

Article

Research in Life Extension of Electrical Motors by Controlling the Impact of the Environment through Employing Peltier Effect

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Abstract: This paper explores the application of thermoelectric cooler/heater (TEC) modules (Peltier heat pumps devices) to control core and winding temperatures, aiming to reduce the effects of thermal cycling and moisture issues that affect the life of electrical machines. Electrical windings in a motor will fail for a variety of reasons, and a major contributor to adverse effects of a motor's life is humidity. Due to thermal cycling, air containing moisture is drawn into a motor through a variety of access points such as terminal boxes, bearings, end covers and mounting systems. Even spare or replacement motors specially stored in heated spare equipment stores suffer from moisture ingress because of normal daily temperature changes. The better a machine can be kept warm, the less it is affected by moisture and the effects of mechanical stresses from cycling temperatures. A series of experiments were conducted, whereby a TEC was attached to a section of motor core and was set up to pump heat into the core segment. The thermal properties of the core material and the capacity to control winding temperatures along the core in specific locations and over time was measured. The results of this research demonstrate that the temperature of the motor can be tightly controlled, thus enabling the reduction of the effects of moisture, and reducing core and winding temperature differences. This has a positive influence in reducing the thermal stresses, which will result in improved insulation life and machine reliability.

Keywords: motor; condensation; thermoelectric device; moisture ingress; insulation; Thermal Management



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1. Introduction

The most utilized electric motor is the induction motor. Because of its high reliability, low maintenance costs and application flexibility, it is extensively used in industry.

Electrical motors fail for a variety of reasons [1,2] but 40% of motor failures are attributed to electrical insulation failure [3,4]. For motors and generators, a key factor leading to winding electrical insulation failure is insulation aging [5], where abrasion issues and micro-cracking effectively thins the insulation [6]. When combined with moisture absorption, leakage currents quickly lead to failure.

Motors when in operation are hot [7,8] and moisture absorption and its negative effects are not normally an issue. When out of service, these motors cool, and this has a detrimental effect. The expansion rate of copper versus electrical insulation between the winding and core are not the same. This cyclic temperature change, from cold (out of service) to hot (in service) and back to cold, continually stresses electrical insulation systems, leading to abraded and damaged surfaces and ground wall (between the conductors and the main electrical insulation) separation [9]. Additionally, because of temperature cycling, air containing moisture [10], is drawn into the motor as it cools. This cold air contains

moisture, and the insulation absorbs the moisture leading to current discharges (tracking) resulting in electrical insulation burning [11]. The older the machine, the greater the degree of insulation damage and the higher the rate at which the winding will absorb moisture. In addition, the moist air drawn into a machine during its cooling cycle through seals, bearings, vents, and terminal fittings, after condensation, accumulates in the machine. This thermal cycling slowly concentrates the internal moisture levels. Even fully enclosed motors will draw moisture into the machine as seals are not gas tight. In special cases, fully enclosed motors have seepage holes installed to help drain moisture away.

There are numerous motor modeling packages [12–16] for motor design, but none has design parameters for aging insulation. Thermal management is part of all design packages and the electrical vehicle industry, spurred on by changing government policy due to resource limitations and pollution mitigation [17], have some of the best combined thermal control systems [18–21], but these are still not perfect as motor design is a balance of performance against desired outcomes. To help combat internal condensation and moisture absorption, manufacturers install electrical heaters in the larger machines, normally located at both ends of the motor and mounted at the bottom of the housing under the winding overhangs [22] (the part of the winding protruding out of the core). This approach helps but still has limitations in delivering heat quickly enough to stop condensation conditions.

While Open Drip Proof (ODP) motors (see Figure 1) are smaller and cheaper to purchase, they have specially designed fans [23] to pump air through the windings to remove unwanted heat. These motors have open vents at both ends of the machine to allow air to be pumped through the motor for cooling, making them very susceptible to pollution and moisture.



Figure 1. Open Drip Proof (ODP) motor.

Motors operated in damp areas seldom last long [24]. Protecting the motor from the elements and paying attention to motor electrical installation requirements is important, as ODP motors can have louvered air intakes to protect from rain and drainage holes to remove any water ingress.

Totally Enclosed Fan Cooled (TEFC) motors (see Figure 2), are better suited to moist conditions but are not impervious to moisture issues. Moisture can still work its way into the motor via mounting support structures, through seals and terminal boxes. For longevity, these motors still require protection from the weather and in very damp conditions may require drainage holes in the housings.



Figure 2. Totally Enclosed Fan Cooled (TEFC) motor.

A major issue exists for motors that are out of service for long periods or have been stored as spares [25]. These motors are still susceptible to condensation and moisture absorption by the electrical winding insulation on a daily and/or seasonal cycles [26,27]. Motors that are stored for long periods of time still experience thermal cycling, even if kept in warm stores. As temperatures increase, air expands and bleeds out of the motor. When it cools, the air contracts, pulling the external air with its moisture into the motor. This effect is also caused by changes in barometric pressure. Even TEFC motors are subject to this process. It has been found that moisture which is drawn into a machine does not come out unless special provisions such as seepage holes are installed. Brand new motors stored in floor heated warm rooms specially set up for motor long term storage have failed initial electrical testing when removed from store for installation. Investigation of the failures found a large amount of water inside the motors [11].

The authors have found that because of the large mass of a motor, the lag in temperature equalization, especially where temperatures can fall to quite low values overnight (a few degrees C in winter in Australia) and rise quite quickly during the day, leads to internal condensation, increasing moisture absorption as water condenses on the internal surfaces and is drawn into the winding [27]. Thus, larger air-cooled motors and generators are particularly susceptible to condensation. The large mass of a motor results in large thermal inertia. The lag in temperature equalization leads to internal condensation, increasing moisture absorption as water condenses on the internal surfaces and is drawn into the winding [27]. To help prevent this condition, heaters are installed to try and keep the internal surface temperatures above dew point [26], a condition that causes the moisture in the air to condense onto the surface [28,29]. Keeping the internal surfaces of large motors above the dew point proves to be difficult to achieve.

