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Thermal Modelling of Permanent Magnent Machines Using double layer winding

Strategies for cooling of PM motors in ship propulsion pods

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Master of Science in Electric Power Engineering
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Master Thesis

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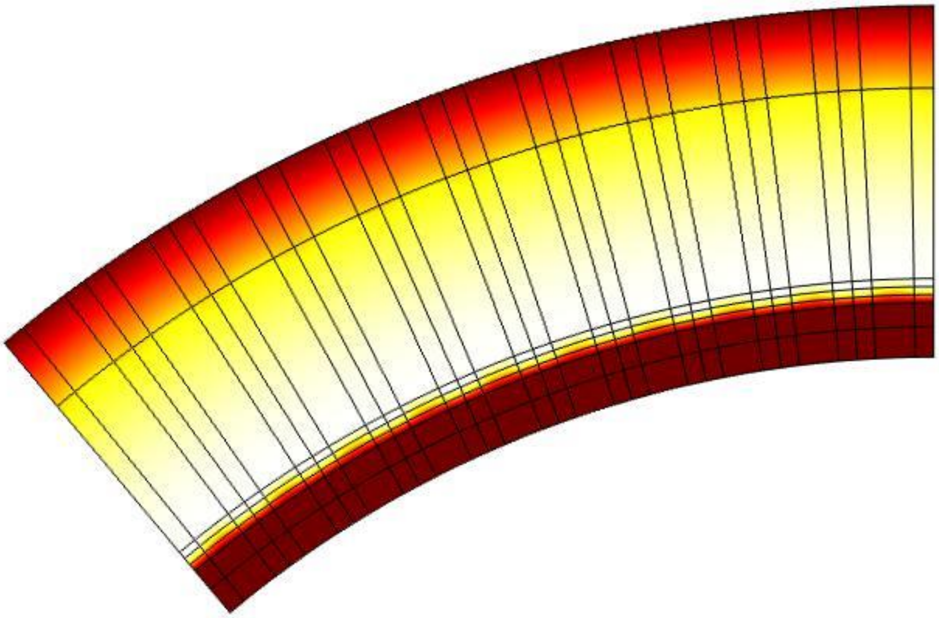

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Focus on 2D Thermal models

Master of Science in Electric Power Engineering

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Abstract— **The trend to carry out thermal analysis of Electric Motor is increasing day by day so as to improve the performance of the machines. This paper deals with the thermal analysis of Electric Motors and their cooling solutions, focusing on Ship Propulsion Pods. Using Finite element analysis (FEM), temperature distribution in two coils in a slot, with different turn profiles are considered in this study. The effect of temperature with the use of different conductor's shapes in slot of the machine, temperature distribution in stator and rotor of electrical machines, effect of heat transfer coefficient and thermal resistance are taken for the study. Cooling of electrical machines and a focus on pod cooling has been done. This thesis is done in cooperation with NTNU and Rolls Royce.**

Keywords— Thermal Model, Double Layer Windings, Two and Four turn profiles, Heat transfer coefficient, thermal resistance.

1. INTRODUCTION

Thermal Analysis has become very important in the design process of Permanent Magnet Electrical machines with high power densities. Temperature increase in high power density machines, as the heat density increases, which in turn affects machine performance, life expectancy due to thermal damages in insulation materials and also lead to demagnetization of the magnets. Thus to ensure the high power density, new machine design with enhanced thermal design is on demand [1].

With the increasing desire of efficiency, cost reduction and overall performance of the machines it is necessary to analyze the thermal design of electrical machines as an electromagnetic design [2]. Thermal analysis can be divided into two types: Analytical and Numerical methods. In an Analytical approach, a network model (Lumped parameter Model) defines a circuit with main heat transfer paths. The analysis consists of calculation of conduction, convection and radiation resistances from different parts of the motor. In a Numerical approach any device geometry could be modeled and these approaches are in high demand in terms of computational time and model setup. Computational Fluid dynamics (CFD) and Finite Element analysis (FEA) are the two types of numerical approaches. Here in this paper Finite element analysis (FEA) is used to model the heat transfer in solid components of the machine [2]. Finite Element Analysis (FEA) is a standard tool for study of 2D and3D thermal models. For accurate prediction of thermal performances, FEA requires the knowledge of geometrical and material properties of the machine construction. In this paper FEA is used for calculation of conduction heat transfer in complex geometric shapes like copper in a rectangular shaped slot, calculation of equivalent thermal conductivity and for the analysis of temperature distribution in stator [2]. The temperature distribution in machine with the effect of heat transfer coefficient and thermal resistance are examined. In addition to thermal study of the machines, certain cooling strategies for permanent magnet machines and ship propulsion pods are also discussed in this paper ,as they decide the capacity of heat dissipation. The goals for the thesis is to build competence on how to model and describe temperature distributions in the electrical machine. Furthermore, this competence is used to describe cooling strategies in ship propulsion pods.

2. LITERATURE REVIEW

In electrical machines the thermal analysis is equally important as the electromagnetic design analysis, as the temperature rise in the machine determines the output power with which the machine could be loaded. Thus the management of heat and fluid transfer in electrical machines is often considered as a complicated issue [3]. Widespread research has been dedicated to the thermal studies of electrical machines. A literature survey of thermal analysis of Electrical machines, which includes both analytical and numerical approaches is presented here.

In [4] thermal analysis of permanent magnet machines that uses both analytical lumped circuit and numerical finite element method is studied. In lumped circuit analysis, program MOTOR CAD is used and finite element method make use of FEMLAB. Equivalence between thermal and electrical networks are used in lumped circuit analysis to understand thermal problems. A realistic representation of the main heat transfer path and losses within the machine is achieved by connecting thermal resistances and heat sources in steady state and with the power flow between the nodes, temperature at various nodes could be calculated. Thermal capacitances are added in transient analysis to account for the change in energy with time [4].

In [4] the FEM approach temperature resolution of more complex shapes are gained in conducting regions of the motor where the boundary conditions for radiation and convection boundaries are set. Analytical and empirical strategies used in lumped circuit technique was also applied here [4].

In [5] a lumped parameter thermal model that consist of 12 thermal resistances to determine the temperature at 9 critical points like stator end windings, rotor magnets and bearings of the multi barrier interior permanent magnet machine are included. This model was specially designed for automotive applications. Equivalent circuit was designed to inject losses independently into magnet layers. To estimate the temperature of the coils embedded in the stator core and end windings, two distinct nodes were allocated to the stator windings. Separate nodes were allocated to two magnet layers so as to estimate their temperature as they are vulnerable to irreversible demagnetization at high temperature [5].

A Lumped parameter thermal model in [6] identifies the temperature in end winding and rotor of the machine. In this model the motor is divided into a number of lumped components which has bulk energy storage. For interconnections and heat generation to nearby components a liner mesh of thermal impedance is used. Thermal performance of the machine was characterized by eight thermal time constants which could track the winding temperature. This model was also applied to three induction motors from different manufactures having diverse ratings and the model was able to predict the stator winding temperature during stationary cooling and load variations [6].

Thermal point of view of electrical machines is always focused on stator winding and the cooling system, in [7] modelling of heat transfer in these two critical parts are considered. The stator winding and the cooling system is divided into number of angular segments in this thermal model and was experimentally performed on directly cooled induction machine. To estimate the coolant circulation in cooling channels and outer surface of end winding simple CFD (Computational Fluid dynamics) simulations were used and these results were further used to model the convective heat transfer to the coolant in the resulting Lumped parameter thermal model [7]. The model was experimented with on induction machine where the winding of the machine was impregnated with epoxy and varnish. It was found that the model could accurately predict the hot spot temperature in end winding body for coolant flow rates and different losses [7].

Thermal analysis of permanent magnet assisted synchronous reluctance machine for hybrid electric vehicles is described in [8]. In this approach a thermal model is described where the stator slots are divided into a number of impregnation layers and elliptical copper and this model gives definite temperature distribution for slot geometries. Partial Finite Element Analysis(FEA) and Lumped parameter thermal modelling is used to describe the stator winding. Accurate temperature distribution in different parts of the machine were found when five axial layers were used and the end windings was modeled as a solid body with boundary condition based on FEA thermal models [8].

In [9] a 3D thermal–magnetic finite element analysis (FEA) is used to study the thermal behavior of axial flux synchronous permanent magnet machines with soft magnetic composite core. Machine parameters and electromechanical variables are assessed by Finite element analysis (FEA) and to achieve thermal field the thermal source is coupled to magnetostatic solver and a thermal and fluid -dynamic model which could be modelled by Navier -Stokes equations. It was found in [9] that the rotor core was remarkably hotter than estimated and the temperature stayed below 403 K(Kelvin) essential by the epoxy.

When considering the cooling part of the electrical machines it is been found in [10] that axial flux permanent magnet machines adopts water cooling through aluminum water jacket which is been inserted between two slotted stator cores. For examining the cooling performance Computational Fluid dynamics (CFD) and for determining stator temperature Lumped parameter model has been used. Winding temperature for different coolant rates were determined by coupling the physical parameters with equivalent thermal models [10].

Different approaches by different tools were discussed here for studying the thermal behavior of the electrical machines. Each method has its own way to describe the temperature distribution in the machine. In this paper the tool, Finite element analysis (FEA) is been used to study the thermal analysis of electrical machines used in Ship propulsion pods.

3. THEORETICAL BACKGROUND

Heat transfer through complex components of electrical machines like wound slot, endcaps airflow and temperature drop across the interface between the components is often considered as a three dimensional thermal management problem [11]. Heat in the electrical machines can be removed by conduction, convection and radiation process to the ambient air and surroundings [12].

3.1 Thermal Conduction

Heat is transferred from high temperature(T_{hot})to low temperature region (T_{cold}) ,when a temperature gradient exists in permanent magnet, insulation, copper or steel of an electrical machine [12]. According to Fourier's law it is given as,

$$\Delta Q_c = -kA\frac{\partial T}{\partial x} = \frac{kA}{l}\,(T_{hot} - T_{cold}) \qquad (1)$$

Where, ΔQ_c : rate of heat conduction
k : thermal conductivity
A : area of the flow path
l : length of the flow path

3.2 Thermal Convection

When heat is transferred from a surface to a moving fluid convection occurs [12]. The rate of convective heat transfer is given according to Newton's law as,

$$\Delta Q_v = hA(T_{hot} - T_{cold}) \tag{2}$$

Where, ΔQ_v : rate of convective heat transfer
h : convection heat transfer coefficient

With the velocity of the cooling medium relative to the cooled surface the heat transfer coefficient increases and for a surface with forced ventilation it could be used as [12],

$$h_f = h_n(1 + c_h\sqrt{v}) \tag{3}$$

Where, h_f: heat transfer coefficient for forced convection
h_n: heat transfer coefficient for natural convection
v : linear velocityu of cooling medium
c_h : empirical coefficeint ≈ 0.5 to1.3

3.3 Thermal Radiation

Radiation is the energy exchange between two surfaces with a temperature difference [12]. If heat is transferred by radiation between two surfaces of size $A_1$and A_2 and temperature T_1 and T_2 then the rate of heat transfer is given as,

$$\Delta Q_r = \sigma \frac{(T_1+273)^4-(T_2+273)^4}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1}+\frac{1}{F_{12} A_1}+\frac{1-\varepsilon_2}{\varepsilon_2 A_2}} \tag{4}$$

Where, ΔQ_r : rate of radiation heat transfer
σ : Stefan − Boltzmann constant
F_{12} : shape factor
$\varepsilon_1, \varepsilon_2$: emissivities

3.4 Losses

Distribution of heat in different parts of a permanent magnet machine has also to be considered in addition to the heat removal as they are important in performing thermal analysis. When distribution of losses in different parts of the machine and power are precisely known, the distribution of heat could be calculated definitely [3]. Losses in electrical machines includes stator loss, rotor loss and windage loss [13].

Stator losses in electrical machines consists of copper losses and iron losses. When the current goes through the armature windings copper losses occur and it consists of I^2R losses and stray load losses. Stray load losses arise due to skin effect from source conductors and proximity effect from adjacent conductors sharing the same source. I^2R losses are due to flow of large current in the conductor with high resistance. Copper losses are calculated at the estimated copper temperature as it is temperature dependent [13]. Losses produced in the magnetic material is the Iron losses and it is divided into two, hysteresis loss and eddy current loss. When a fluctuating magnetic field is applied to magnetic material due intermolecular friction hysteresis losses occur and when a conducting material is subjected to a magnetic field, electric currents are induced in it causing eddy current losses in the machine [13].

Rotor losses are generated by the eddy currents in the permanent magnets and shaft. Removing heat from rotor of the machine is more challenging than from the stator, thus prediction of rotor losses at high speed is significant. Rotor losses are caused by no load rotor eddy current in the slots, on load rotor eddy currents by harmonics of the windings and by on load rotor eddy current losses by time harmonics due to pulse width modulation [13].

Windage losses occurs due to relative motion of fluid between stator and rotor of the machine in electrical machine. These losses are function of shaft speed and properties of fluid like pressure, density and temperature [13]. It is always good to have an estimation of the losses of the electrical machines for the thermal study of the machine.

4. WINDINGS OF PERMANENT MAGNET MACHINES

Permanent Magnet machines are becoming widespread over the past few years due to the advantages of the windings its provides. High power density, short end turns, high efficiency, low cogging torque, high slot fill factor, fault tolerance and flux weakening capability are some of the advantages which makes it more popular [14]. These machines are also well suited for the high speed application as the permanent magnets and the armature windings are located on the stator and the rotor [15].

In this thesis thermal analysis of Permanent magnet machines with double layer windings are being focused. Double layer winding means two coils within in a slot as in Figure 1. Advantages of the double layer winding like smaller torque ripples, shorter end windings, less eddy current losses and smaller space harmonic components of MMF and EMF makes it suitable for the study thermal analysis of permanent magnet machines in ship propulsion pod [16].

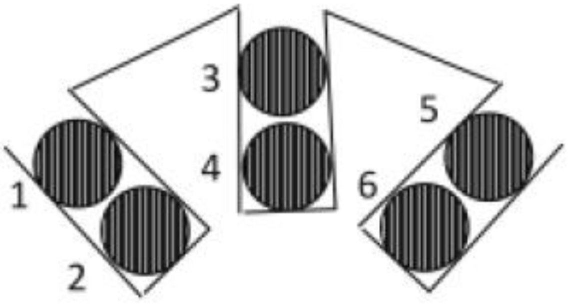


Figure 1: Double Layer Winding (two coils per slot), [17]

Thermal models which gives accurate information about the thermal material properties could only define the behavior of the electrical system, particularly in high temperature environments. Temperature rises to its maximum in the winding of the machine, so it is considered as one of the main problem in the thermal study of electrical machines [18]. However, with the help of the numerical tool finite element method (FEM) it is possible to determine the hot spot in the slots due to its structure and presence of conductors with small geometric dimensions when associating to the machines ones [18].

4.1. Slot Geometry

When designing electric machines lot of factors have to be considered like thermal calculations, electromagnetic calculations, mechanical computing and performance test etc. Here in this thesis for the thermal analysis of electrical machines for ship propulsion pod application Finite element method (FEM) is preferred and for the analysis to be done certain slot geometries are chosen.

While putting the windings in slots it offers many advantages like [19],

a) Reduction in magnetization current
b) Easy manufacture and placement of winding in slots
c) Better heat transmission and mechanical rigidity
d) Magnetomotive force (mmf) per unit length of the winding height is increased and large power machines could be built efficiently.

Depending upon the power and type of the magnetic wire round or rectangular cross section from which the coils of windings are made the slot geometry varies [19]. Slot geometries could be trapezoidal or rounded trapezoidal and rectangular as shown in Figure 2, a and b. Here for the thermal analysis rectangular slot geometries are preferred for different winding profiles.

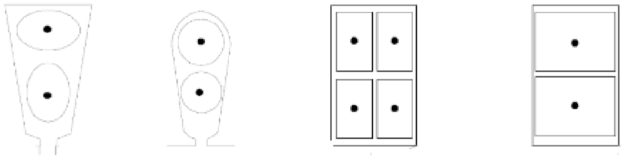


Figure 2 : Slot geometry a) trapezoidal or rounded trapezoidal and b) rectangular [19]

4.2. Two turn and four turn profiles of Windings

4.2.1. Two turn profiles of Windings

All Electrical machines existing today are subject to electromagnetic and thermal constraints imposed by copper, insulation, magnetic materials etc from which their key components are built [20]. Mostly temperature builds up in the center of the coil of an electrical machine. For thermal improvement in [20] one slot of permanent magnet motor as shown in Figure 3 (a), is considered, where some sort of varnish or resin is put between the conductors so as to provide good thermal conductivity, mechanical integrity and for protection from foreign particles. For achieving an enhanced thermal conductivity and to obtain a better distribution of heat over the slot area in [20] a heat path was introduced as shown in Figure 3(b). In [20] to improve the temperature distribution in slot of electrical machine simple technique is used. Similarly, certain simple case profiles of windings in a slot of a machine are considered here to study temperature distribution in it.

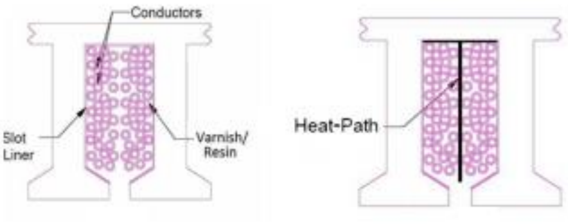


Figure 3: a) Slot area and b) Slot with heat transfer path [20].

In this section to study the temperature distribution of two coils in a slot certain cases are considered based on arrangement of copper conductors, insulation, by using numerical method (FEM). Two coils are positioned in a slot of an electrical machine with bundle of conductors closely packed and insulated from each other as shown in Figure 4 to study the temperature distribution in slot. Three configurations of two turn profiles are considered and their temperature distribution in the slot are compared to each other using finite element method. Heat source value for the three cases were taken as $4.25e^5\ W/m^3$ and the boundary temperature as 40˚C. Air gap is 2mm. Diameter of one strand of copper is 1.06 mm and along with varnish as insulation it is 1.157 mm.

In Case 1 two turn profile as shown in Figure 4 the copper conductors are arranged in layer inside the slot of the machine. Each copper conductor and the space between the conductors is surrounded by varnish as insulation.

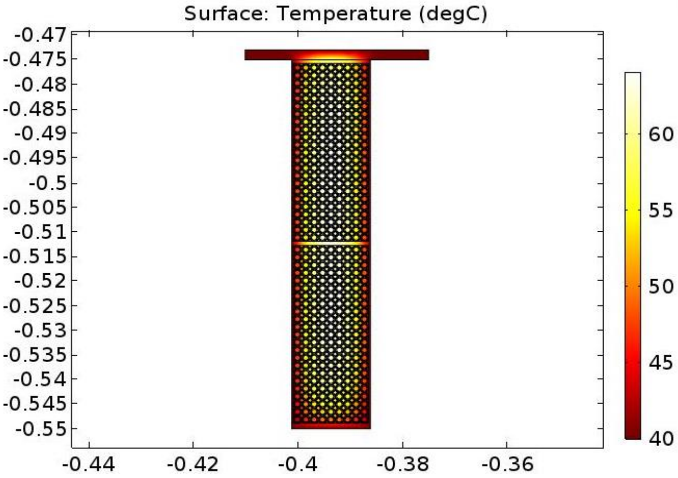


Figure 4: Case 1: Two turn profile conductors packed close to each other space filled with varnish.

In Case 2 two turn profile as shown in Figure 5 the copper conductors are arranged in layers inside the slot of the machine with varnish as insulation around each copper conductor. Here space between the conductors is filled by air.

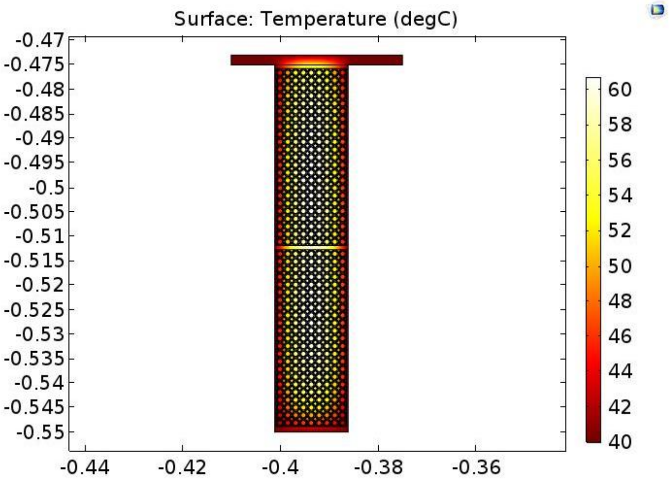


Figure 5: Case 2: Two turn profile round conductors packed close to each other space filled with air.

In Case 3 two turn profile as in Figure 6 copper conductors are arranged randomly and each conductor is surrounded by varnish as insulation. Space between the randomly packed conductors is filled by air.

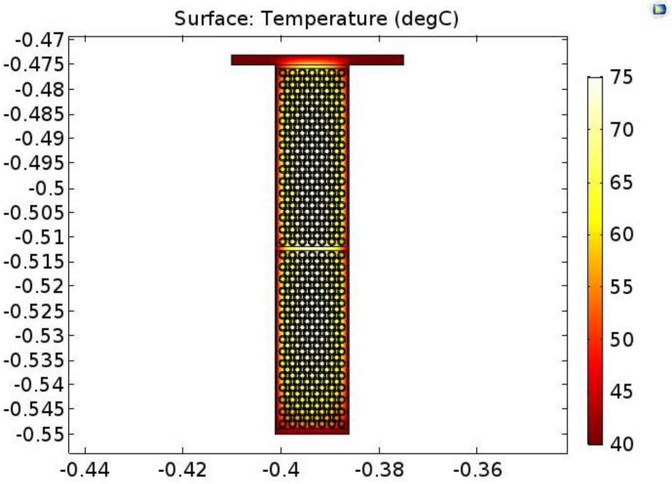


Figure 6: Case 3: Two turn profile randomly arranged round conductors.

When considering the temperature distribution in three cases it is observed that the temperature distribution in the slot of the machine in Figure 6, Case 3 is found to be 75˚C, Figure 5, Case 2, temperature is 60˚C and Figure 4, Case 1 temperature is above 60˚C. Thus by comparing all the cases when the conductors space is filled with air its gives the best thermal performance. In [21] its being told that winding technology play an important role in the high power density and efficient machines through the enhancement of copper fill factor. Copper fill factor is the ratio of copper cross section area per slot to total slot cross section. With the enhancement of the copper fill factor, the efficiency of the machine can be increased as it reduces the copper losses and as the copper losses depends on the temperature of the machine, based on the increase and decrease of the copper losses the temperature of the machine varies. Here in Figure 5 the temperature distribution in slot is found to be 60˚C and it could be concluded that here the copper losses will be less when compared with Figure 4 and 6.

In [22] When considering the heat flow in the coil, heat is generated inside copper material it is flowing through the insulating material and the temperature increases. But as the thermal conductivity of the copper is higher than the insulation temperature across the copper conductor is uniform. Here in Figure 5 as the strands are closely packed and having small gaps between the individual conductors it means less waste of heat which in turn means lower temperatures [22].

4.2.2. Four turn profiles of Windings

Design of electrical machines make use of layers in designing winding to reduce the high frequency losses since 1920. When the layers are thin the skin depth is beneficial and when the number of layer increase losses due to proximity effect increases [23]. Some four turn profile configurations are considered here to study the temperature distribution in slot of the machine. Boundary temperature is 40˚C and the heat source value for all the four turn profile cases is $4.25e^5\ W/m^3$.Air gap 2mm. Layer conductivity and layer thickness is taken as 0.2 W/m-k and 0.5 mm respectively for all the cases considered here.

In Case 4 four turn profile as in Figure 7, layered copper conductors are surrounded by varnish as insulation and the temperature was found to be above 52˚C.

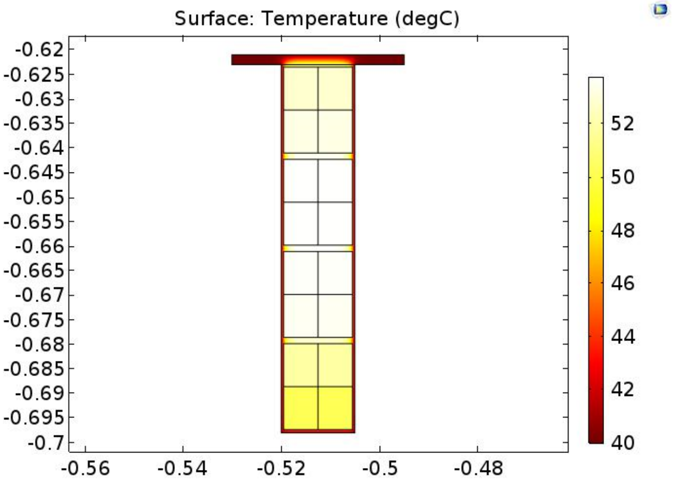


Figure 7: Case 4: Four turn profile layered copper conductors varnish as insulation.

In Case 5 as in Figure 8, in four turn profile the temperature was found to be 60˚C when layered copper conductors was surrounded by air as insulation.

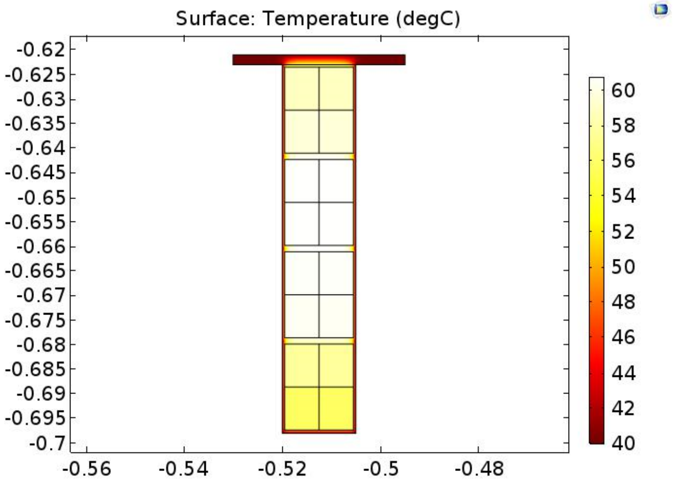


Figure 8: Case 5: Four turn profile layered copper conductor with air as insulation.

In Figure 9, Case 6 a space filled with air has been introduced between the layer copper conductors in four turn profile to examine the temperature distribution in the slot and it was found to be 80˚C.

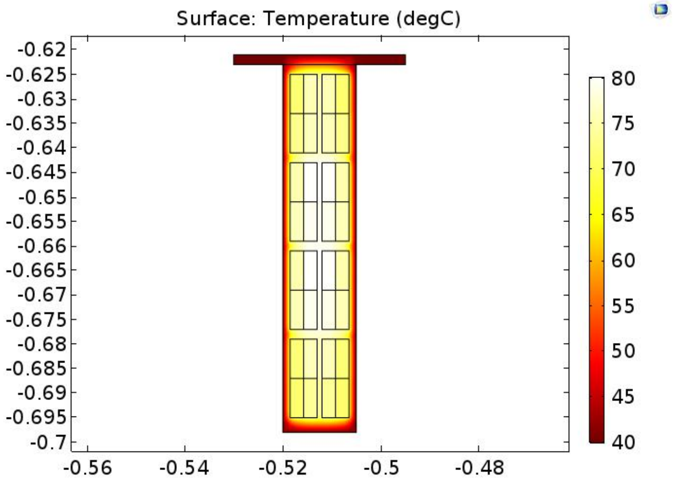


Figure 9: Case 6: Four Turn profile space between layered copper conductors filled with air.

Skin and Proximity effects dominates copper losses at high frequency. Non uniform distribution of time varying currents in conductors is known as skin effect and proximity effect is the influence of alternating current in one conductor on the current distribution in nearby conductor [24]. The losses in the winding is due to copper resistance and it increases as the frequency increases [24]. In [24] it's been told that different shapes of cross section of conductors, arrangement of conductors in slots and changes in gap width could change the distribution of current in winding and could reduce the skin and proximity effect. When these effects coincide current distribution changes and conductor resistance increases which in turn increase the temperature of the winding.

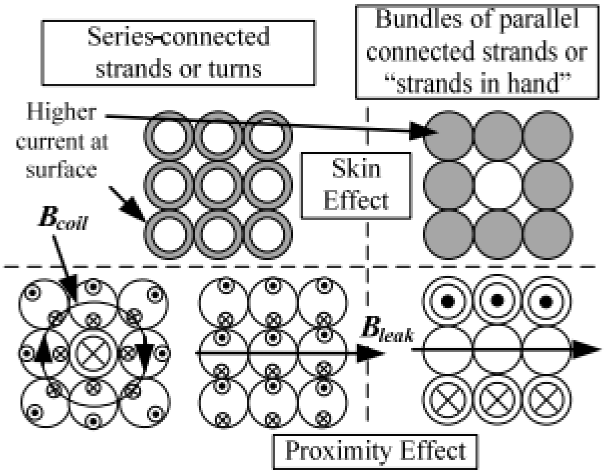


Figure 10: Skin and Proximity effect on coils [25]

With round strands it has been found the copper losses are less and rectangular shape of conductors have not gained much attention in loss reduction [24]. So with the help of the cases of two turn winding profiles as in Figure 4,5 ,6 and four turn winding profiles as in Figure 7,8,9 with round and rectangular conductor's, the temperature distribution in slot of machine could be easily examined and it could be useful for the machine design while choosing the conductors.

4.3. Equivalent thermal conductivity model

Thermal conductivity [26] is the property of a material to conduct heat and it is measured in watts per kelvin meter $(W/(K.m))$. Thermal conductivity [27] can be expressed in terms of temperature difference, heat flux, length, cross sectional area and material dimensions as in (5) and it could be obtained by applying heat flux to a sample and measuring the temperature difference across the sample.

$$k = \frac{Ql}{TA} \tag{5}$$

Where, k : Thermal conductivity
Q: Heat flux
l : Length
T: Temperature difference
A : Cross sectional area

In [28] some approaches of equivalent thermal conductivity model are described. It is being told here that to model the temperature from slot wall to center of slot it is effective to model the average distribution of materials in slot. One method is to streamline the model to use equivalent thermal conductivity of the insulation and winding impregnation. The thermal resistance between the stator lamination and winding could be easily calculated if the equivalent thermal conductivity is known by (6).

$$k_{cu,ir} = 0.2425[(1-k_f)A_{slot}L_{core}]^{-0.4269} \qquad (6)$$

Where; $k_{cu,ir}$: $thermal\ conductivity\ of\ insulation$
k_f : $slot\ fill\ factor$
A_{slot} : $slot\ area$
L_{core} : $axial\ core\ length$

Another method in [28] to find equivalent thermal conductivity of the winding is by carrying out numerical analysis of rectangular shaped copper conductors in slot. Boundary conditions are applied to outer surface of stator lamination and the temperature difference between winding hotspot and stator back iron was calculated [28].

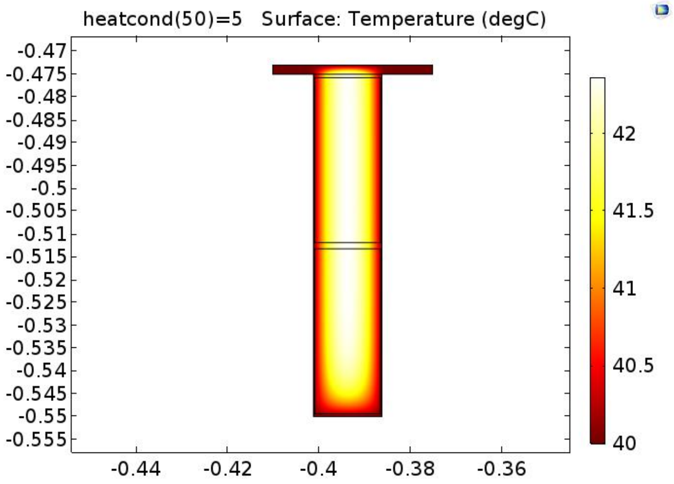


Figure 11: Equivalent thermal conductivity model for two coils in a slot.

Similarly, numerical analysis of an equivalent thermal conductivity model for two coils in slot was carried out as shown in Figure 11. Boundary condition is set as 40˚C around the rectangular shaped copper conductors with heat source of $4.25e^5\ W/m^3$,to find the equivalent thermal conductivity with temperature in the windings. Rectangular shaped copper conductors are in the slot.

It was found that as the temperature drops, thermal conductivity increases as shown in the graphical representation of two coils in a slot in Figure 12. This finding was further useful for the 2D modelling of thermal models in this thesis to study the temperature distribution in stator and rotor of the machine and also to the study of temperature distribution in slot of machine with heat transfer coefficient and resistance effect. It helps in saving time while modelling and performing 2D thermal analysis. Equivalent model could also be used in 3D modelling of end winding while modelling flow.

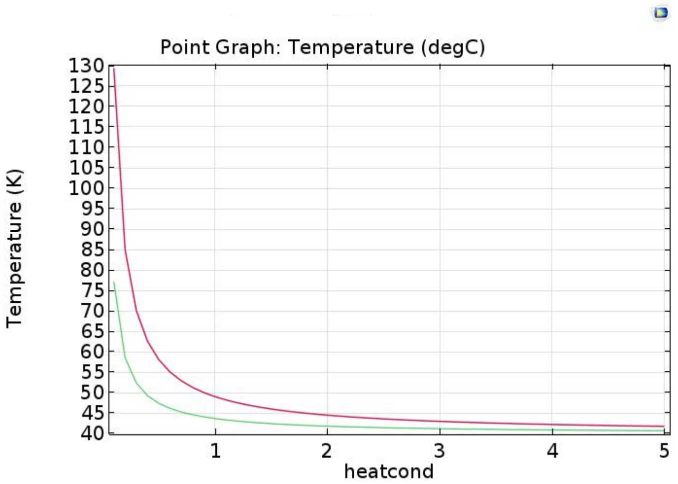


Figure 12: Graphical representation of Equivalent thermal conductivity model.

4.4. *Thermal Analysis of Stator and Rotor*

Heat transfer analysis of Stator- Rotor in electrical machines is very important while designing the machines so to prevent overheating [29]. Rotor gets demagnetized if the internal temperature of the machine exceeds its critical value and also the resistivity of the copper windings in the machine increases with temperature rise which in turn affects the efficiency of the machine [29]. Thermal analysis of permanent magnet machines has gained interest in the past few years and for the estimation of temperature distribution tools like Finite element, Computer fluid dynamics (CFD) and lumped parameter has been in picture for a long time.

In [30] a 3D finite element thermal analyses for rotor and stator have been performed. For reducing modelling and computational effort slot conductors and insulation were smeared and equivalent thermal properties were used. