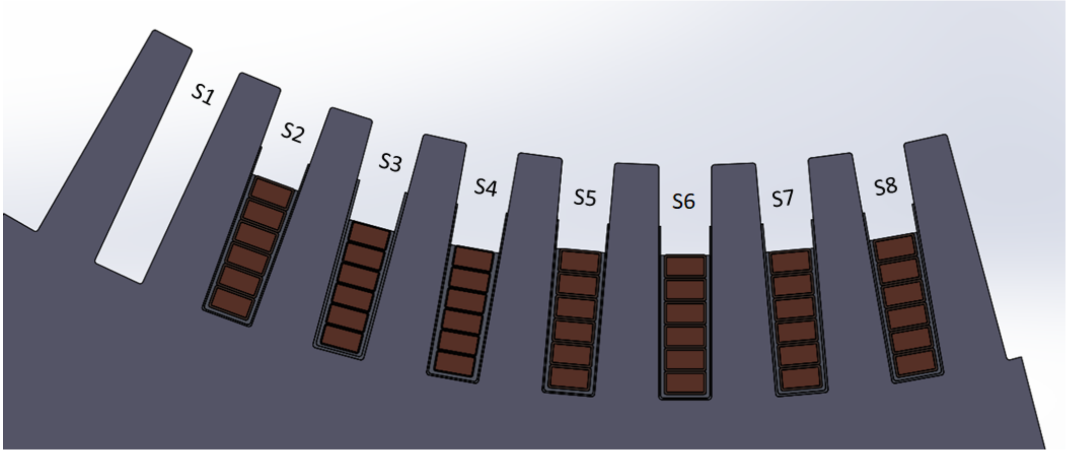

Figure 3.1: Motorette slot nomenclature.

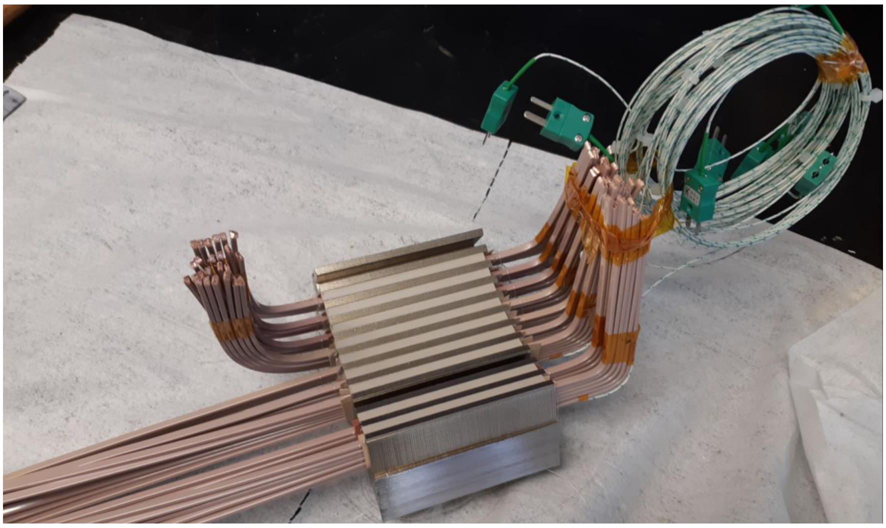

Figure 3.2: The assembled motorette half way before getting the impregnation.

4

Partial Discharge Measurements

4.0.1 PDIV

Partial discharge Inception Voltage (PDIV) is the voltage at which the insulation material undergoes failure and starts conducting the charges between the conductors. This occurs because of the polymer breakdown in the material due to high voltage stress. It is one of the important criteria which help in selecting the suitable material for the application based on their operating voltage ranges.

Thus, in addition to the thermal properties, the PDIV value of the materials will also determine the feasibility of the material for the operating conditions. The following tests were conducted at KTH:

Between the conductor and Stator Segment:

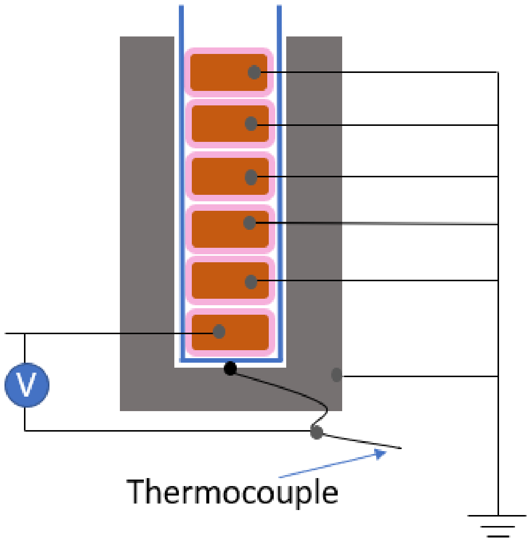

Figure 4.1: Connections for the PDIV measurements

As seen in figure 4.1, the bottom most conductor (with maximum surface area to the stator element) and the thermocouple are subjected to high voltage while the remaining conductors are grounded. The voltage is increased in the steps of 100 V until the first discharge is noted and further the steps are gradually reduced.

Between the conductors:

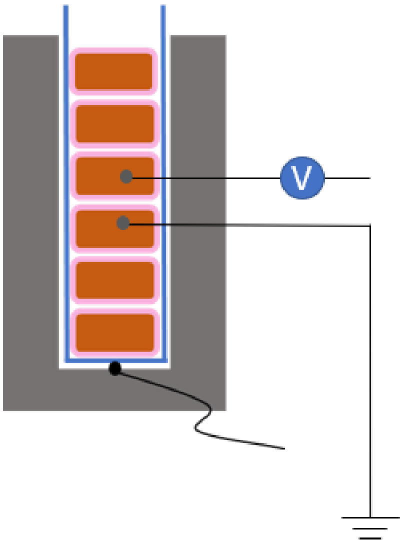

Figure 4.2: Connections between wire to wire for PDIV measurements

As represented in figure 4.2 the voltage is applied on the 2 conductors (center) and similar procedure of testing method is used.

The main data of interest for this thesis is the PDIV value between the conductor and stator element which provides an additional information about the materials alongside the thermal conductivity which benefits in selecting the appropriate material.

5

Methods of Generating Heat

Very similar to the electrical circuit where the known voltage is applied, current is measured and resistance is calculated, heat is applied on one end of the insulation system, temperatures are measured, and thermal conductivity is further computed from the data.

With the motorette setup the heat source had to be determined on either side of the insulation system. This could be done in two ways.

- The stator element could be heated while the copper coils will be kept at room temperature or subjected to active cooling.
- The copper coils are heated somehow and the stator being at the room temperature or subjected to active cooling.

Both the heating methods were looked into. While there could be several ways of heating the stator and cooling the copper coils like using induction heating, or placing the stator in oven and isolating the environment while keeping the coils in room temperature or convective cooling the coils with pressurised air. This method seemed certainly feasible when in comes to methods of heating, but it had its own limitations. While the measurements are made individually on a certain slot at one time, the stator having the higher thermal mass would further distribute heat to other slots. These slots directly or indirectly contribute to the heat flow of the slot undergoing measurement. This might result in elevated or decreased temperatures thereby influencing the accuracy of the results.

Further leading to the investigation of the second method where the copper coils in a particular slot were heated while the motorette was introduced to free convection over the air or active cooling. The idea is to take the advantage of higher temperature coils and cooler motorette and use the temperature difference to take the necessary measurements.

Several ideas were brainstormed, and some of the following were tested to evaluate to see if they would develop significant temperature differences.

5.1 Method 01: Single coil heating

The inner most coil was initially introduced to heating and the temperature on the copper insulation for it were noted. The end over hang of the coil was dipped in the boiling water. The copper temperature on the other end is also noted to observe the effect.

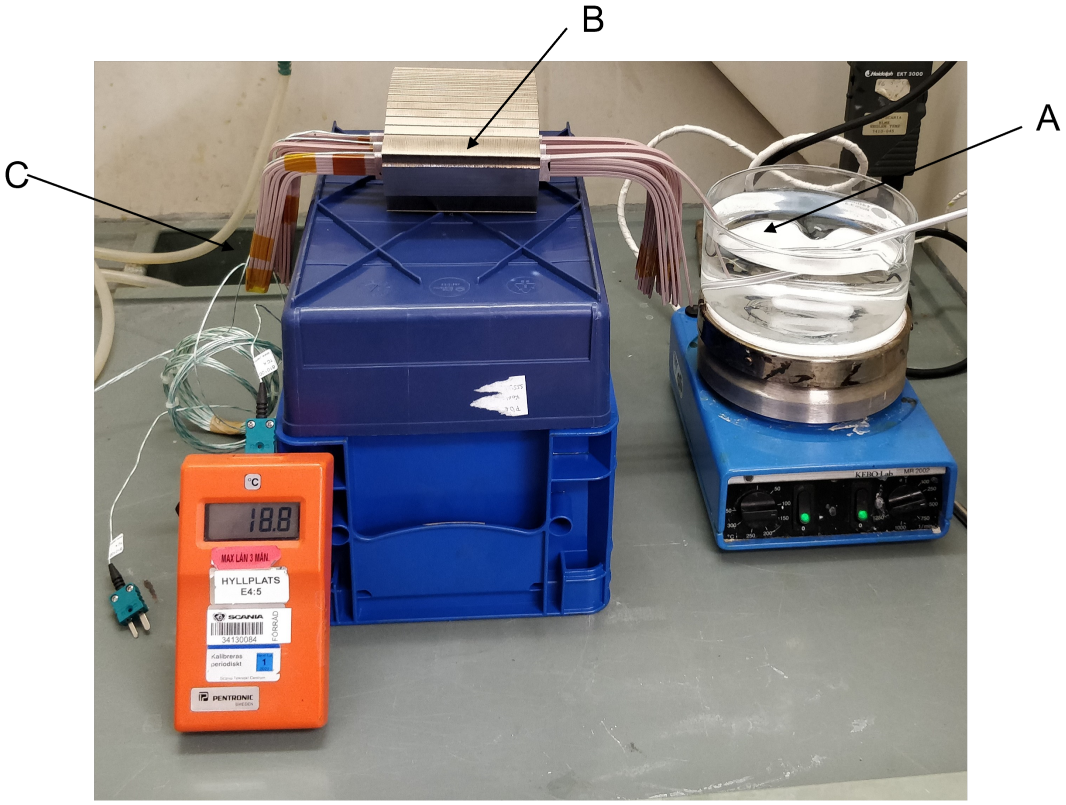

Figure 5.1: Method 01: Single coil dipped in water boiling at 100 °C

Table 5.1: Method 01: Temperatures logged at the corresponding positions at 20 min interval

T(A) [°C]	T(B) [°C]	T(C) [°C]
90	22.4	18.8
95	27.1	18.7
95	27.7	18.8

Verdict of Method 01
The temperature reading over the different positions of the coil reflects that heat was not sufficient enough to carry on to the other end in-spite of the copper being the best thermally conductive.

5.2 Method 02: Multi Coil heating

Carrying forward with experiments and improvising, all the coils in the single slot were submerged in the boiling water unlike the single coil as in the previous experiment.