Section 2 explains dew point levels, how it can be calculated and the effect on insulation resistance (IR) and the effects of IR on safe operating limits. Section 3 shows the critical location of winding and insulation within the motor core. Section 4 looks at thermoelectric coolers (TEC's) and a set up arrangement that tests the performance of various easily available TEC's. Section 5 looks at a test core setup with TEC to test their ability to pump heat into a motor. Section 6 shows the experimental setup, Section 7 shows the results of testing and Section 8 the results conclusion.

2. The Effects of Moisture on Insulation

Electrical insulation materials best suited to electric machines needs to have high thermal conductivity and low leakage current when stressed by the applied voltage. The higher the thermal conductivity and lower the leakage current the better the insulation.

Small motor windings are predominantly wound with enamel insulated copper wire. There are various types of enamel used for this insulation and normally consist of polyamide-imide resin and polyester-imide resin alternately layered. Testing this insulation to gauge life under various situations is an ongoing process with OEM's (Original Equipment Manufacturer) having their own enamel formulas and layering requirements [30]. In high voltage motors (>3 kV) there are various materials and resins employed to make up the electrical insulation. There are three key areas that require different properties of insulation and flexibility. They consist of main ground wall insulation, end winding insulation, and turn to turn insulation. In these larger machines there can be various materials and resins employed to make up the electrical insulation layer or ground wall insulation as well as the turn-to-turn insulation [31,32], but the application of different materials, different layer thicknesses, order of insulation [30] and various epoxy resins is always a compromise between electrical insulation properties, thermal conductivity and mechanical strength. Thermal cycling damages this insulation and damaged insulation is very susceptible to moisture absorption.

The conditions for motor internal condensation can easily be achieved, with reference to Figure 3 produced from data from F.E. Branch [28], with an air temperature of 27°C and a humidity of 60%, the dew point is 18°C .

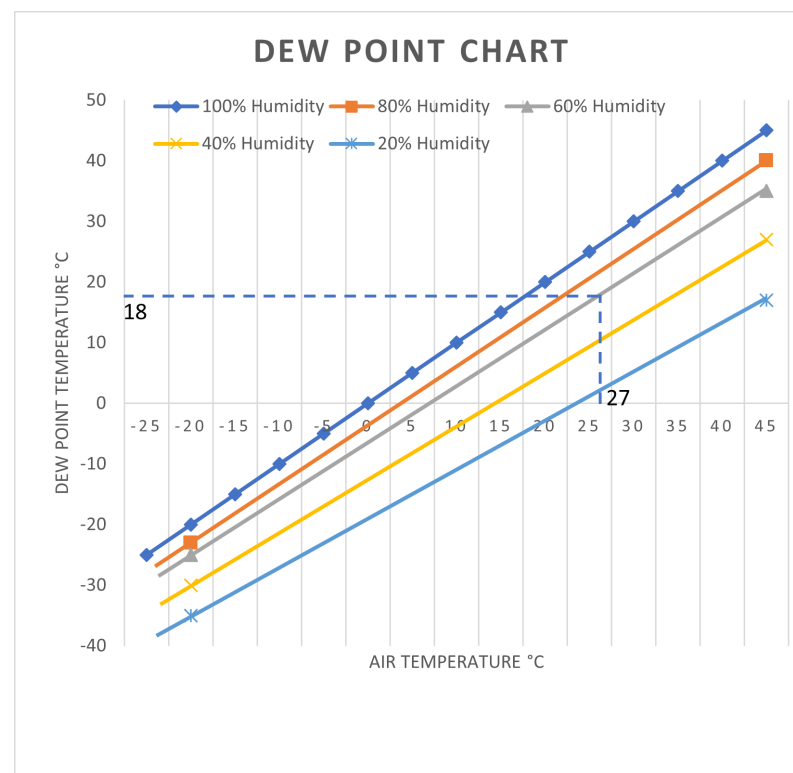


Figure 3. Relationship of air temperature, dew point and humidity for elevations of 0 to 1524 m (adapted from [28]).

Earlier this year, we ran specific electrical tests. 12 generators with similar air temperature conditions were tested and found with poor insulation resistances (IR). Winding temperatures were at approximately 15°C , well below the 18°C minimum limit from

the chart or the 19 °C minimum limit calculated below, thus, moisture was a problem. A simplified equation for calculating dew point is shown in Equation (1) [33]:

$$Td = T - ((100 - RH)/5) \quad (1)$$

where Td is dew point temperature (in degrees Celsius), T is observed temperature (in degrees Celsius), and RH is relative humidity (in percent). Applying this equation to the above example, yields the following example calculation:

$$Td = 27 - ((100 - 60)/5) = 19^\circ\text{C},$$

which is a worse result than the data extracted from Figure 3. Motors that have been out of service for long periods need to be tested before being placed into service. IR testing is a simple 60 s test performed with an insulation tester [27].

For large motors and generators, the recommended minimum insulation resistance (R_{min}), for armature and field windings can be seen in Figure 4, and can be calculated using Equation (2) [28]:

$$R_{min} = V_t + 1 \quad (2)$$

where R_{min} is recommended minimum insulation resistance in megaohms at 40 °C of the entire electrical winding. V_t is the rated line to line voltage (name plate voltage) in, kV RMS [28].

