Improvement of heat transfer for DC motor windings

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Abstract. Temperature rise due to energy losses in the windings can reduce the performance of a motor as well as its service life. High temperature will damage the insulation on the windings and can eventually cause a short circuit that will permanently destroy the motor. Two different modifications which are internal modification and external modification will be implemented on a DC motor in order to improve the heat dissipation rate. Internal modification is responsible to improve the heat transfer rate between the windings and the casing while on the other hand, external modification will improve the heat transfer rate between the casing and the ambient air. In order to come out with effective strategies to improve the rate of heat transfer of a DC motor, different components temperature in a DC motor will be studied thoroughly to understand which component in a DC motor is affected the most by the heat waste produced when current is allowed to flow through the windings. Three different designs for heat sink which is also the external modification will be analysed in this paper to understand the relationship of their respective geometry and their heat transfer performance. By allocating the same amount of material for each heat sink modification, we can identify which design can increase the natural heat convection of the DC motor by the largest margin. Furthermore, comparison between the internal modification and external modification are studied to determine which method is more effective in removing the heat waste generated by the windings.

Keywords. DC motor; Heat transfer; Winding; Thermal conductivity; Casing; Heat sink; Convection

1. Introduction
DC motor is a rotary electrical machine that converts direct current electrical energy into mechanical energy. The motor consists of several components, such as casing, windings, brush, bearing, armature core and permanent magnets which are shown in figure 1. When current is allowed to flow through the windings, it will create a magnetic field around the windings. The magnetic field of the permanent magnet will create a repulsion force against the windings which then rotate the motor’s shaft.
Figure 1. DC motor components disassembled.

Thermal behaviour of an electrical motor is a crucial issue to be looked into to ensure that the motor can be operating in good condition [1-4]. This is depending on application and environment. It is necessary to ensure that the motor is not being submitted to a temperature that can damage its components.

1.1. Heat sources / losses in a DC motor

Understanding the heat sources in a DC motor is crucial in improving the heat dissipation rate of the motor. Heat are generated when current is allowed to pass through the windings due to a few phenomenon such as copper losses and iron losses.

Copper losses or Joule heat losses are due to the electrical resistance of the winding material. Joule’s first law states that the heat loss generated by a winding is proportional to the product of its resistance and the square of the current:

\[ P = I^2R \]  

(1)

Assuming adiabatic conditions, Soeren Gies [1] shows that the temperature increased, \( \Delta T \) can be calculated by integrating equation (1) as follows:

\[ \Delta T = \frac{R' \cdot \int_0^1 I^2(t) dt}{m_c \cdot C_c} \]  

(2)

where \( m_c \) is the mass and \( C_c \) is the constant specific heat capacity of the conductor.

In direct current applications, the effective resistance equates to:

\[ R_c = \frac{L_c}{A_c \cdot K_c} \]  

(3)

\( L_c \) is the length of the winding, \( A_c \) is the cross sectional area and \( K_c \) is the specific electrical conductivity of the material. The longer the winding or the smaller the diameter of the winding, the higher the resistance of the winding. Thus, more heat waste will be generated.

On the other hand, iron losses in windings are also known as hysteresis losses which is caused by the repetitive and continuous magnetization and demagnetization of the winding as shown in figure 2. Magnetic fields are created when electric current is allowed to flow through the windings. The strength of the magnetizing force is proportional to the increased in the current provided.

In ideal scenario, when the motor brushes lost contact with the commutator, the magnetizing force should be reduced to zero as the current is cut off. Bertotti’s study on magnetic hysteresis proved that some magnetic flux will still exist in the material even after the current is cut off [2]. This phenomenon is known as retentivity. When opposite current flows into the material, it will create an opposing magnetic field which will remove the residual magnetism left on the material. This additional force is known as coercive force and it will contribute to additional energy waste.
Figure 2. Hysteresis loop for silicon-iron alloy used in transformer core [2].

1.2. Internal modification
From figure 1, there are gaps between each armature core and each of these gaps are filled with air (rotor assembly on the right). Air have a very bad thermal properties especially in small cavity such as inside the casing of a DC motor. Heat transfer coefficient for free heat convection of air is \(10 \text{m}^2 \text{K}/\text{W}\). However, according to the research done by Luis E. Juanico [3], the heat transfer coefficient for 1cm thickness of air layer in an enclosed cavity ranges between \(2.2779 \text{ W} / \text{m}^2 \text{K}\) to \(7.9365 \text{ W} / \text{m}^2 \text{K}\). Table 1 shows the heat transfer coefficient for air in enclosed cavities.

| Air cavity placement               | Thickness of air layer (mm) | Heat Transfer Coefficient (W/m²K) |
|------------------------------------|-----------------------------|----------------------------------|
| Vertical                           | 10-20                       | 7.15                             |
|                                    | 20-50                       | 5.88                             |
| Horizontal (Heat flow from bottom to top) | 10-50                       | 5.88                             |
| Horizontal (Heat flow from top to bottom) | 10-50                       | 4.76                             |

And the heat transfer rate can be computed using Newton’s law of cooling:

\[
Q_{\text{conv}} = h A_s (T_W - T_c)
\] (4)

where \(h\) is the average heat transfer coefficient on the air and \(A_s\) is the heat transfer surface area.

The equation can be rearranged into

\[
Q_{\text{conv}} = \frac{(T_W - T_c)}{R_{\text{conv}}}
\] (5)

where the thermal convection resistance \(R_{\text{conv}}\),

\[
R_{\text{conv}} = \frac{1}{h A_s}
\] (6)
By replacing the air around the gaps with a different material, the natural heat transfer between the armature core and casing can be enhanced. Table 2 shows the thermal properties for several materials that are taken into consideration while choosing the suitable material to replace air. Solids are a better substitution choice as they require less maintenance and more robust compare to liquids or gasses. Risks of leakage will always be present if liquids or gasses are used. In this paper, polyurethane foam will be used to fill the gaps around the armature core due to their low density and ease of handling as well as cheaper cost compare to other solid materials. Materials with higher density will reduce the performance and efficiency of the motor.

| Materials                  | Thermal Conductivity (W/m·K) | Specific Heat (J/kg·°C) |
|----------------------------|-------------------------------|-------------------------|
| Copper                     | 385                           | 385                     |
| Aluminium                  | 205                           | 897                     |
| Copper-Diamond Composite   | 454                           | 463                     |
| Steel                      | 50.2                          | 510                     |
| Gold                       | 315                           | 125                     |
| Water at 30 °C             | 0.61                          | 4182                    |
| Polyurethane               | 0.03                          | 1800                    |
| Air                        | 0.024                         | 1005                    |
| Hydrogen                   | 0.172                         | 14304                   |
| Helium                     | 0.142                         | 5193                    |

By filling the gap with polyurethane foam completely, we can use equations for heat conduction in calculating the rate of heat transfer. Fourier’s law of heat conduction can be expressed as:

$$Q_{\text{Cond}} = -kA \frac{dT}{dx}$$

(7)

where $k$ is the thermal conductivity of the solidified polyurethane foam while $A$ is the surface area involved in the conduction heat transfer.

By integrating and arranging the equation (4), we can calculate the rate of heat transfer with the temperature of windings, $T_W$, casing temperature, $T_C$ and conduction resistance.

$$Q_{\text{Cond}} = \frac{T_W - T_C}{R_{\text{Cond}}}$$

(8)

where thermal conduction resistance, $R_{\text{Cond}}$

$$R_{\text{Cond}} = \frac{L}{kA_S}$$

(9)

By using equation (6) and equation (9), we can determine the thermal resistance of the gaps for air and polyurethane foam.

1.3. External modification

External modifications are modifications done on the outer surface of the casing in order to increase the heat transfer rate between the casing and the ambient temperature. Rate of heat transfer rate can be
increased by increasing the surface area exposed to the ambient air. Heat sink is one of the better strategy in improving the heat dissipation rate of a motor as it doesn’t require any maintenance, robust and cheap.

Heat sinks are usually quite heavy but with study and research, the volume and weight of heat sinks can be reduced. Most of the time, heat sink design process is not regarded as important as other processes involved and they are often oversized [6]. The material used in the fabrication of heat sinks in this project is Aluminium 3104 which is usually used to manufacture beverage cans. It has a thermal conductivity of 170 W/m•K and a heat capacity of 880 J/kg•ºC. In this paper, three different heat sink designs will be proposed to understand the relationship of their geometry particularly the heat sink height and gap between fins with their respective rate of heat dissipation.

In the analysis of heat sinks done by [7], the value of convection heat transfer coefficient varies along the surface of the fins. At the fin base or where the heat sink is attached to the motor, the value of the coefficient is usually a lot lower compare to the other end because the heat from the fin is surrounded by solid surfaces near the base, causing it to encounter more resistance to be dissipated. On the other end, the heat from the fin tip has little contact to solid surfaces, which allow it to be dissipate much more easily.