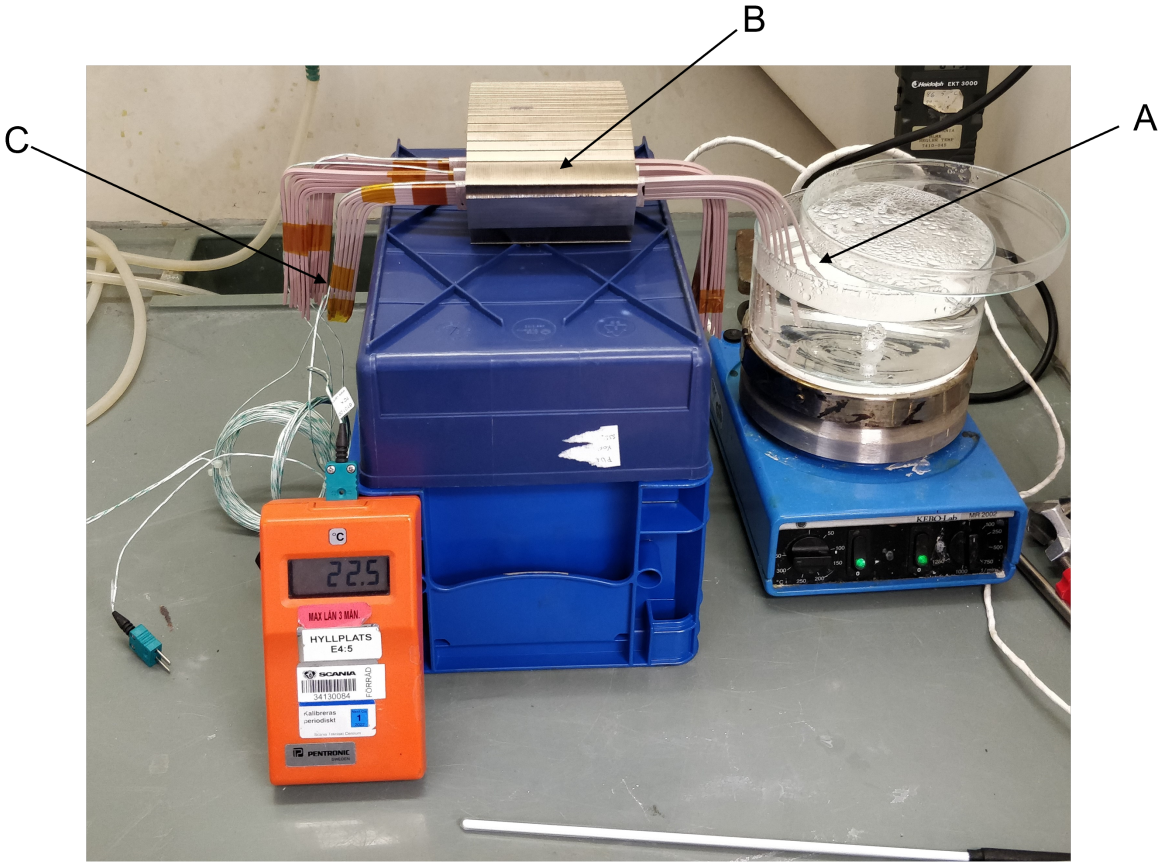

Figure 5.2: Method 02: Multi coil heating dipped in water boiling at 100 °C

Table 5.2: Method 02: Temperatures logged at the corresponding positions at the interval of 20 mins

T(A) [°C]	T(B) [°C]	T(C) [°C]
90	27.4	22.4
95	27.8	22.4
95	28.0	22.6
95	28.0	22.8

Verdict of Method 02

The measurements show temperatures higher than the previous results but still the temperature at the point B (on the Cu insulation) was not significantly high enough to evaluate the material properties.

5.3 Method 03: Introducing higher boiling point liquids

This test is similar to the previous method conducted but this time using the hydraway white oil. This oil has the flash point of 170 °C [11] and thus the temperature of the liquid was set to 150 °C . Alongside having higher boiling point than water, it was also inert to the copper and copper insulation material thereby not reacting with either of them.

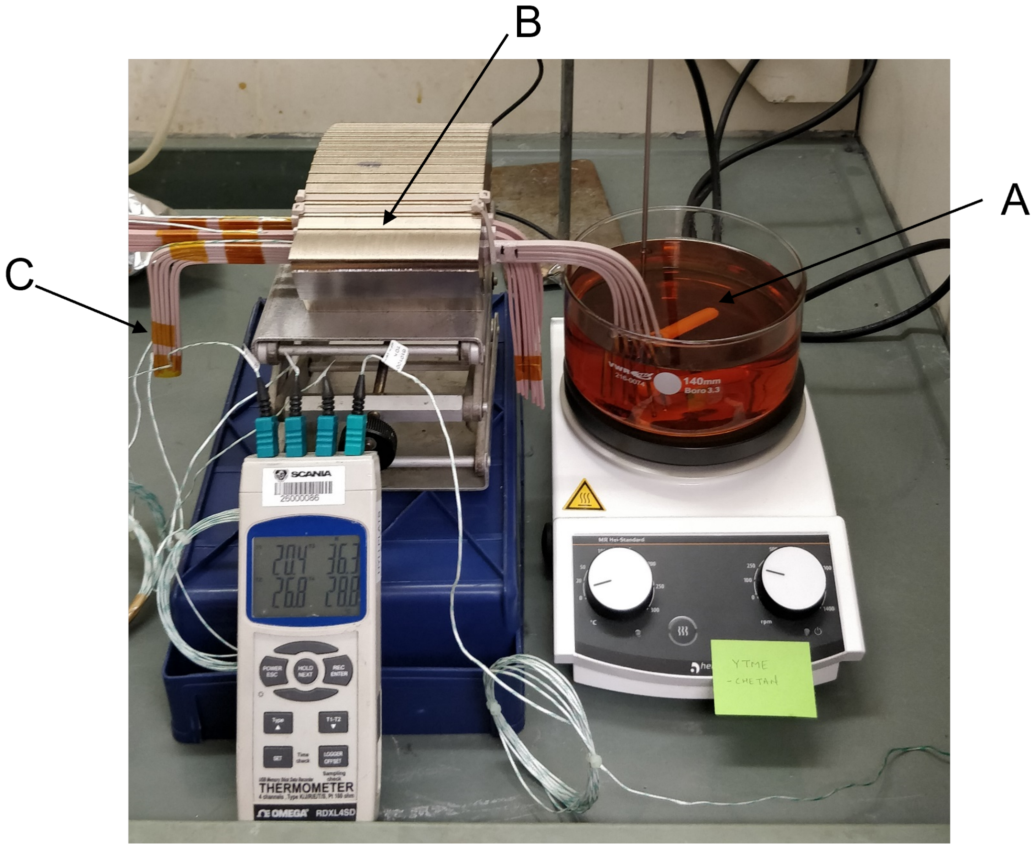

Figure 5.3: Method 03: Multi coil heating dipped in hydraway white oil at 130 °C

Table 5.3: Temperatures logged at the corresponding positions at the interval of 20 mins

T(A) [°C]	T(B) [°C]	T(C) [°C]
122.0	31.0	24.5
128.0	32.0	24.5
128.3	32.5	25.2
129.0	32.4	25.1

Verdict of Method 03

The hydraway white oil temperature is limited to 130 °C from the heater feedback.

It is evident that as the temperatures on the source increases, the temperatures measured on the other points also increased. The results were not optimum to draw the thermal measurement readings.

5.4 Method 04: Heating using soldering gun

With the interest in further increasing the temperatures, soldering gun is another alternative with increased temperatures upto 450 °C.

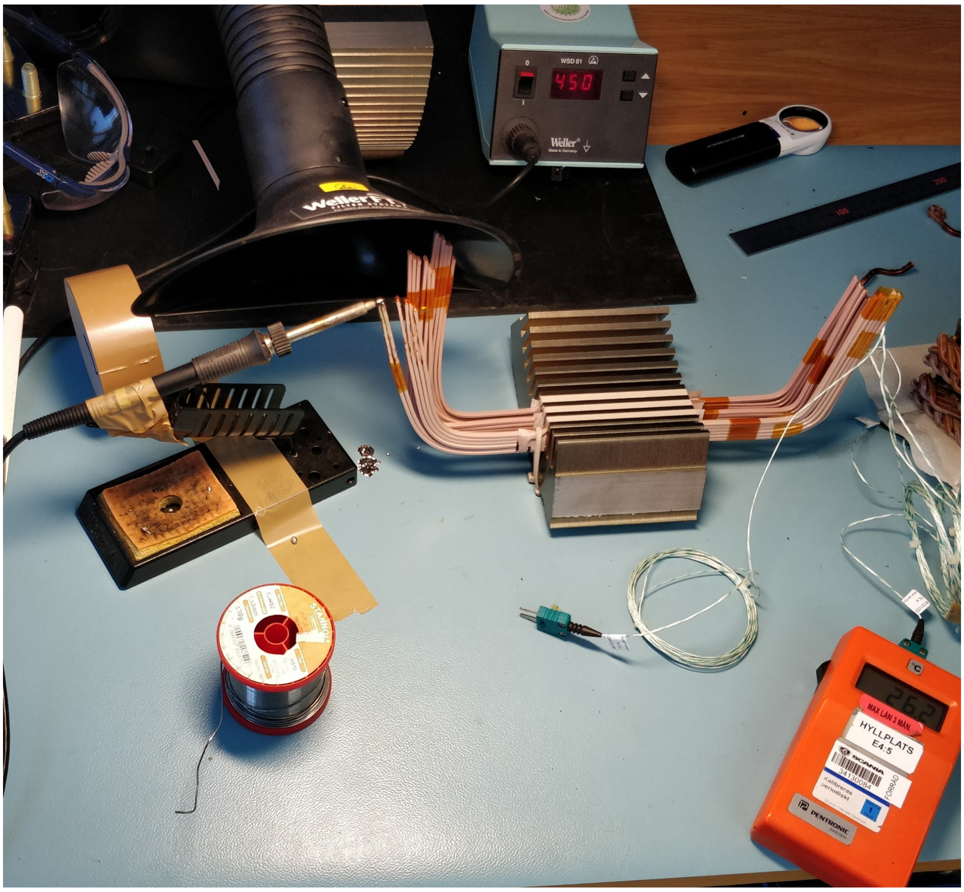

Figure 5.4: Method 04: Heating using soldering gun at 450 °C

Verdict of Method 04
The metal to metal contact is better established with tin (filler) that of earlier methods and higher temperatures is observed. Setting up the experiment and heating all the coils, repeating the experiment for different slots is limited with lot of challenges alongside establishing same type of contact. Due to these obvious reasons, this method is further not taken into consideration.

5.5 Method 05: Inductive heating

The induction method is an alternative non contact type heating method where a high resistance heating element is wrapped around the coil and is used to generate heat.