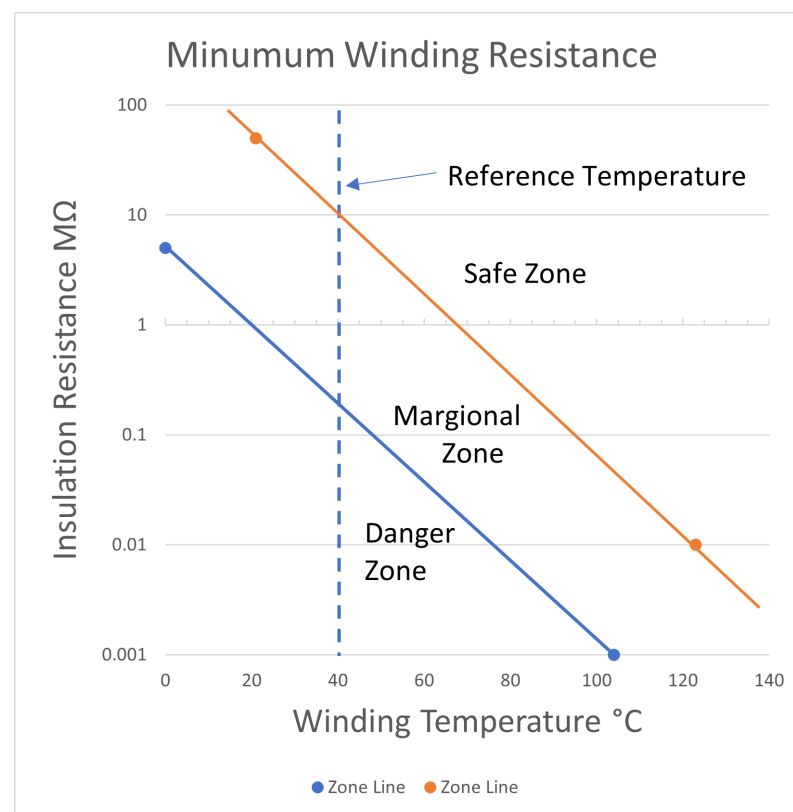


Figure 4. Insulation resistance measurement guide for low voltage motors (adapted from [11]).

Measurements of minimum IR values or a drop in IR measurement larger than 50% from initial IR measurement [25] should not be ignored. It is not uncommon to have winding failures caused by moisture which had been tested and shown to have low IR values with the decision made to run the motor anyway. If the low IR is due to a thin layer of moisture on the surface, running the motor circulates the air and pulls this moisture off very quickly, giving the impression that the low IR readings are not a problem. After witnessing this apparent fix, the impression is created that a low IR can be easily dealt with. However,

the risk of failure is high, as water reduces insulation break down voltages and applying voltage to a wet winding can lead to catastrophic failure. Drying the motor out is a relatively easy process, but it can take a few days. The cost of failure can easily result in down time of weeks and costly repairs.

All motors and generators in operation suffer from thermal cycling, resulting in mechanical stresses, insulation damage and moisture issues. There is no technical solution in the state of the art that can reliably shield electrical machines from the adverse effects of the environment. This is the reason this research was carried out. Thus, the Hypothesis we test in this paper is: “The addition of TECs, solid-state heat pumps can assist with thermal stability of an electrical machine (thereby extending its life)”.

In this research, a thermoelectric cooler (TEC) was employed to pump heat into the core to raise winding temperatures, to reduce the danger of condensation and water uptake by the windings. To the authors’ knowledge, application of TECs to heat a motor (or to reduce/eliminate the influence and impact of adverse environmental conditions) has not been applied anywhere to date. TECs are solid state heat pumps that can pump heat in two directions: out of a core when required to assist the cooling of the electrical machine, or, by reversing the TEC supply connections, the hot side and the cold side are reversed enabling the TEC to pump heat into the core.

This paper investigates the ability of a TEC (using the Peltier Effect) to pump heat into a motor core sample to establish if the temperature of the inner windings can be controlled and maintained above condensation levels. Our previous studies explored using TECs to extract heat from motor cores to lower winding temperatures and help compensate for changing environmental conditions [34,35].

3. The Critical Inner Core with Winding and Insulation

The critical thermal location in a motor is where the stator electrical winding is installed with its copper (or sometimes aluminium) conductors covered with insulation, in the winding slot, shown in Figures 5 and 6.



Figure 5. Motor Stator Inner Core Area with Winding.

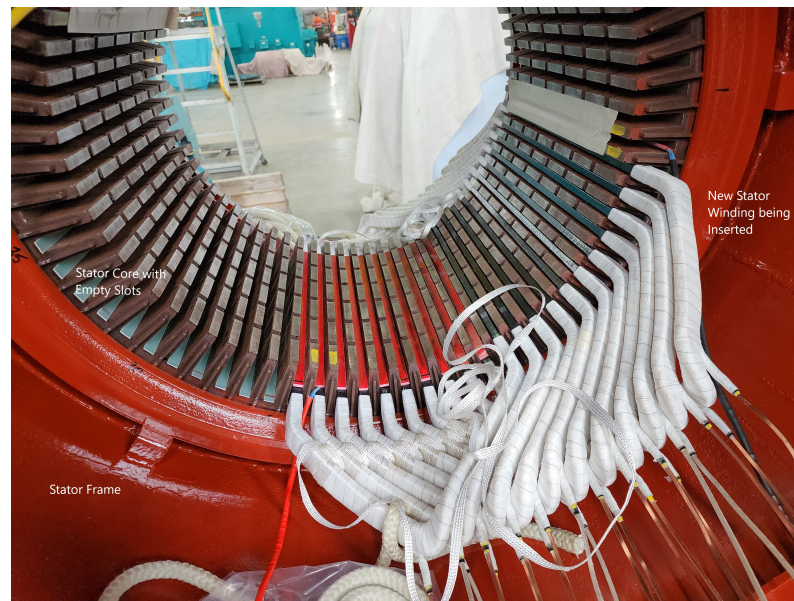


Figure 6. Motor stator core with winding.

It is this inner core area that holds the electrical winding that affects the overall life of a motor. When in operation, the inner core is the hottest part of the motor. The heat generated in this area is removed by conduction from the inner core to the outer core, then to the housing, and, by convection, to the surrounding air. Because of this, the inner core electrical winding temperatures will go from nominally 100 °C when in stable rated operational load, down to ambient 20 °C or lower when cold and off. The temperature difference and constant thermal cycling stresses insulation as the core, the copper winding and the electrical insulation all have different rates of thermal expansion. When running and hot, moisture is not normally a problem, but when the motor is off, the normal daily change in temperature will draw moist air into the motor and any imperfection or damage in materials is susceptible to allow the drawing of moisture into the insulation leading to electrical leakage currents (tracking) and winding failure.

Keeping the inner core above the dew point is critical to reduce the danger of high levels of moisture ingress and the associated damage it creates [24]. This research investigates the application of TEC's to reduce thermal cycling and keep the internal temperature above dew point. The practical outcome of the research could lead to an increase in mean time between failure (MTBF) caused by thermal cycling of an electrical machine.

4. The Experimental Setup to Characterise and Select TECs

There are several thermoelectric cooler/heater (TEC) modules on the market with varying operational parameters. These vary in price and capability and the most available or easily purchased can be found as Peltier Modules [36]. The expected life of these units is 200,000 hrs if maximum ratings are not exceeded.

To test the performance of the TEC in a realistic, open environment (rather than in a lab with the cold side of the TEC held at 0 °C), a TEC test frame was constructed from two heat exchange units made up of fan cooled radiators attached to a heat sink via heat pipes. One heat exchanger was attached to the TEC hot plate and the other heat exchanger was attached to the TEC cold plate as shown in Figure 7. Six commonly available TECs with different current ratings, were tested, the type of each TEC is displayed in Figure 8, and all TECs had the same area (40 mm × 40 mm). Each TEC was supplied with current, in steps, up to name plate rating and the resulting plate temperatures of the hot side and the cold side surfaces recorded. The experimental temperature measurement results can be seen in Figure 8 and the watts transferred in Figure 9. This open environment testing reflects the TEC performance as a heat pump in normal environmental conditions and temperatures.

Data about this scenario does not exist in any data sheets and was required to gauge the capability of the various TECs to help in selecting units most suited to the task.

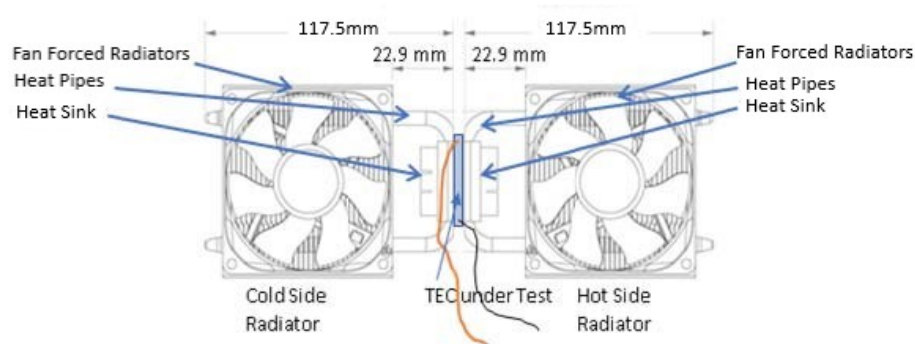


Figure 7. Test setup for testing thermoelectric cooler (TEC).

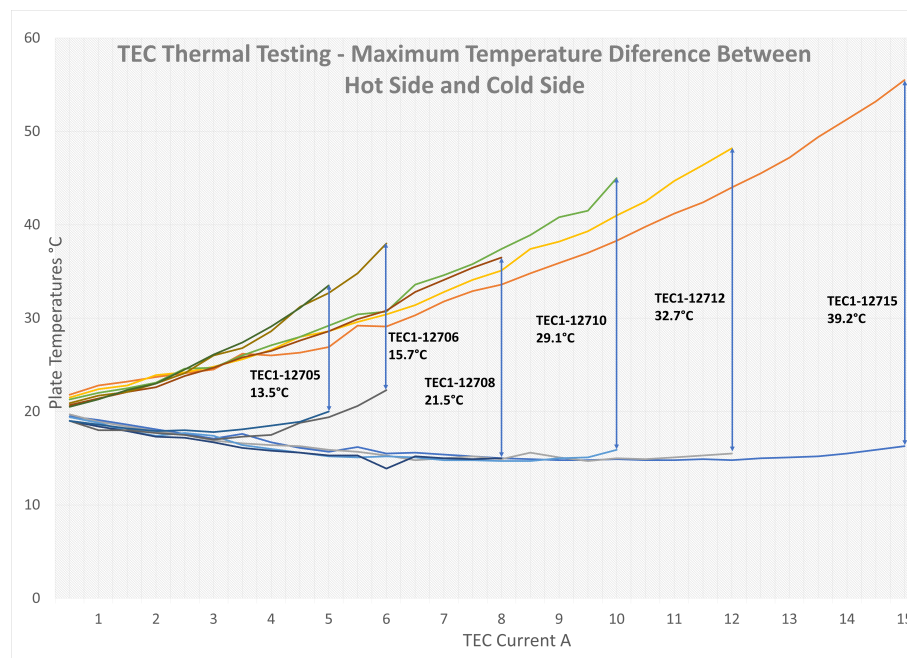


Figure 8. Plots of thermoelectric cooler (TEC) test temperatures.

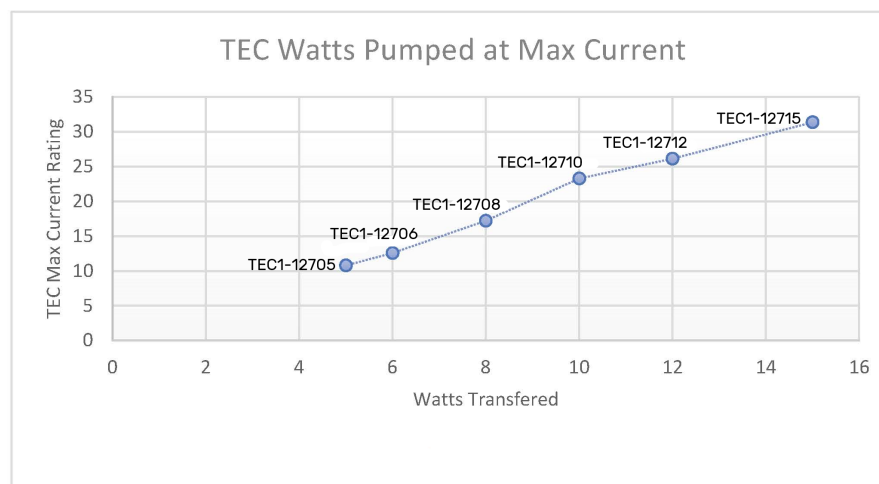


Figure 9. Watts pumped per 16 cm² (TEC area) at maximum current at room temperatures.

The measured and plotted performance in Figure 9 are less than data sheet values, but this can be explained, considering the data sheet values are measured in ideal conditions with the cold plate at 0 °C. The performances measured with this test arrangement are at indoor temperatures, as expected in operational conditions. As shown in Figure 9, TEC performance is approximately linearly proportional to the size or maximum current rating of the TEC.

The thermoelectric cooler (Peltier Module) chosen for this study was the TEC1-12706. Data sheets for these units indicate that they have a nominal 60 W heating/cooling (dependent on current direction) capability at 6 A. Depending on temperature, these units have the capacity of a hot to cold plate difference of 15.7 °C as shown in our test results in Figure 8, and the data sheets show a maximum supply capability of 17.2 V at 6.1 A. These units were the most easily obtainable and were the least expensive, making them ideal for test purposes.

5. Test Core Characterisation

To test the ability of the TEC to affect the inner core temperature of a motor, a core section was set up to represent the thermal characteristics of a motor that we could attach TEC's and monitor thermal results. With the core section with resistive heaters attached on the inner surface representing the winding, then the test piece was well insulated with just the upper surface exposed, simulating the thermal environment for a motor. With the internal resistors unpowered, the test piece represented an unpowered motor. A section of a stator core was cut to match the 40 mm × 40 mm thermoelectric devices. The core segment was cut 40 mm wide, 80 mm long and 35 mm deep containing 150 laminations, approximately 0.473 mm thick (Figure 10). Five 2 mm holes were drilled into the sample segment to enable K type thermocouples to be inserted so that temperatures at both surfaces and 3 positions across the core sample could be measured. Eight 22 Ω, 10 W resistors were glued to the inner surface and connected in parallel (80 W capability) and for this analysis, it represents a motor winding and winding insulation. The core segment was then insulated with only the top surface exposed, representing the outer motor surface. Two TECs with heat sinks were then attached to the upper surface, utilising thermal grease for improved thermal conduction. The general setup can also be seen in Figure 11.

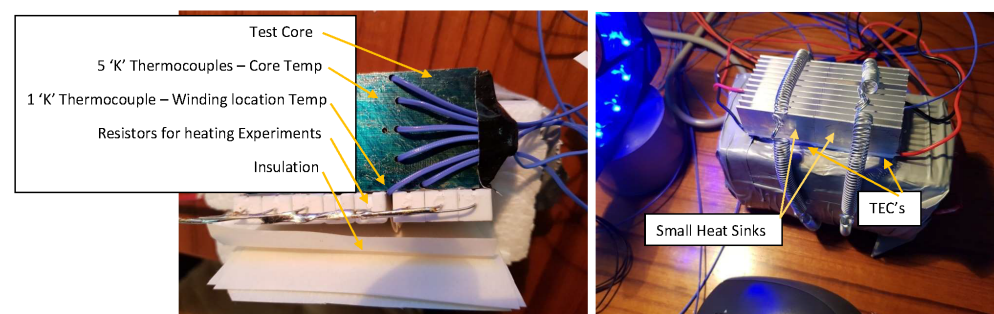


Figure 10. Sample arrangement with K type thermocouples and thermoelectric coolers (TECs) with heat sinks.

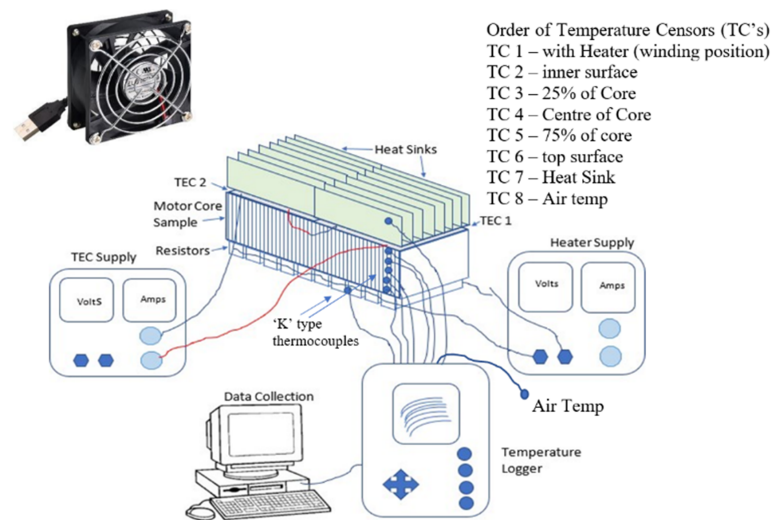


Figure 11. Experimental motor core sample setup.

The most utilised material for motor cores is M19 and work by Pieterse [37] shows that thermal conductivity of motor core material M19 (2.75% silicon steel) varies between $22.8 \text{ W/m} \times \text{K}$ at 22°C , $24.7 \text{ W/m} \times \text{K}$ at 100°C and $26.6 \text{ W/m} \times \text{K}$ at 180°C as shown in Figure 12. The figure shows that thermal conductivity slightly increased with temperature.

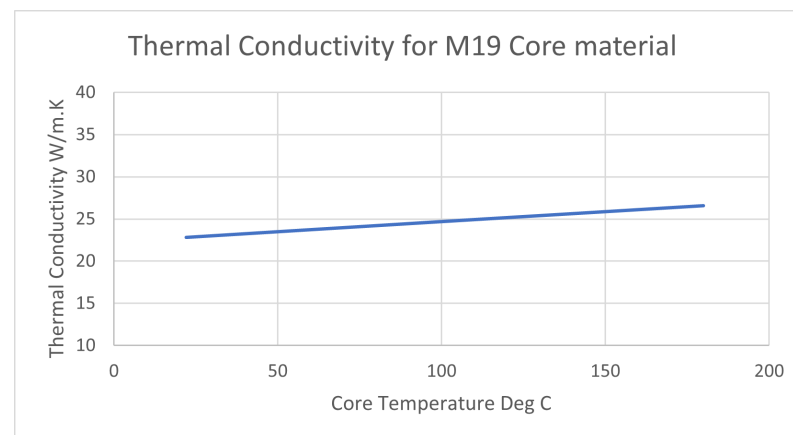


Figure 12. Thermal conductivity of M19 core material.

For this core segment, the thermal constant can be calculated. For one-dimensional heat transfer through an object, the conductive heat flux, $\dot{q}_{cond}$, is given by Fourier's law,

$$\dot{q}_{cond} = -k_x \times \frac{dT}{dX} \quad (3)$$

where, k_x is the thermal conductivity of the material in direction x . Rearranging this equation to calculate thermal conductivity

$$k_x = \dot{q} \times \frac{dX}{dT} \times \frac{1}{A} \quad (4)$$

where dT is the difference between inside surface temperature and outside surface temperature, in this case 55.1°C and 48.2°C . In our sample, the losses in heat from the sides and bottom were approximately 15%. Maximum power supplied was 7.3 V, 2.5 A, giving

$$P = V \times I = 18.25 \text{ W} \quad (5)$$

Input power minus 15% for losses

$$\frac{18.25}{1.15} = 15.87W = \dot{q} \quad (6)$$

In our sample: Area, A was 40 mm by 80 mm (0.04×0.08), thickness, dX was 35 mm (0.035). Applying our measured results,

$$k_x = 15.87 \times \frac{0.035}{(55.1 - 48.2)} \times \frac{1}{(0.04 \times 0.08)} = 25.1 \text{ W/m} \times K, \quad (7)$$

confirming that the core sample was M19 core material.

6. The Experimental System

In the test setup in Figure 11, the TECs were attached to a 15 V/30 A laboratory power supply. The thermocouples were attached to a temperature data logger connected to a laptop to capture and plot each of the thermocouple temperatures. Additionally, there was a local weather station allowing temperature, humidity, and pressure in the test area to be recorded during testing. A small 12 V computer fan with supply was set up to provide a fixed low velocity airflow across the sample. The layout of the equipment can be seen in Figure 13.

The core arrangement was to simulate a motor, unpowered, and sitting in its normal position or stored for future use. The procedure was to apply voltage and current to the TEC and pump heat into the core and raise the temperature at the winding position. A number of fixed current settings were used and the system allowed to thermally stabilise at each current setting. The results were collected for analysis.

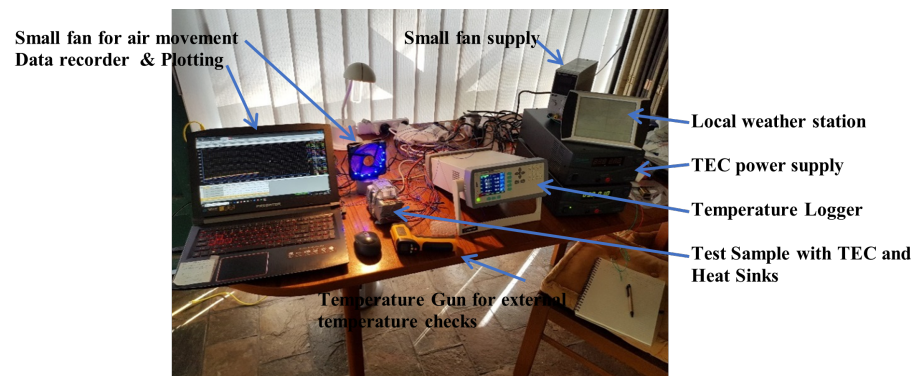


Figure 13. Layout of testing equipment.

7. Measurements and Discussion

The test core sample was positioned clear of other items and in front of a small computer fan, allowing unobstructed movement of a low speed air current, as shown in Figure 11. Seven power settings (0.5 A–0.5 W, 0.9 A–1.62 W, 1.3 A–3.51 W, 1.7 A–6.63 W, 2.2 A–11.66 W, 2.7 A–19.44 W and 3.2 A–28.8 W) were supplied to the TEC modules to pump heat into the core sample. Temperature change of the core sample location per unit of power into the TEC is reported here as $^{\circ}\text{C}/\text{W}$. Temperatures of each thermocouple were recorded and plotted, shown in Figure 14, and magnified end temperatures Figure 15, using a data logger and the temperatures allowed to stabilize (specifically TEC1 and TEC2 the winding position test points—approximately 1 h at each setting) before final temperatures and environmental conditions were recorded.