On the other hand, height of the heat sink is also another important criteria to be determined during the fabrication process. Longer fins yield larger surface area, but this doesn’t mean that the rate of heat transfer will increase infinitely along with the increase in height of the fins. The temperature of the heat fin is highest at the base and drop exponentially toward the tip until the temperature reaches the environment temperature at a certain length. The part of the fin beyond this length will not contribute to any heat transfer as the temperature of it, is equilibrium to the environment. The additional length will just contribute to material waste, excessive weight and in the worst scenario, reduce the convection heat transfer. The purpose of the three different heat sink designs is to investigate the relationship of the height of the fin and the gap between each fins, where same amount of material is allocated for each design.

If $10^3 < Gr \cdot Pr < 10^9$, the flow can be assumed to be laminar. Since the value of $Gr \cdot Pr$ for the three designs is smaller than $10^9$, we can ignore the flow for turbulent flow. With Prandtl number:

$$Pr = \frac{\mu C_p}{k}$$

where $\mu$ is the dynamic viscosity, $C_p$ is the specific heat and $k$ is the thermal conductivity of fluid at film temperature.

Grashof number:

$$Gr = \frac{\rho^2 \beta C_p g (T_c - T_w) L^3}{\mu k Pr}$$

where $\rho$ = density at film temperature
$\beta$ = coefficient of volume expansion
$g$ = gravity constant
$L$ = height of the fins
$Pr$ = Prandtl number

Below shows the heat transfer coefficient formula for laminar flow.

Heat transfer coefficient for laminar flow:

$$h = C_1 \frac{k}{L} (Gr \cdot Pr)^{0.25}$$
where $C_1$ is dependent on the geometry of the system and can be found from the table for empirical constants for natural convection. In this case $C_1$ is 0.548.

![Figure 3](image.png)

**Figure 3.** Efficiency of circular, rectangular and triangular fins [8].

Rate of heat transfer from the fins can be calculated using the formula below.

$$ Q_{TotalFin} = n[\eta_{fin}hA_{fin}(T_C - T_w) + hA_{unfin}(T_C - T_w)] $$  \hspace{1cm} (13)

Where $n$ is the number of fins and $\eta_{fin}$ is the fin efficiency which can be found in figure 3 above.

![Figure 4](image.png)

**Figure 4.** Heat sink design 1, 2 and 3.

Figure 4 above shows the proposed heat sink design. The heat fin is made of 0.1 mm thickness Aluminium 3104 which is attached on the motor casing using thermal paste. The joint is further strengthened using epoxy. Thermal paste is used to ensure that there is no gap between the heat fin and the casing. If any air gap is present between the heat sink and the surface of the casing, it will act as a layer of insulation. As we can see in figure above, design 1 consist of 10 pieces of 7cm × 1.5cm × 0.1mm heat fins. Design 2 consist of 15 pieces 7cm × 1cm × 0.1mm heat fins. For design 3, there are 30 pieces 7cm × 0.5cm × 0.1mm heat fins. All the heat sinks for each design are all fabricated using the same amount
of material. Rate of heat transfer of the three heat sink designs can be calculated by using the equations (13) and shown in Table 3 below.

| Case | Heat fin weight, g | Fin height, mm | No. of fins | Total surface area, $mm^2$ |
|------|--------------------|----------------|-------------|---------------------------|
| HS1  | 4.633              | 15             | 10          | 21100                     |
| HS2  | 4.638              | 10             | 15          | 21135                     |
| HS3  | 4.624              | 5              | 30          | 21240                     |

2. Methodology

In this chapter, fabrication methods to improve the heat transfer for the windings in a DC motor are discussed. In section 2.1, the test bench used in this project will be explained. Basic motor modifications will be explained in section 2.2. In the following section, both internal and external motor’s modifications in order to improve the heat transfer of the windings will be explained. Modifications will be done on two different motors while the third motor will act as a control. The results obtained from the two modified DC motors will be compared to the control.

2.1. Test bench

This experiment is conducted by magnifying the effect of copper losses to increase the temperature of the DC motor in a shorter period of time. Copper losses is referring to the unwanted heat produced by electrical current in windings. This heat contribute to the majority increased in the temperature of a DC motor. Joule’s first law stated that the relationship between heat produced and the current flowing through the winding is proportional as shown in the equation below.

$$Copper\ Losses = I^2R$$

Where, $I =$ Current
$R =$ Resistance

As we can see from equation (14), the copper losses are proportional to the resistance, $R$ and by changing the current, it is possible to manipulate the copper losses in the windings. Current can be increased by increasing the resistance acting on the motor shaft. The test bench used in this project as we can see in figure 5 (top left). The test bench is fabricated using bicycle’s sprocket, chain and braking mechanism. Loads are applied onto the nylon string which is connected to the braking mechanism which will then produce frictional force on the sprocket as shown in figure 5 (top right). The power supply used in this experiment is Keysight U8031A triple output DC power supply (figure 5 bottom left) that provides excellent load regulations. Figure 5 (bottom right) shows the Picolog data logger and type K thermocouple which are used to measure the temperature of the bearing, casing, magnet, brush of the DC motor and also the ambient temperature.
2.2. Motor’s instrumentation

In this section, the instrumentation of thermocouple and modification process to improve the rate of heat transfer will be discussed. Modifications will be done on two different motors and the third motor will act as a constant.

First, the coating on all the motors need to be removed to improve the conduction heat transfer via the heat sink and the casing. Coating for the constant motor needed to be removed to ensure that the operating conditions for all the motors are the same. Figure 6 shows the constant motor.

Three holes are drilled at strategic locations to allow the entry of thermocouple to measure the temperature of each respective position. As we can see from figure 6, one through hole is drill to allow the measurement of the temperature of the magnet inside the casing and the other is a half drilled hole to allow the thermocouple to measure the temperature of the casing.
Another hole is drill on the casing cover as shown in figure 7 (top right) to allow the thermocouple to measure the temperature of the bearing. As we can see from figure 7 (bottom left), the thermocouple is attached onto the magnet using a thermal paste through the hole drilled. In figure 7 (bottom right), the thermocouple is attached onto the brush. All of the holes are then covered with thermal paste to minimize heat loss through the hole. Another thermocouple is used to measure the ambient temperature, bringing it to a total of five thermocouples used for this experiment.

2.3. Internal modifications
After instrumentation of the motors with thermocouples are done, we proceed with modifying the internal structure to add its thermal conductivity. It is done by adding polyurethane spray foam between the gaps of the windings in the rotor slot. We are using Bossman general purpose polyurethane spray foam as our chosen material. The polyurethane foam will solidified in about thirty minutes. Extra polyurethane that is protruding the surface of the windings were removed to ensure that it will not disrupt the rotation of the shaft when the motor is switched on, as shown in figure 8.

Figure 7. Top left: DC motor’s casing. Top right: thermocouple measuring the temperature of the bearing. Bottom left: thermocouple measuring the temperature of the magnet. Bottom right: thermocouple measuring the temperature of the brush.

Figure 8. Extra polyurethane is removed.
2.4. External modifications

Next, we proceed with modifying the external surface of the casing. For this experiment, we are reusing the aluminium sheet from beverage drink cans. The first step is to remove all the coating from the aluminium sheet using sandpapers.

The dimensions of the heat sink are drawn onto the aluminium sheet and then cut out. It is then bent to create an L shape. One of the bended surface will be attached onto the surface of the casing. After the heat sink is bent, a thick layer of thermal paste is applied onto the heat sink and attached to the surface of the casing. The thermal paste is spread out evenly and uniformly across the surface to ensure that no gap will present between the heat sink and casing. Presence of air gaps will reduce the efficiency of heat sink as they will act as a layer of insulation. After the heat sink is placed at their respective position, the joint will be strengthened by using epoxy. All the three heat sink design and the constant motors are shown in figure 9.

![Figure 9. From top left to bottom right: Constant motor, heat sink 1, heat sink 2, and heat sink 3.](image)

After all the modifications are done, we can now proceed with testing the performance of our DC motor. Each DC motor are fed with a voltage of 5V and they will be run for three times for 0N load, 200N load and 400N load until they reach their peak temperature (steady state temperature). The maximum temperature, settling time and time constant for each of them will be recorded and tabulated.

3. Results and analysis

In this chapter, overall improvement of heat transfer rate and thermal behaviour of each motor’s modifications will be analysed numerically and discussed. In Section 3.1, effects of temperature rise on different positions in a DC motor will be investigate. The part which the highest temperature will be analysed in the following sections. Next, Section 3.3 shows the thermal behaviour for motor constant, motor with internal modification and motor with external modification. Heat sink design analysis will be done in Section 3.4.