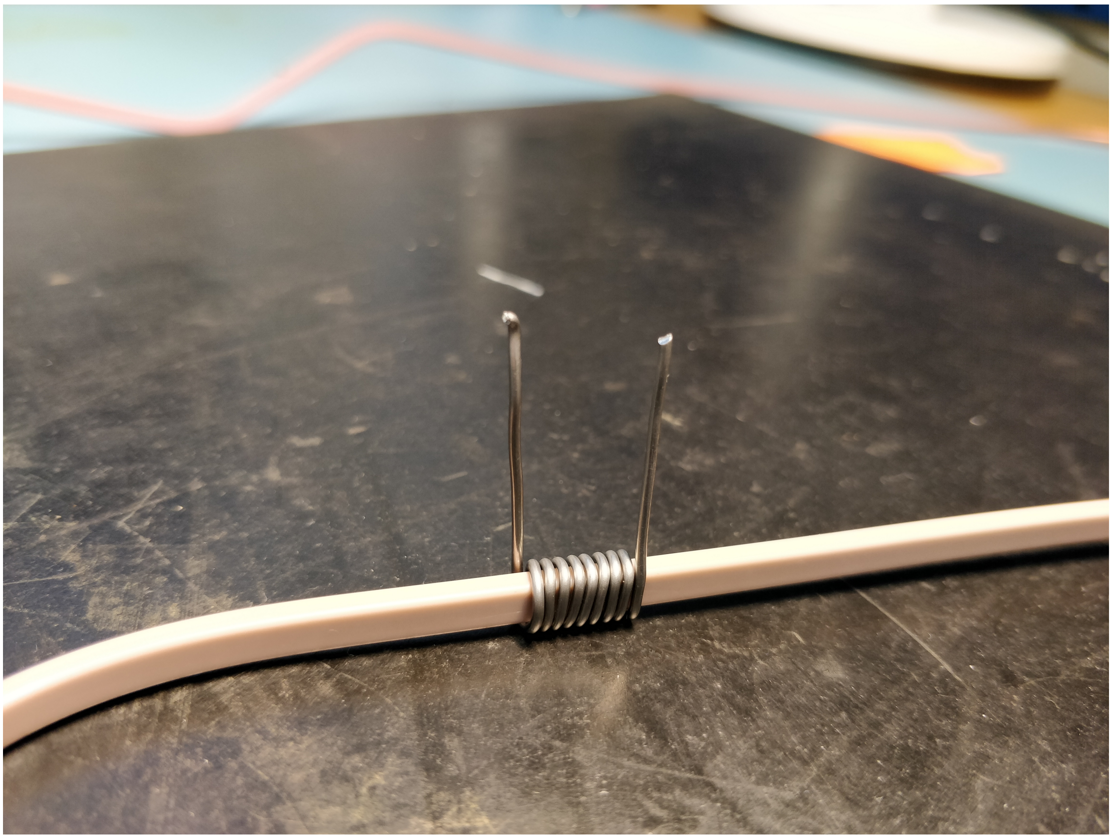

Figure 5.5: Resistive element rolled around the copper coil

Verdict of Method 05
The total number of coils in a slot is 6 with 12 ends. This method involved 12 ends to be having same number of turns to generate even heating. Controlling the power source for the resistive element involves lot of components and huge amount of setup time. This method is good alternative for smaller test samples.

5.6 Method 06: Joule heating

All the previous methods involves the source of heating the end winding in the particular slot. This has the inevitable temperature gradient along the length of the copper coil. With joule heating, uniform temperature in the copper coils is attained. With varying the amount of current we pass the copper coils, the heat is also controlled thereby controlling the temperatures in the system. Copper is one of the best current conductors with least electrical resistance. To maximise this resistance and increase the heat generated, all the copper coils are connected in series using lugs as a positive contact and soldering at the junctions for minimising the contact resistance.

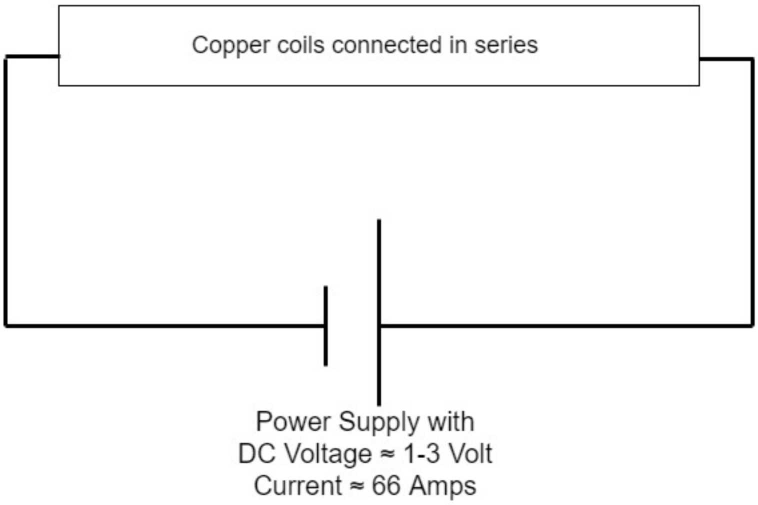

Figure 5.6: Schematic diagram of the Joule heating concept

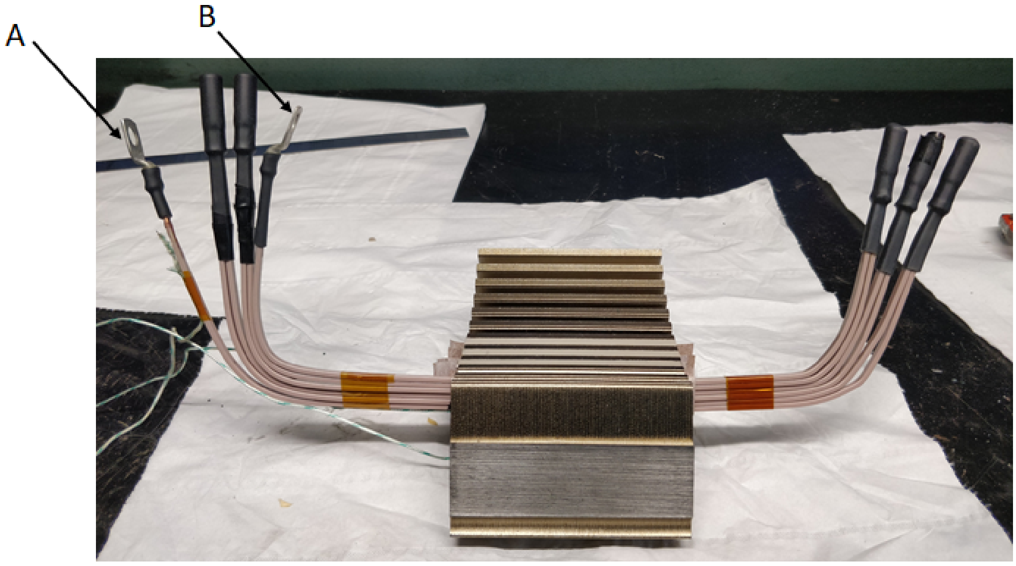

Figure 5.7: The copper coils in the motorette connected in series

The cross section area of the copper coil is
The potential is applied to the end terminals A and B. Limiting the current to 10 A/mm^2 and using the available cross section area, the maximum amount of current that could run in the copper coils is,

$$I_{max} \leq Area * 10A/mm^2 = 60A \tag{5.1}$$

The current in the setup is limited to 60A for all the test cases.

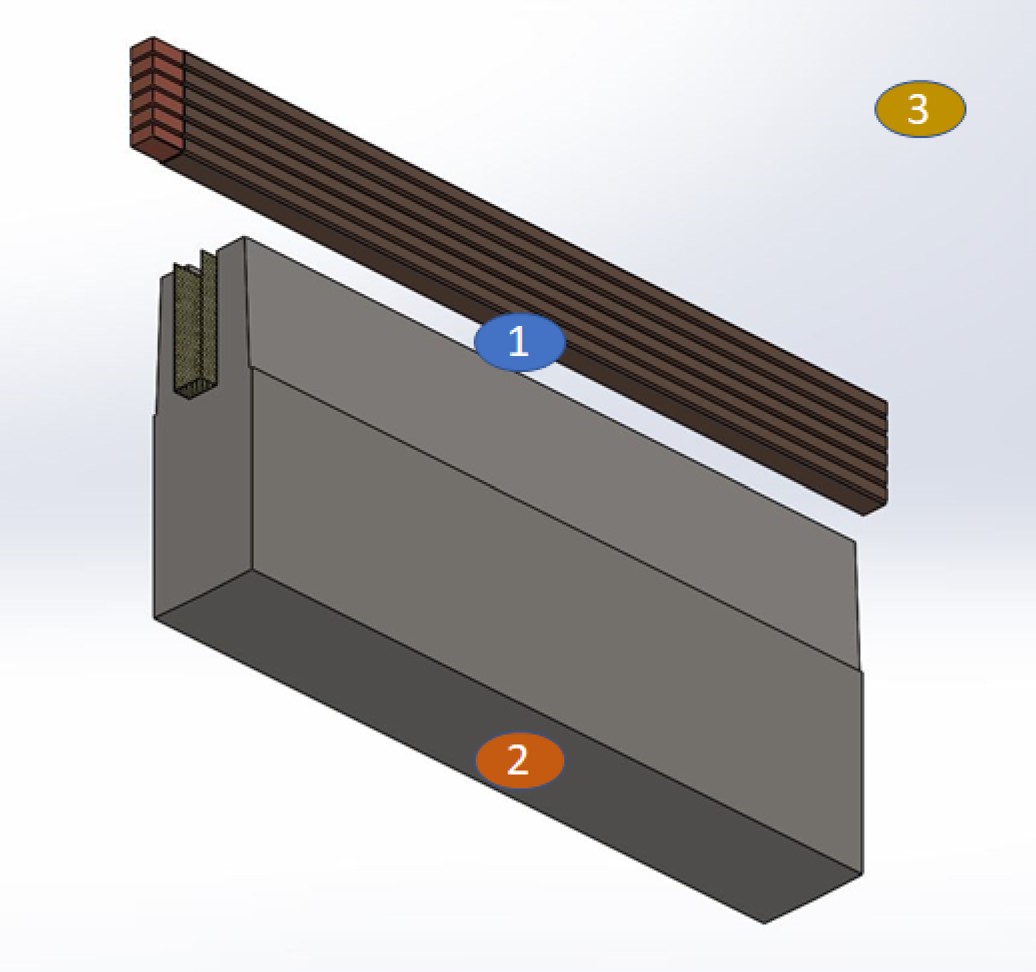

Figure 5.8: Method 06: The junctions 1, 2, 3 are the thermocouple positions.

Table 5.4: Method 06: The thermocouple details.

Thermocouple	Comment
1	Measures the temperature on the Copper insulation (PEEK)
2	Measures the temperature on the Motorette
3	Measures the ambient temperature

Table 5.5: Method 06: Temperatures logged at the corresponding position at the interval of 15 mins

Voltage [V]	**Current [A]**	**T1 [°C]**	**T2 [°C]**
0.7	60	45.3	35.2
0.8	60	50.7	40.1
0.8	60	53.3	42.5
0.8	60	53.8	44.4

From the above table, the temperatures observed were significantly higher than the earlier methods. Thus with the uniform heat generated throughout the coil using the ohmic heating otherwise known as joule heating proved to be easier setup, delivers higher temperatures and quick method for repeating the tests once the copper coils are connected in series. This demonstrates that the experiments could be repeated easily just by plugging the thermocouples and power supply.

The resistance of the resultant coil at room temperature (almost in the beginning of the experiment)

$$R_1 = \frac{Voltage[V]}{Current[I]} = \frac{0.7}{60} = 0.011\Omega \tag{5.2}$$

The voltage increase by 0.1 V over the time as the heat in the system builds up. This is caused as the result of the increase in resistance due to temperature. It is not highly sensitive to the temperature and thereby the voltage stabilises over time. The resistance of the coil starts to settle down once the temperatures start to saturate and reach closer to the steady state values.

$$R_2 = \frac{Voltage[V]}{Current[I]} = \frac{0.8}{60} = 0.013\Omega \tag{5.3}$$

6

Aging

The electrical insulation material in the system are exposed to air and other chemicals used for cooling etc. With electrical and thermal stresses experienced by the material when the machine is being operated and exposure to air or chemicals, the materials tend to undergo change in their chemical compositions. These reactions cause the material to change in its physical properties and affect the material properties like PDIV and thermal conductivity over the time. Thus it becomes necessary to study the behaviour of the material under these conditions.

Using the accelerated aging technique, the materials are heated over the operating temperature to age quickly and the thermal measurements are further noted to evaluate the change in properties. The motorettes are aged in air for 500 hours at 210 °C to study the effect of aging on thermal properties.

Figure 6.1: Motorettes after undergoing aging in oven

7

Test Setup

7.1 Components of the test setup

7.1.1 Thermocouple

Type K is the most commonly used thermocouple. Its error is 0.1 °C for measurements of temperature less than 100 °C, from 100 °C to 400 °C [12] the error is 1°C. Although it is widely used, its characteristics can vary depending on the type of probe used. In addition, its Curie point is a factor that influences output. For the test setup, the operating temeratures were between +12 °C to 95 °C. The thermocuple's output format is analog with 0 V to 5 V.

Figure 7.1: Type K thermocouple used in the experiment.

7.1.2 Data Logger

A data logger is a device that collects and stores data. It can be used to monitor and record details for long periods of time without any monitoring. They are self or independently powered equipment with its own processor, memory and ports for picking the data from the sensors. It also has a compatible output which can be further connected to a computer and the recorded data is further transferred, post processed and monitored if needed. The analog output from the thermocouple is connected to data logger. The data logger used for this particular test setup is INTAB 3000i [13] [14]. This logger has a RS-232 COM [15] port which can communicate with the PC using a USB-A or USB 3.0. The EASYVIEW [16] software on the computer is essentially developed to interact with the INTAB 3000i hardware and records the data in the digital format.

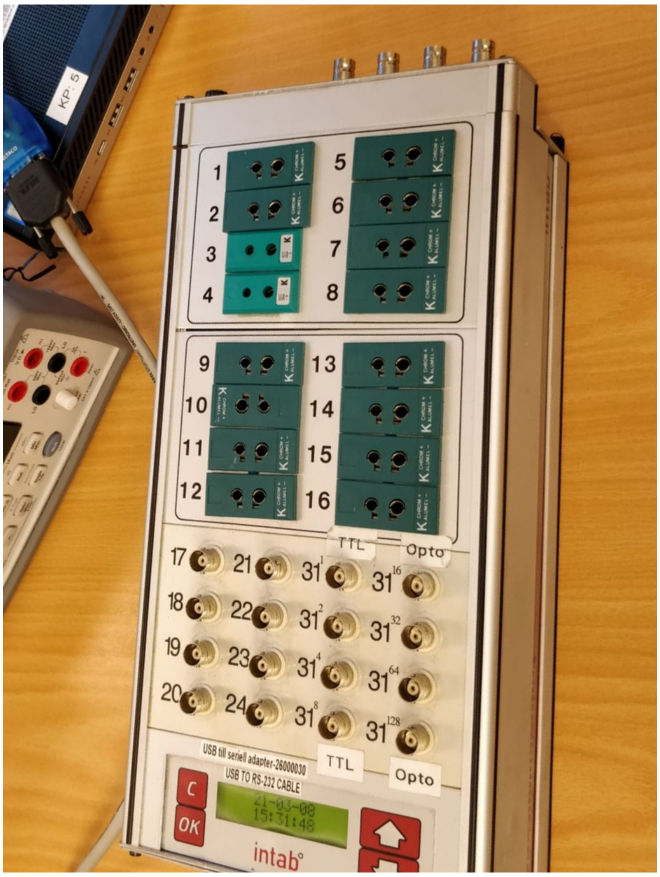

Figure 7.2: INTAB 3000i Data logger with ports for connecting thermocouples.

7.1.3 Power Supply

A device that provides electrical power to a load is called power supply. Its primary function is to convert electric current coming from a source (input) to the appropriate voltage and frequency (output).Some power supplies are standalone equipment, while others are built-in into the load appliances that they're designed to power. Some of the functions that these supplies can perform are limiting the current drawn by the device and protecting the environment from potential surges and electronic noise.

Sorensen SGI [17] series high power DC supply was used in the test setup with the following set parameters for operation. The DC output can be connected with a lugs having a 10mm hole on the power supply and with lugs of 8 mm hole to the motorette.

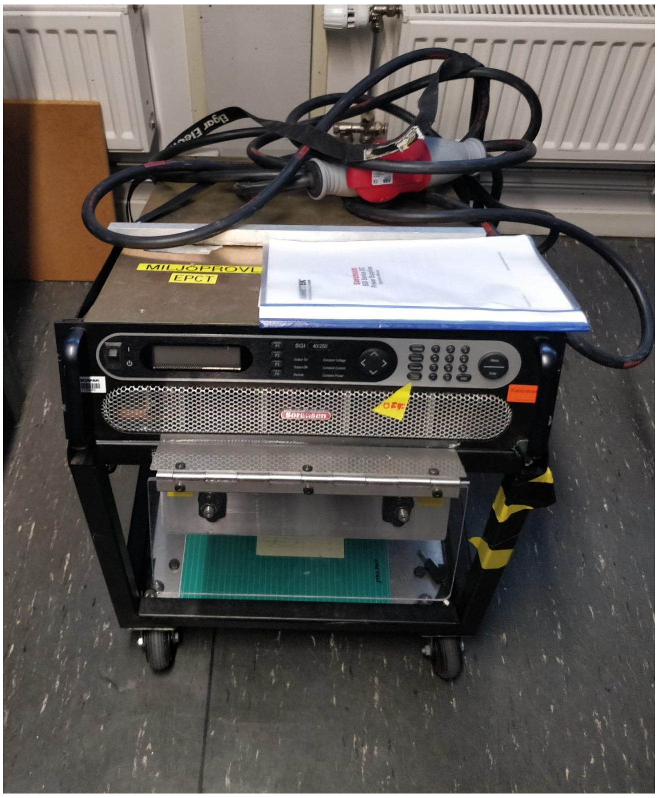

Figure 7.3: High power DC power supply by Sorensen [18]

Table 7.1: Method 06: The High power DC supply input parameters.

Parameter	**Value**
Operating Voltage	2 V
Maximum safety Voltage	2.5 V
Maximum limiting current	60 A

7.2 Experimental Setup

The thermocouples were placed in the motorette as shown in figure 5.8. The sampling frequency set for all the temperature logs is 1Hz, while the test was conducted for about 5400 seconds (1 hour 30 minutes) until the temperatures reach closer to steady state.

Table 7.2: Method 06: The components in the test setup

Designation	**Comment**
1	DC power supply
2	Motorette
3	Data Logger
4	Computer

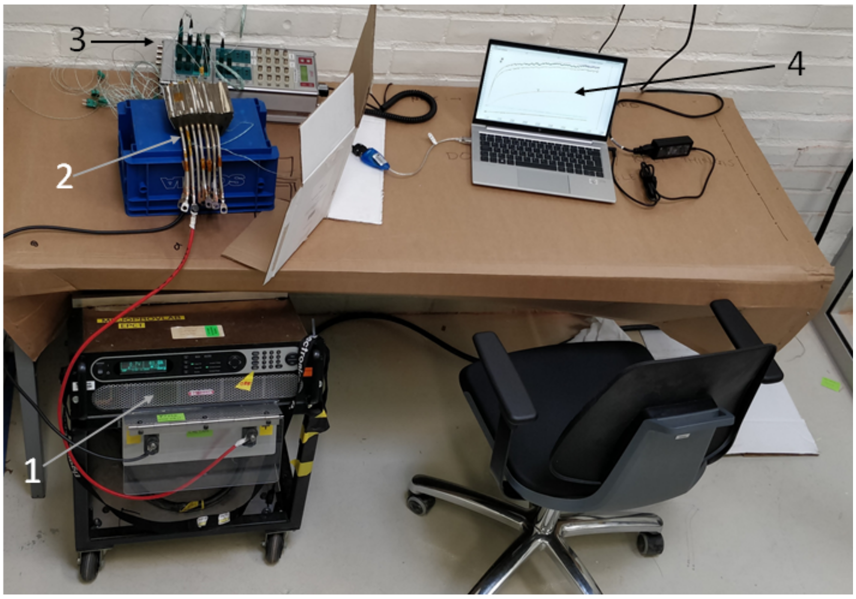

Figure 7.4: The thermal measurements test setup running in progress.

8

Evaluating the thermal conductivity

8.1 1D evaluation

The test setup is finalised and now the required thermal measurements are logged. Using the 1D heat flow analysis in the motorette, the data obtained is post-processed.Here, q_x is heat flux and Tc_1 is the temperature measured on the copper insulation and the Tc_2 is the temperature measured on the motorette.

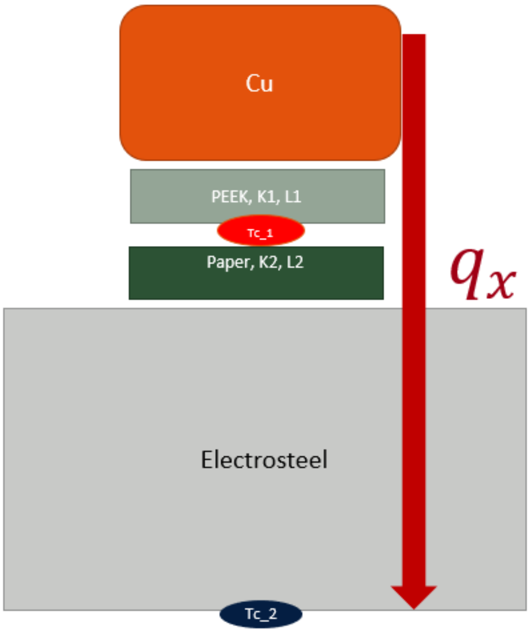

Figure 8.1: 1D heat transfer.

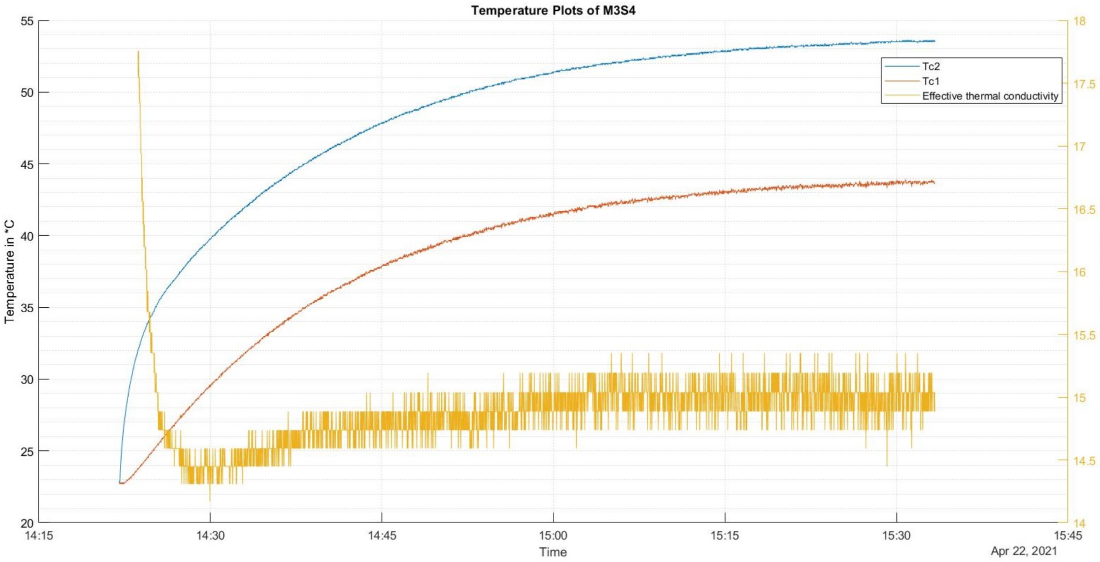

Figure 8.2: The effective thermal conductivity of the Epoxy with particles and for B1 slotliner and for THIN copper insulation.