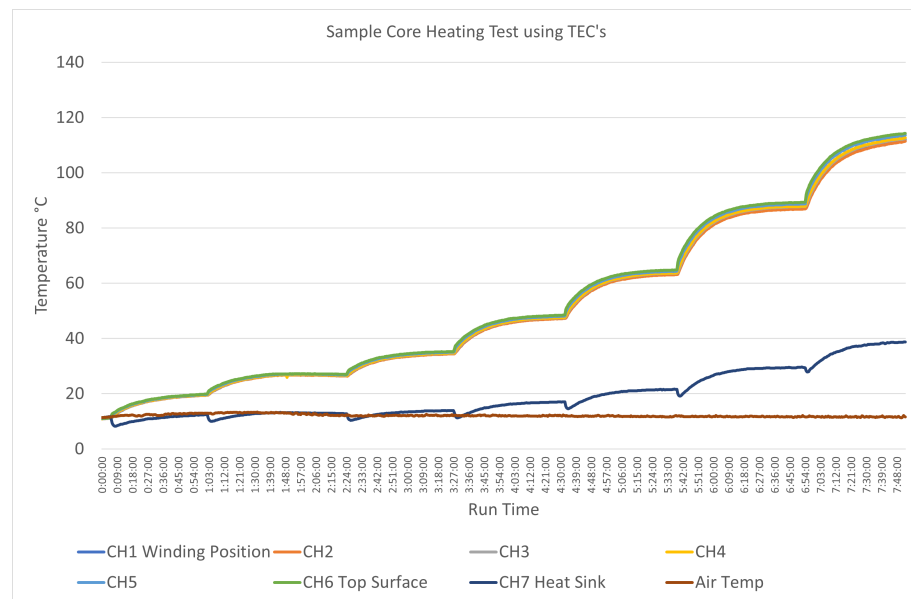


Figure 14. Temperature results of the core sample at 7 TEC power settings.

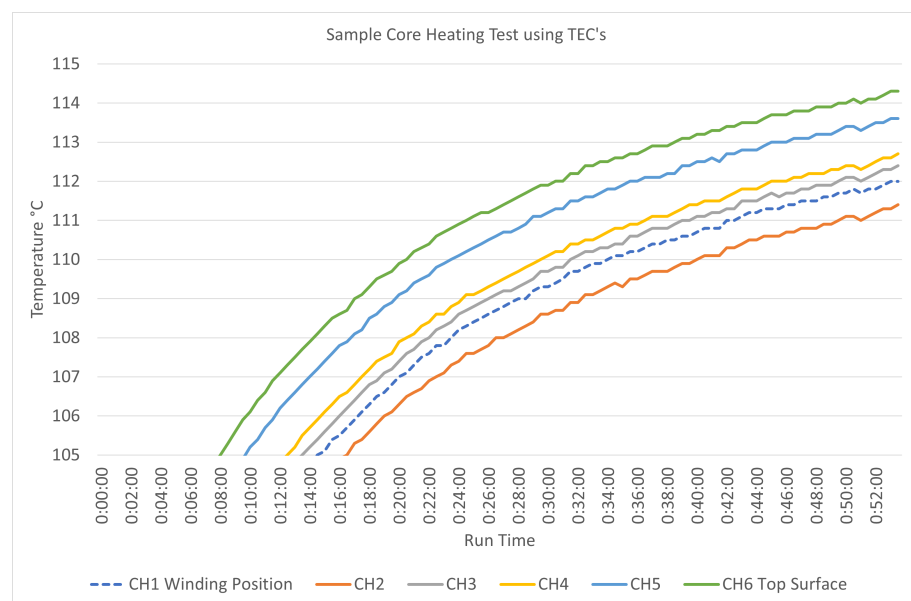


Figure 15. Zoomed final core temperature results.

The heat transfer through the test core was linear with only a 6.9 °C difference between TC2 to TC6 (across the test core) as can be seen in Figure 14. The rate of temperature rise at the winding position thermocouple 1, Figure 14 was 2.6 °C/W. The slight step at the current increase point (CH7 Heat Sink) was caused as the supply was disconnected for a short time to set the current for the next step. Keeping the inner core hot greatly reduced the magnitude of thermal cycling, and we infer, thermally induced mechanical stress and should reduce moisture ingress into the motor.

The sample core set up was heated to normal full load temperatures and then allowed to cool naturally. As can be seen in Figure 16, the cool down time was approximately 2.5 h. This time lag in normalising temperatures is a major problem in the industry. A relatively small temperature difference and high humidity, see Figure 3, will produce condensation. The lag in thermal stabilization because of the large mass of the stator and rotor cores is a major problem and even in good weather, temperature difference can lead to internal condensation. Hot motors are not affected by moisture [7,8], and keeping motors hot, or well above dew point [28,29] is difficult. These tests were able to show that the

temperature at the winding position was able to be pushed to $>100\text{ }^{\circ}\text{C}$ which is well above dew point temperatures which on the graph is $50\text{ }^{\circ}\text{C}$ at maximum. These temperatures are consistent with the temperatures found in fully loaded motors.