3.1. Effect of temperature rise on different positions in a DC motor

Temperature of four different positions in a motor was monitored while the motor is allowed to run until the motor reach its peak temperature. Tables 4 below show all the data obtained from Picolog by running all the modified motors under different loads.
The temperature rise in a DC motor is not uniform throughout the entire motor. Some positions in a DC motor will have a higher temperature while the other positions will have a lower temperature. Highest temperature in a DC motor must be determined to make sure that the modification done has a direct impact toward that particular temperature. From the data tabulated in the table 4, 5, and 6 above, by increasing the load applied to the brake, the overall temperature of the motor will increase as well, except the bearing. The temperature of the bearing is inversely proportional to the load applied to the brake. When the load applied increases, the gripping force of the braking mechanism will increase as well. The increased in the frictional force on the brake disc slows down the rotation of the shaft, which reduce the frictional force in the bearing.

The rise of the temperature in the windings has the highest effect on the temperature of the brush. This is because the brush is directly in contact with the commutator. When current is allowed to flow through the windings, energy loss in the form of heat will transfer from the windings to the commutator which then heat up the brush. The temperature of the brush is the highest in every motor and it will be the temperature that we are going to analyse in the following section. From the tables shown above, the motor filled with polyurethane foam has a better heat dissipation rate compared to the heat sink.

However, at load 400N, heat sink design 3 has an overall lower temperature compare to the motor filled with polyurethane foam. This shows that at higher temperature, polyurethane foam will not going to be sufficient enough in dissipating the heat waste generated.

The casing is cooler compared to the magnet in every situation. This is due to the fact that the casing is directly in contact with the cooler, circulating ambient air which allow for a higher heat exchange rate. On the other hand, the magnet is in a small cavity with the high temperature windings which will result in a higher temperature of the magnet compare to the casing.

### Table 4. Motors running under 0N load.

| Constant | PU | HS1 | HS2 | HS3 |
|----------|----|-----|-----|-----|
| Bearing  | 29.734 | 29.576 | 29.508 | 29.741 | 29.718 |
| Brush    | 34.012 | 30.647 | 31.643 | 31.256 | 31.134 |
| Casing   | 30.105 | 27.787 | 28.919 | 28.456 | 28.204 |
| Magnet   | 30.608 | 28.294 | 29.198 | 28.871 | 28.611 |

### Table 5. Motors running under 200N load.

| Constant | PU | HS1 | HS2 | HS3 |
|----------|----|-----|-----|-----|
| Bearing  | 29.687 | 29.333 | 29.466 | 29.473 | 29.44 |
| Brush    | 36.646 | 33.053 | 33.909 | 33.388 | 33.237 |
| Casing   | 33.153 | 30.012 | 30.292 | 30.164 | 30.071 |
| Magnet   | 33.732 | 30.534 | 30.779 | 30.659 | 30.582 |

### Table 6. Motors Running under 400N Load.

| Constant | PU | HS1 | HS2 | HS3 |
|----------|----|-----|-----|-----|
| Bearing  | 29.147 | 28.98 | 29.011 | 29.023 | 28.991 |
| Brush    | 38.777 | 34.879 | 35.751 | 35.034 | 34.83 |
| Casing   | 34.899 | 31.42 | 32.176 | 31.793 | 31.343 |
| Magnet   | 35.629 | 32.165 | 32.907 | 32.535 | 32.064 |
3.2. Thermal behaviour for different modification

Thermal behaviour for each motor will be studied and investigated in detail. All the motors will be fed with a voltage of 5V and run under different loads, 0N, 200N and 400N respectively. Peak temperature, rise time, settling time and time constant for each modification will be extracted from the graph obtained from Picolog and analysed.

Peak time refers to the highest temperature reached by a motor. From section 3.1, the brush of a motor has the highest temperature compared to the other position such as bearing, casing and magnet. The brush’s temperature will be the peak temperature of a DC motor and rise time, settling time and time constant for the brush will be investigated. Rise time refers to the time it takes for the motor to rise from 10% to 90% of the peak temperature. This parameter is a measure of the response of a motor’s temperature when current is fed through the windings. In motor, longer rise time is preferable as most processes do not require the motor to run for a long period of time until the motor reaches its peak temperature. On the other hand, settling time refers to the time it takes for the motor to reach 98% of its peak temperature or within 2% of the peak temperature. The difference between settling time and rise time is that settling time includes the propagation delay which is the time needed for the temperature of a motor to reach a steady state. For settling time, longer duration is preferable. Time constant can be defined as the time needed by a motor to reach 62.3% of its peak temperature. It is known as the time delay to determine the initial response of the motor when voltage is initially applied.

![Motor constant running under 0N load.](image1)

**Figure 10.** Motor constant running under 0N load.

![Motor with Polyurethane foam running under 0N load.](image2)

**Figure 11.** Motor with Polyurethane foam running under 0N load.
Figures 10, 11 and 12 show the thermal behaviour for different positions of each DC motor subjected to different modification, running under 5V with 0N load.

Figure 13 show the comparison between three different motors running under 0N load. The peak temperature from the bar chart shows that both of the modifications done, had successfully improved the rate of heat transfer of the windings. The improvement of heat transfer for the polyurethane modification compared to the motor constant is 9.89% while 7.48% for heat sink design 1. Heat sink design 1 shows an overall very short rise time, settling time and time constant. This means that the temperature of the motor for heat sink design 1 will reach its maximum temperature in a shorter period of time compared to the other two motors. This is undesirable as most application do not require motor to run for a long period of time and this motor will reach its peak temperature in a matter of no time. On the other hand, the overall responses of the motor with polyurethane foam is a lot better compared to the motor with heat sink design 1 with a longer duration in rise time, settling time and time constant and most importantly the peak temperature is lower compared to the motor constant. The same observation can be applied to motors running under 200N and 400N.
3.3. Heat sink design analysis

The peak temperature, rise time, settling time and time constant for each heat sink designs were recorded and tabulated as shown in figure 14. Heat sink design 3 has the lowest peak temperature with the longest rise and settling time. The time constant of all the heat sink designs are similar. On the other hand, heat sink design 1 shows the highest peak temperature with the shortest rise time and settling time. The result shows that motor with heat sink design 1 will reach its peak temperature at a faster rate compared to motor with heat sink design 3. This data proved that shorter fins with smaller fin gaps are better compared to longer fin with larger fin gaps when the total amount of material used for the heat sinks are the same for all the design. This is due to the fact that temperature of the heat fin is highest at the base of the fin and starts to drop exponentially toward the tip until the temperature reaches equilibrium state with the environment temperature at a certain length. The part of the fin beyond this length will not contribute to any heat transfer as the temperature of the fin, is equilibrium to the environment. The part nearest to the base will have the highest heat transfer rate. The same observation can be applied to motor running under 200N and 400N.

| Heat Sink Design | Peak Temperature, °C | Rise Time, Min | Settling Time, Min | Time Constant, Min |
|------------------|-----------------------|----------------|-------------------|-------------------|
| H1               | 31.643                | 17             | 25                | 6                 |
| H2               | 31.256                | 20             | 26                | 7                 |
| H3               | 31.134                | 25             | 28                | 6                 |

Figure 14. Comparison between three heat sink designs running under 0N load.

Figure 15. Comparison of reduction in temperature.

Heat sink design 3 shows the highest improvement in term of heat dissipation rate compared to the experiment constant while heat sink design 1 shows the least improvement. From the trend line shown
in the figure 15 above, there is a huge improvement gap between heat sink design 1 and heat sink design 2. There is a much smaller improvement gap between heat sink design 2 and design 3. If we prolong the trend line, it will eventually reach a constant, which means that room for improvement is limited. When the trend line reaches a steady state, fins that are even shorter with smaller gaps will not show any more improvement.

4. Conclusions
The effect of temperature rise on different position in a DC motor are investigated and the temperature rise in the windings has the largest effect on the temperature of the brush. Heat waste generated from the windings do not contribute to the increase in temperature of the bearing. Major contributor of heat for the bearing is due to the frictional force in the bearing. When the load applied onto the braking mechanism is increased, the rotation speed will decrease which in turn will reduce the frictional force and temperature of the bearing. Then, it is found that the temperature of the casing is always cooler compared to the temperature of the permanent magnet as it is directly in contact with the cooler, circulating ambient air.

Next, two different modifications had been done and both of it successfully improved the heat transfer rate of the DC motor. Internal modification shows an overall better performance compared to the external modification as it has much longer rise time, settling time and time constant while having the similar peak temperature with the external modification. However at higher temperature, the heat sink can achieve a lower peak temperature compared to polyurethane foam. Polyurethane foam is good for low temperature usage but it is not sufficient enough in dissipating the heat waste generated when the motor is subjected to additional load.

All of the heat sink designs were built using the exact amount of material. From the experiment done, it can be concluded that longer fins with larger fin gaps do not perform as well as shorter fins with smaller fin gaps. This is due to the fact that temperature tends to drop across the length of the heat fins and the highest heat transfer rate occurred at the position closest to the base of the fins.

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