The sampling rate of the temperatures logged is at 1Hz and the temperatures are sensitive to the environment and thus causes the noise in the output (effective thermal conductivity). Filtering the output becomes necessary. 1-D digital filter is used to filter the noise with the following function which is quite commonly used with maually set windowsize.

$$y = filter(b, a, x)[19] \tag{8.1}$$

where,
a = denominator coefficient of rational transfer function (non zero).
b = numerator coefficient of rational transfer function.
x = Input data (noisey).
y = filtered data.
windowsize = 200.

$$b = \frac{1}{windowsize} * ones(1, windowsize) \tag{8.2}$$

The filtered data further settles down as the motorette tends to reach towards steady state as it is observed in the last 15 minutes of the testing in the following figure.

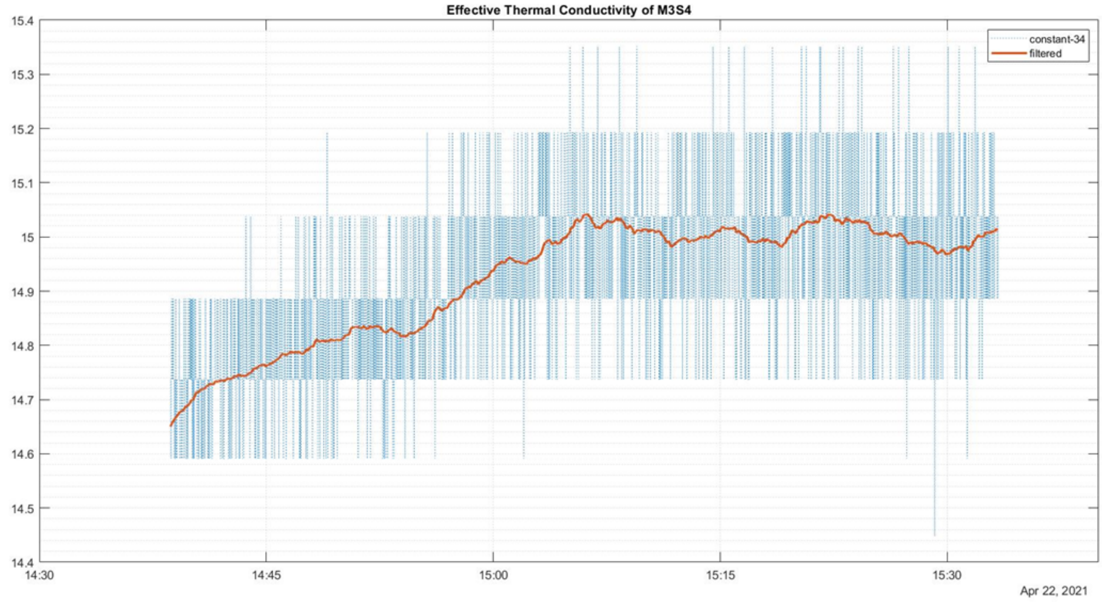

Figure 8.3: After filtering the noisey data.

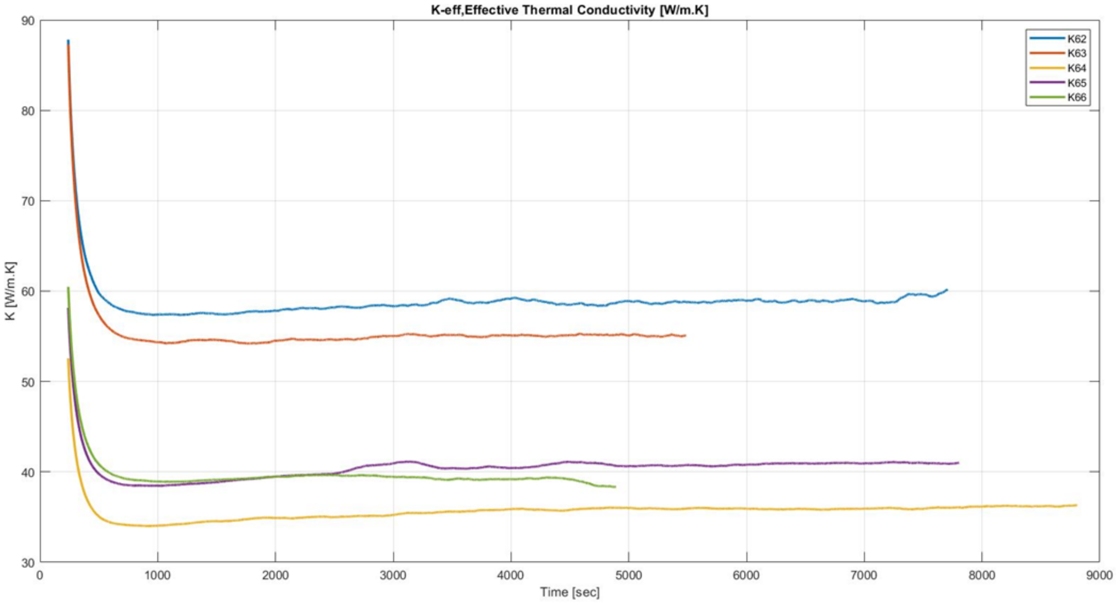

Figure 8.4: Comparing the thermal conductivity values of different slots of motorette 6.

The concept of effective thermal conductivity is proposed with this setup as there is no thermocouple measuring the temperature between the insulation and the electrosteel junction. Thus the results were the effect thermal properties of the slotliner, impregnation and the electrosteel. This evaluation method posed the limitations of the results. The thermal properties are a function of the electrosteel thermal conductivity and its thickness and not solely the properties of EIS. Altering the electrosteel material and thickness will not hold the same results valid for the EIS and this could not be used further to validate the material properties.

8.2 Evaluation using simulations

8.2.1 2D Steady State Simulations

The 1D evaluation of the thermal properties did fetch satisfying and reliable results as it is too simplified model. The heat transfer was accounted in only one direction, the topology of the setup is over simplified.

The simulations can solve a complex topology, shapes and multi-physics systems can be setup and initialised based on the complexity and the required accuracy. The complex heat transfer is now accounted with the model. The 2D heat transfer setup is made to evaluate the behaviour of the model and quantify the results. The models are designed in Solidworks 2018 and assembled. The corresponding 2D format of the same model is further exported to run the simulations. COMSOL Multiphysics 5.6 is used for all the type of simulations run to evaluate the thermal properties.

Method

- The last few minutes of the temperature data is of particular interest when the system reaches closer to the steady state and the rise in temperature is not observed.

- Using this data the copper insulator temperature, Tc_1 is given as input as shown in 8.1.

- The thermal conductivity of the impregnation and slot liner is assumed as an array.

- The output temperature on the motorette, Tc_2 is evaluated with the setup for every value of assumed effective thermal conductivity of slotliner and impregnation combination.

- The thermal conductivity of EIS which correctly coincides with temperature of the test data at the Tc_2 junction defines the thermal properties of the impregnation and slot liner.

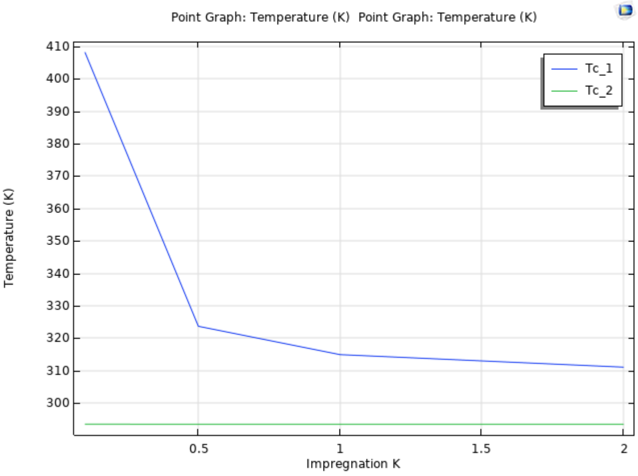

Figure 8.5: Thermal conductivity of the impregnation and slotliner (K_eff) which is not coinciding with the test data

As seen from the figure 8.5, the curves does not follow the trend of how the temperatures rise according to the test data. The motorette temperature Tc_2 is almost similar and as the thermal conductivity of the EIS decreases, the copper insulation temperature, Tc_1 rises rapidly which was not observed again in the test case.

Verdict
While the 2D simulations are advanced over the 1D simulations, the results are still not reasonable. This is because,

- The simulation is still primitive.
- The simulation does not include the heat transfer in the Z direction as the motorette is made of stacked sheet metal and has an-isotropic properties.
- Single point values of the temperatures lead to the uneven heating of the different elements.

8.2.2 3D Parameter Estimation Method

3D simulations could represent the whole motorette. This adds the representation of the scaled motorette over the simplified models as seen earlier. An-isotropic properties in the materials can now be introduced. Temperatures can be averaged over the surfaces rather than points which gives better results.

The time dependent study can be introduced to represent the realistic test situation in the simulation. Combining that with PARAMETER ESTIMATION method [20] model in COMSOL will fetch the unique solution agreeing with the test data.

NOTE: The motorette 03, Slot 08 is chosen as an example to elaborate the 3D simulation setup in COMSOL.

8.2.2.1 Filtering the Data

The sensitivity of the temperatures logged at 1Hz as discussed earlier is noisy. To reduce the noise and decrease the sensitivity in the simulation environment, moving average method is implemented which assures the temperature of the curve is maintained.
The test setup was run for 4321 seconds for this particular slot. With the interest in minimising the simulation up-time for fetching the solution, MATLAB code is developed to reduce the data points and preserve the trend and values on the curve at certain intervals. Maximum of 24 points on the curve is fixed which exhibit the curve of the temperature logged. This provided larger time steps of 241 seconds between the intervals (for all the data) and still satisfy the conditions for the time dependent study. The MATLAB code generates the .csv format file which is compatible with the COMSOL and it can be uploaded directly.

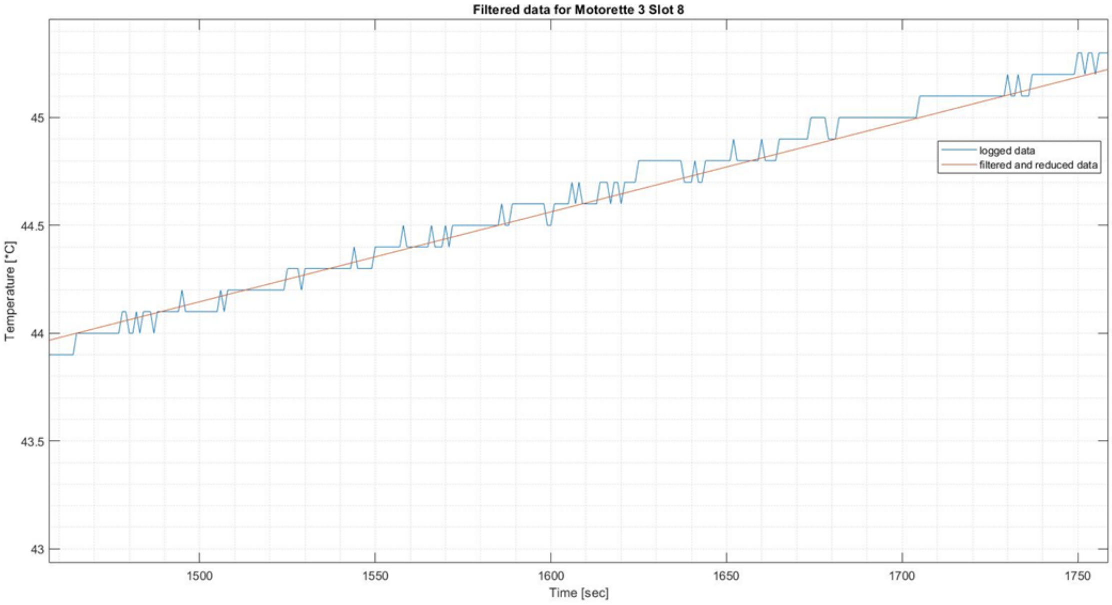

Figure 8.6: Moving average filtering on the logged data (Motorette surface temperature, Tc_2) for the smooth curve to be implemented in simulation environment.

8.2.2.2 Defining parameters in COMSOL

Table 8.1: Thermal conductivity of the components in the motorette defined in the simulation environment and x,y,z is shown in figure 8.7

Material	Thermal conductivity [W/(m.K)] (x,y,z)
Copper conductors	400, 400 ,400
PEEK	0.25, 0.25, 0.25
AISI Steel (Motorette)	28, 28, 0.37
Slot liner and Impregnation	K_eff

Table 8.2: The global definitions defined in Heat transfer in solids.

Name	Expression and value	Description
htc	5 [W/(m^2.K)]	Heat transfer coefficient between steel and air
T_amb	21.63 [degC]	Avg Ambient Temperature at the time of experiement
K_eff	0.01 [W/(m.K)]	Effective thermal conductivity initialization
ϵ	0.5	Surface Emissivity

8.2.2.3 Mesh

Every 3D model undergoes the mesh where the model is collectively represented as the tiny bits of vertices and edges which help run the model. The type of mesh used here is **free tetrahedral mesh** and the sequence used in in this setup was **physics controlled mesh**. Thus the system automatically detects the element size and domain, adapts the mesh accordingly. It is clearly observed from the image that the slot liner, impregnation and the copper insulation are meshed finely while the stator core's mesh size is relatively bigger. This locally adaptive mesh reduces the simulation time while still giving the reliable results.

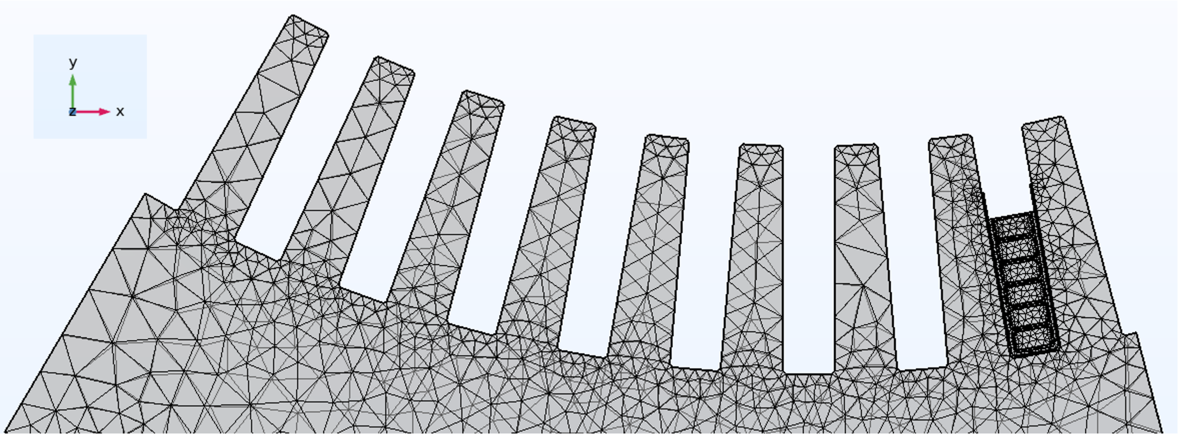

Figure 8.7: Meshing the motorette and the x,y,z axis mentioned in table 8.1

8.2.2.4 Study

There are two ways of using the simulations. The first being the forward approach, the inputs are applied to the system and then the behaviour of the model is observed.

Another approach is using the parameter estimation method, the input and the output is known but the dependent parameter in the material/model is unknown. Using this principle, with the temperatures and the other material properties known and the thermal properties of the EIS being the only unknown, it becomes convenient to use this approach and extract the unknown parameters.

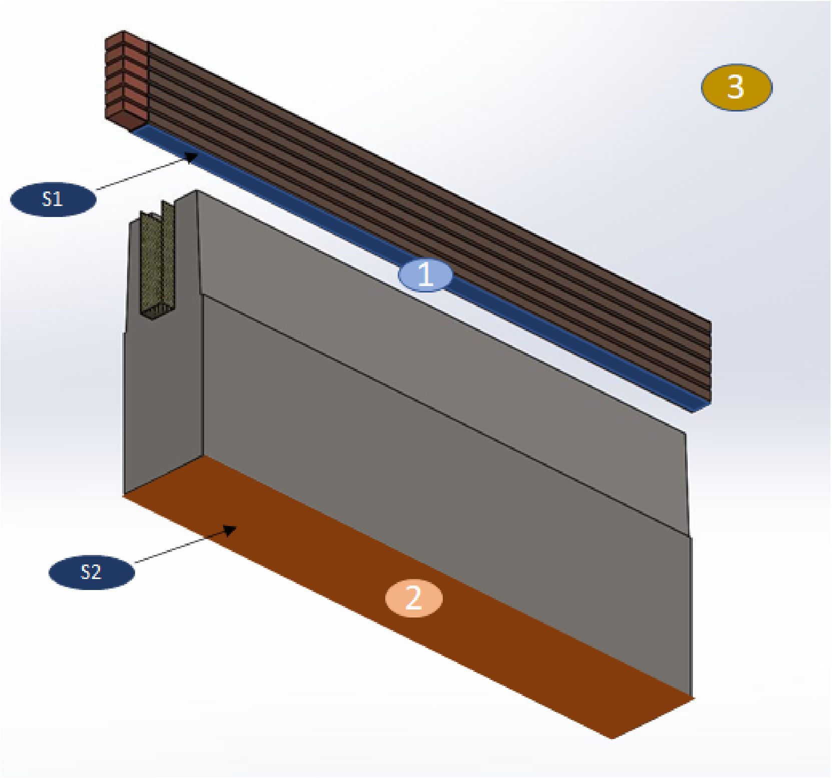

Figure 8.8: Reference image for setting the environment in COMSOL

The temperatures logged from the thermocouple placed in position 1 is introduced as the input to the simulation for the time dependent parameter estimation study. The point temperature measured is averaged over the surface S1. The K_eff is the variable that is initialised from 0.01W/(m.K) to 4W/(m.K) range. The average temperature is measured on the surface S2 for every value of thermal conductivity and is compared to actual temperature logged from the thermocouple 2. There is only one unique solution when the least squared value between the average temperature at S2 and that of the thermocouple 2 under the set tolerance when the simulation will conclude.

9

Results

9.1 Temperature Plots

Using the Parameter estimation method, the average temperature at the S2 against the temperature logged by the thermocouple 2 in figure 8.8 the following over-lap of the temperature curves are represented in figure 9.1:

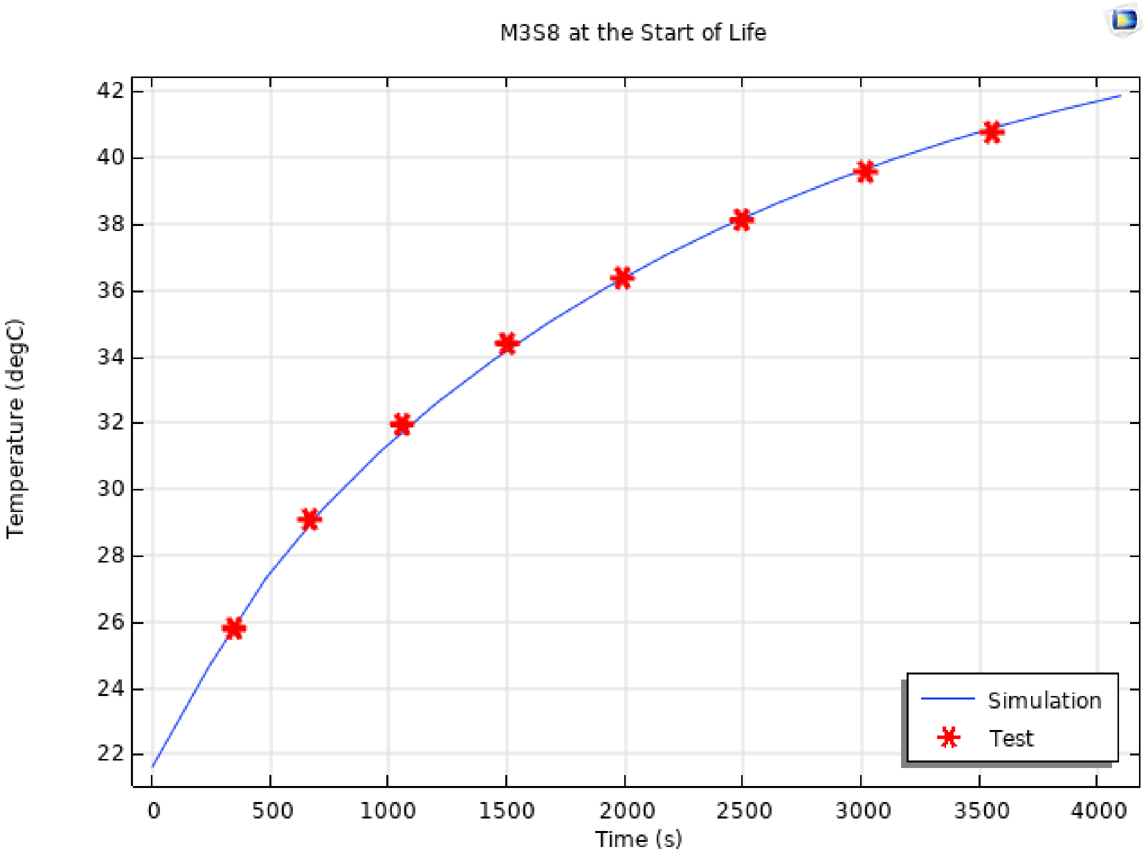

Figure 9.1: The overlap of the actual test data to the simulation data for the motorette 03, slot 08 at the Start of life for the thermal conductivity of value 1.16 W/(m.K).

The same model setup can be used to evaluate the data once the motorettes are aged and the thermal measurements are carried out again.

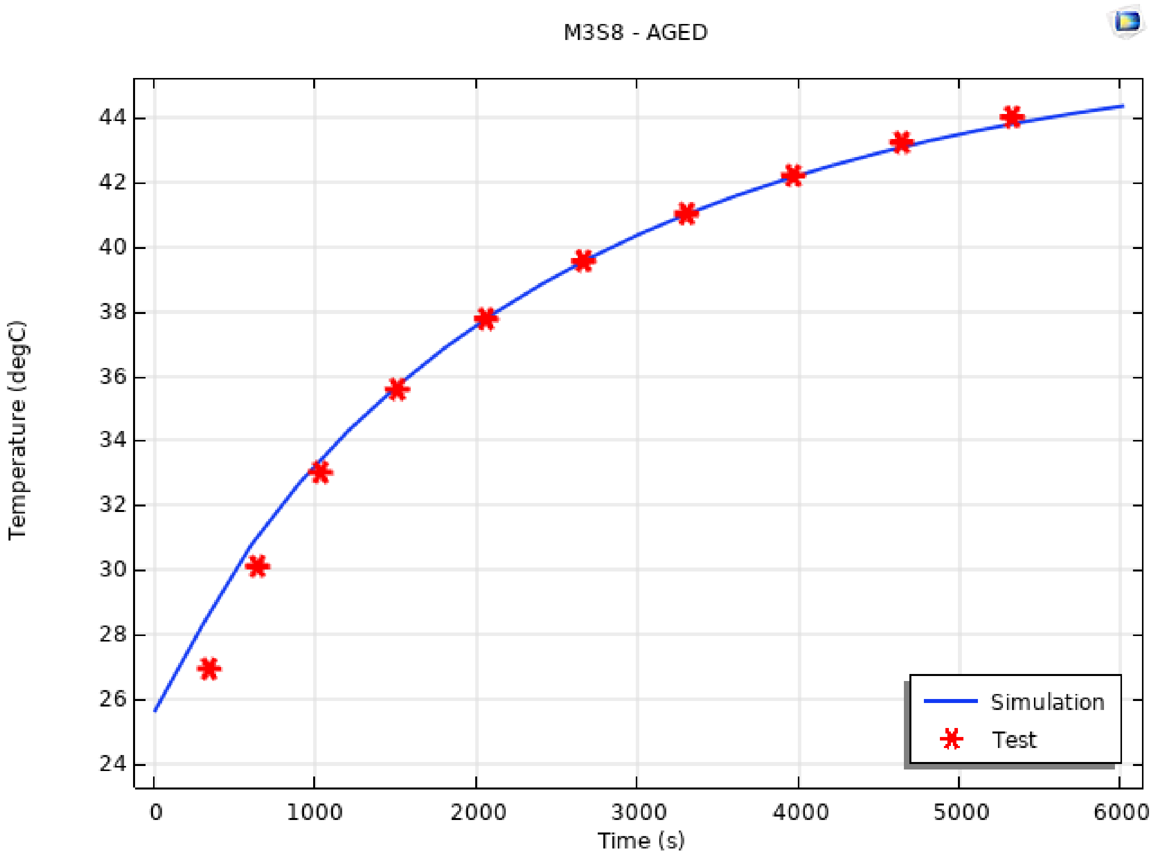

Figure 9.2: The overlap of the actual test data to the simulation data for the motorette 03, slot 08 after the aging for the thermal conductivity of value 0.43 W/(m.K).

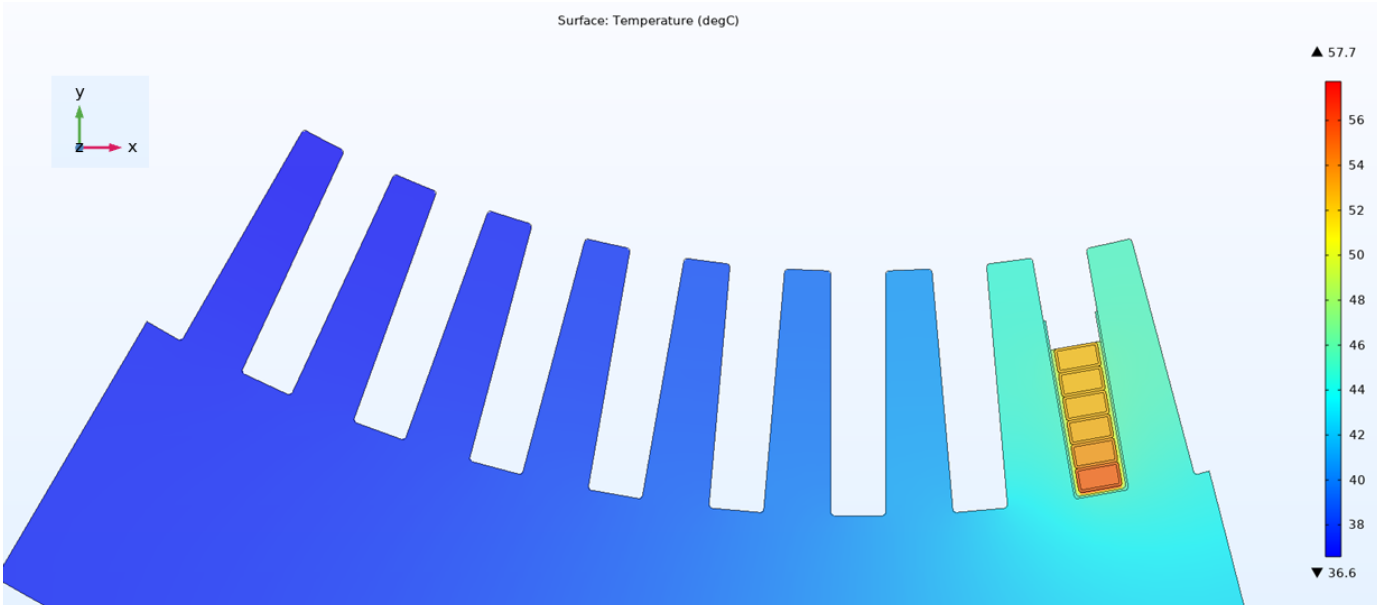

Figure 9.3: The temperature distribution is represented in the form of rainbow coloring for the Motorette 03, Slot 08 after aging.

9.2 Pugh Matrix Evaluation

The Pugh Matrix is a decision framework that uses a set of criteria to identify potential solutions and alternatives. It was developed by Stuart Pugh. It is often used to evaluate the options and rank them in various like selecting the products, suppliers, other dimensions where decision is based on several criteria. It is also used in the field of engineering for shortlisting components or making design decisions.

With different combinations of slot liners and impregnation materials giving us the different partial discharge inception voltage and thermal conductivity of the material combinations, evaluating using a Pugh matrix presents us clearly about the best combinations to opt from the given set.

The **NT** in the following tables represent that they were not tested as the thermocouple terminals are damaged. **SOL** represents the Start of Life.

Table 9.1: Contrast of the VERDICT used in the Pugh Matrix

VERDICT	INDICATION
BETTER	SUPERIOR TO BENCHMARKING
GOOD	SIMILAR TO BENCHMARKING
DISCARD	NOT SATISFYING CONDITIONS
RE-DO	NOT ENOUGH DATA TO CONCLUDE
ADD-ON	BETTER K_eff with 2kV PDIV

Table 9.2: Pugh Matrix of the Motorette 02 with Standalone Polyester - Impregnation

M2 - Standalone Polyester	**BENCH MARK**	**B1**	**B2 (THIN)**	**B1 (THIN)**	**B3**	**B4**	**B5**	**B6**
PDIV at SOL	2.25 kV	2	NT	1.4	1.99	2.25	1.87	1.97
K_eff	0.43 W/(m.K)	0.48	NT	0.47	0.31	0.43	0.60	0.41
PDIV at SOL	2.25 kV	-1	NT	-1	-1	S	-1	-1
K_eff	0.43 W/(m.K)	1	NT	0	-1	S	1	S
Σ(+1)		1	NT	0	0	0	1	0
Σ(S)		0	NT	0	0	S	0	S
Σ(-1)		1	NT	-1	-2	0	-1	-1
VERDICT		ADD-ON	RE-DO	DISCARD	DISCARD	GOOD	DISCARD	ADD-ON

Table 9.3: Pugh Matrix of the Motorette 06 with Polyester + Particles for high heat conduction Impregnation

M3 (EPOXY+ Particles)	**BENCH MARK**	**B1**	**B2 (THIN)**	**B1 (THIN)**	**B3**	**B4**	**B5**	**B6**
PDIV at SOL	2.25 kV	NT	1.81	1.65	2.18	2.05	1.13	2.16
K_eff	0.43 W/(m.K)	1.21	0.76	1.68	1.15	NT	NT	1.17
PDIV at SOL	2.25 kV	NT	-1	-1	-1	-1	-1	-1
K_eff	0.43 W/(m.K)	1	1	1	1	NT	NT	1
Σ(+1)	-	1	1	1	1	0	0	1
Σ(S)	-	0	0	0	0	0	0	0
Σ(-1)	-	0	-1	-1	-1	-1	-1	-1
VERDICT	-	RE-DO	DISCARD	DISCARD	ADD-ON	RE-DO	RE-DO	ADD-ON

Table 9.4: Pugh Matrix of the Motorette 06 with Epoxy + Particles for high heat conduction Impregnation

M3 (POLYESTER + Particles)	**BENCH MARK**	**B1**	**B2 (THIN)**	**B1 (THIN)**	**B3**	**B4**	**B5**	**B6**
PDIV at SOL	2.25 kV	2.34	1.72	1.75	2.6	2.37	2.3	2.24
K_eff	0.43 W/(m.K)	1.75	1.43	NT	0.77	1.05	1.58	0.88
PDIV at SOL	2.25 kV	1	1	-1	-1	1	1	1
K_eff	0.43 W/(m.K)	1	1	1	NT	1	1	1
Σ(+1)	-	-	2	1	0	2	2	2
Σ(S)	-	-	0	0	0	0	0	0
Σ(-1)	-	-	0	-1	-1	0	0	0
VERDICT	-	BETTER	DISCARD	DISCARD	BETTER	BETTER	BETTER	BETTER

Table 9.5: Overview of all the motorettes at the Start of Life

SL I	**M2 (STANDALONE - POLYESTER)**	**M3 (EPOXY + Particles)**	**M6 (POLYESTER + Particles)**
B1	ADD-ON	RE-DO	BETTER
B2, THIN	RE-DO	DISCARD	DISCARD
B1, THIN	DISCARD	DISCARD	DISCARD
B3	DISCARD	ADD-ON	BETTER
B4	GOOD	RE-DO	BETTER
B5	DISCARD	RE-DO	BETTER
B6	ADD-ON	ADD-ON	BETTER

10

Discussions

The simulation results are a function of various aspects like the environment setup, mesh, type of solver used. Likewise, the input parameters (All the temperature variables logged from the experiment) determine how close the simulation results are to the test data. It is observed from the figure 9.2 that at the difference in temperatures from the simulation and test data for the first 1000 seconds is higher as compared the agreement of data over the time. This is because the ambient temperature logged is given as a single value averaged over the time. Only two temperature variables are taken with respect to time in the interest of keeping the 3D simulation convergence time as short as possible.

The ambient temperature certainly influence results and controlling the ambient temperature in the test environment should aid in minimising the disagreement between the test and the simulated data.

The temperatures in the system can be increased further with introducing the A/C current which represent the natural drive cycle of the vehicle. This provides the additional data of thermal conductivity as a function of temperature as well.

10.1 Repeatability test

Repeatability test is also perform to see how close is the results in agreement when the tests and the simulations are repeated. The standard deviation of the test done is 0.036 W/(m.K). In the figure 10.1 it is clear that the values are not overlapping with the errors. However in the figure 10.2 few bars seem to overlap. While more control over the testing and simulation environment will reduce the possibility of the error, additional data from partial discharge data (PDIV) also aids in selecting the materials as discussed in 9.5.

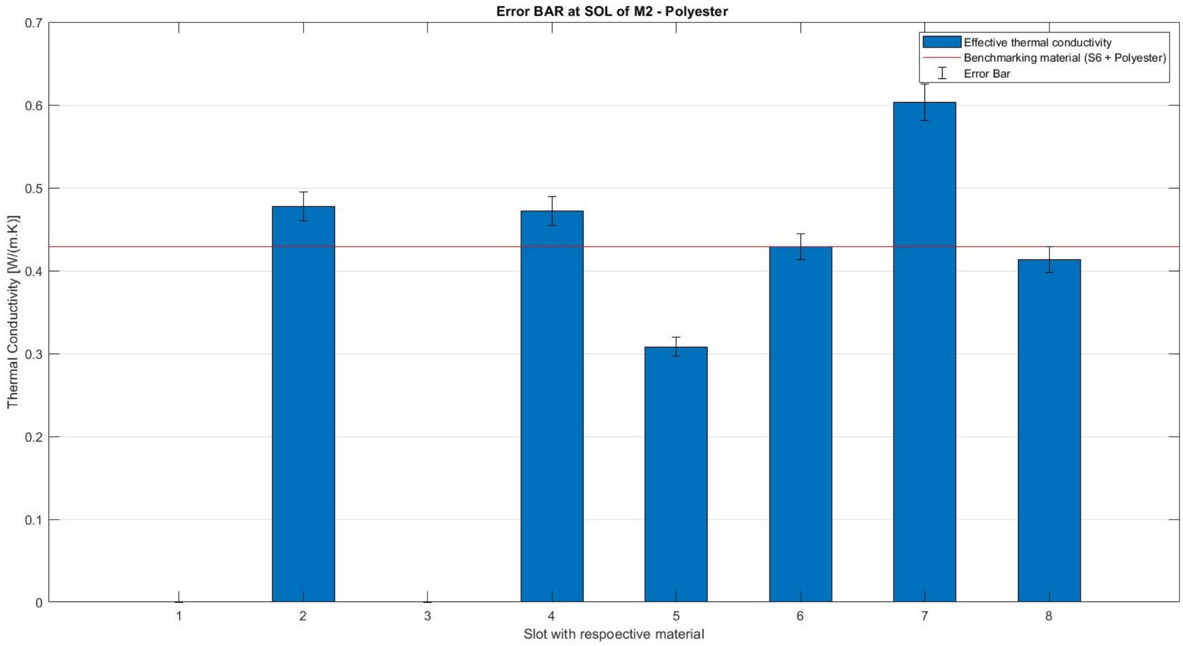

Figure 10.1: Error bars for the standalone polyester

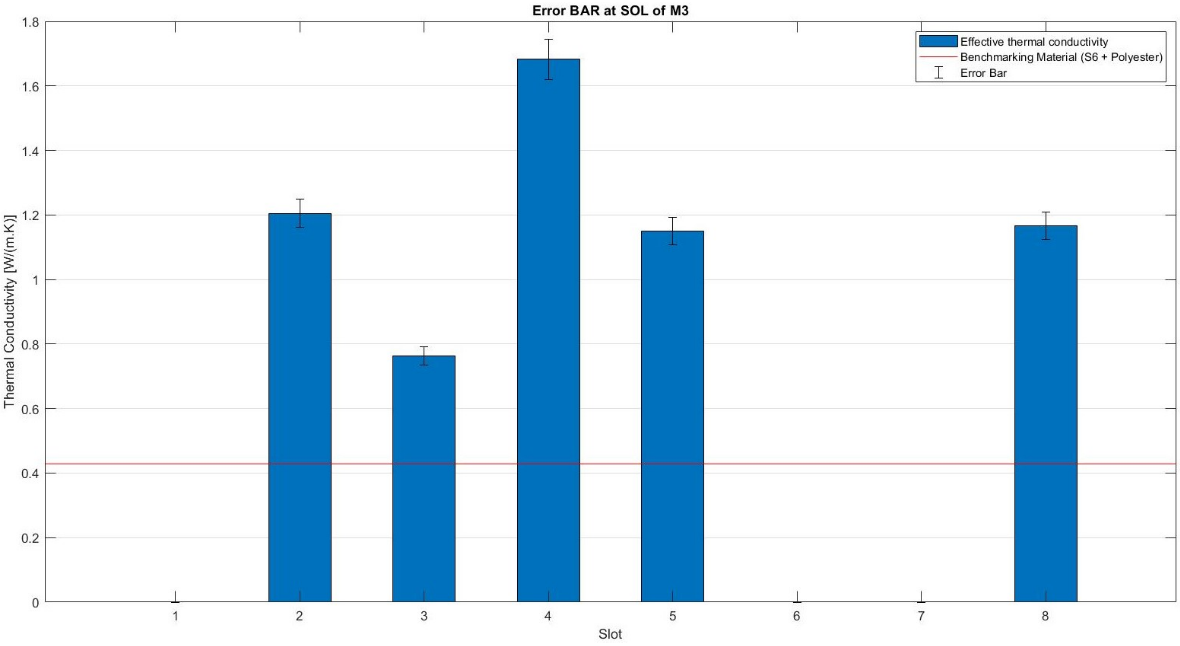

Figure 10.2: Error bar for the Epoxy with particles

11

Conclusion

Climate change represents a potentially irreversible threat to human societies and the planet. Electrification of the vehicles will bring the important balance between both environmental and business sustainability. As the technology and infrastructure matures, with green energy, tailpipe emissions are reduced further promoting the business. In order to obtain electric machines with high efficiency, high power density and high reliability, materials with improved thermal conductivity is important. This study is performed at Scania where the experimental method of evaluating thermal conductivity of different electrical insulation systems.

11.1 Copper Insulation

There are two variants of the copper insulation viz, 230μm also known as Thick and 130μm Thin. As observed from the results data, in the table 9.5 it is clear that the verdict of 230μm is more suitable for the application over the 130μm regardless of the impregnation material. The 230μm presented better partial discharge results as compared to bench-marking material.

11.2 Impregnation

It is clear from the table 9.5 that the polyester with the particles introduced for heat conduction presented the best results from the conducted test on an average for the same slot liners with different impregnation. Epoxy with particles introduced for heat conduction showed better performance over the standalone polyester but more information is needed from same slot liner between these impregnation material to make deeper comparisons.

11.3 Slot Liner

Observing the results, since the slots are arranged in different combination of slot liners, impregnation and the copper insulation, it is only fair to opt for combination of these materials to decide and opt rather than individually picking the corresponding materials.

Polyester with particles for high heat conduction impregnation exhibited best in combination with B1 slotliner. This slotliner being the thinnest among others provide additional advantage in ease of assembly and extra clearance for the viscous epoxy to fill in by different methods. The alternative choices are B5 and B2 slotliners respectively which are thicker compared to B1 slotliner but faintly reduced thermal conductivity. Furthermore, B6 and B3 slotliners also represented almost two times the thermal conductivity as compared to benchmarking material (B2 slotliner with Standalone Polyester). However, B6 turns out to be one of the difficult materials to handle as it is not so much flexible. B3 on the other hand is thickest among the others with very small gaps for the impregnation.

Epoxy with particles for high heat conduction also represented better thermal conductivity in combination with B6 and B3. There is almost no difference in thermal conductivity between these combinations.

12

Future Work

Limitations of the current setup

- The motorette setup physically represented the stator. The amount of heat generated during the experiment is limited due to reasons mention in equation 5.1. The actual temperature inside the motor with the full assembly and operating conditions might influence the temperatures.
- The temperatures at the insulation system are between the range of 50-90 *C during the experiements conducted.
- Detailed information is necessary at the optimal temperatures while the machine is running in the realistic scenario and validate the thermal conductivity.
- The thermocouples are measuring the surface (skin) temperature on the motorette and are sensitive to the air flowing around. Experiment in the contained enclosure will minimise the influence of the forced convection due to ventilation or other reasons in the room.

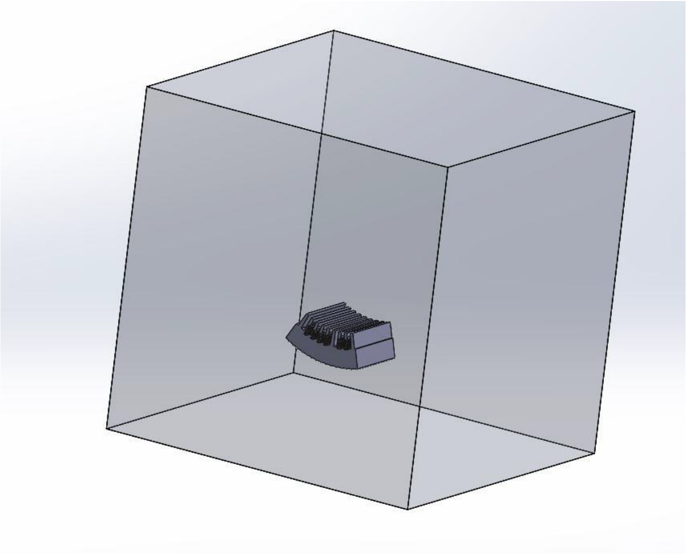

Figure 12.1: Virtual representation of the enclosure

- The impregnation is a chemical containing epoxy and hardener substances which are found to have reacted with the glass fiber on the thermocouples used in the current setup. Replacing with better thermocouples should reduce the preparation time for the setup.

Figure 12.2: PT100 thermocouple, a better alternative resistant to the impregnation compound

- Positive lock mechanism for connecting the conductors in series serves better over the extended temperatures undergone at aging as compared to the soldering which can melt and cause an open circuit or have higher junction resistance.

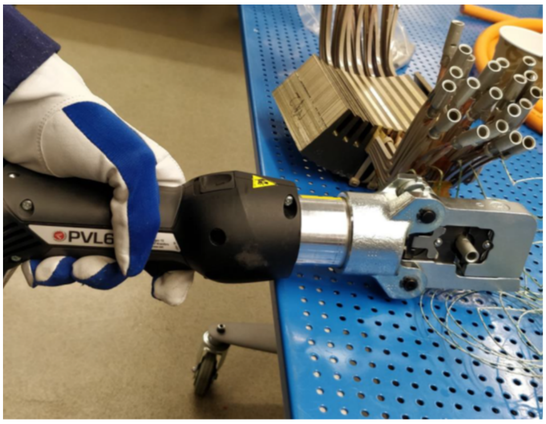

Figure 12.3: Crimping the junctions.

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