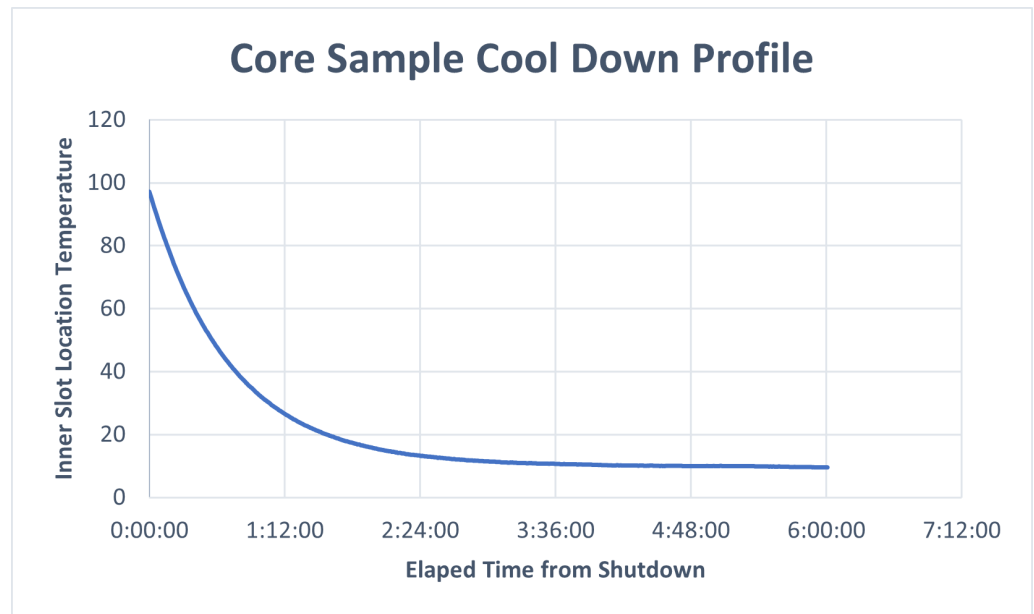


Figure 16. Core sample configuration cool down profile.

Recorded temperatures shown in Figure 17, indicate that the temperature across the core segment thermocouples T2–T6, Figure 17, only varied by approximately $2.9\text{ }^{\circ}\text{C}$.

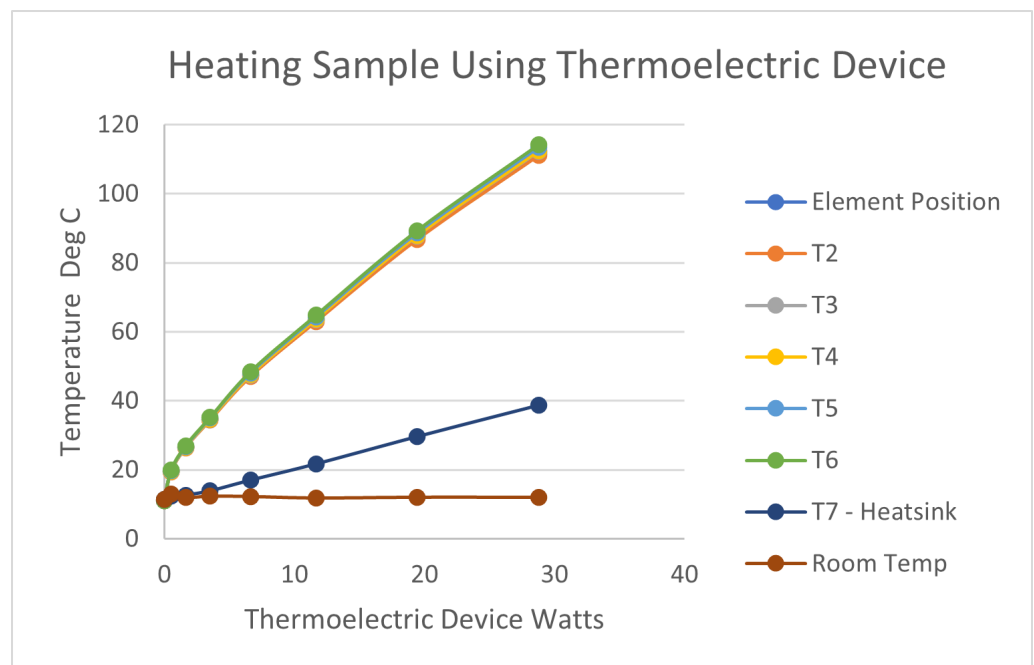


Figure 17. Graphed results of core sample thermal heating testing.

The heat transfer through the core segment was linear and was very close as can be seen in Figure 17, T2 to T6 as described above. These are the temperatures across the core segment. The difference is an indication of the losses from the sides and from the inner surface through the insulation. The rate of temperature rise at the winding position, TC1, Figure 17, was $2.6\text{ }^{\circ}\text{C}/\text{W}$. This enabled the inner core position temperature to rise to greater

than 110 °C, Figure 17, well above dew point conditions. All the temperatures as shown in Figure 17 were below normal full load operating conditions and would not cause damage. Rather, maintaining the elevated temperatures should reduce thermal cycling stresses and improve insulation and motor life.

8. Conclusions

The purpose of this study was to examine whether a thermoelectric cooling module (solid state heat pump) with a reversed polarity supply, thus acting as a heating module, can contribute to the heating of a standard core configuration, by increasing temperatures at the winding location.

The research presented in this paper supports the hypothesis. Keeping the windings hot helps control the temperatures so as to postpone condensation/moisture issues and reduce thermal expansion stresses which often result in increased insulation life and operational reliability.

The application of TEC (heat pump) to a test sample made from a motor stator core was set up to replicate a normal motor arrangement shown in Figure 11. The arrangement enabled the TEC to pump heat into the core segment via the outer surface, raising the temperature of the inner core. The tests have shown that the winding position temperatures can be significantly increased with a relatively small amount of power. Temperatures greater than 110 °C were reached with only 30 W of input power.

Keeping motors warm and eliminating moisture problems results in increased motor life, reduces life cycle costs and material consumption.

Future expansion of this research will involve their application to a real motor set up with various cooling arrangements to gauge the effectiveness of keeping motors above dew point conditions and thus, stopping moisture condensation affecting winding insulation systems. It is predicted that it may be possible to reduce thermal differences between in-service and out-of-service conditions and reduce thermal stress to the insulation systems. If successful, the long-term application of these devices and their location either on the surface or between the core and the frame will probably be a justifiable addition to most large motors.

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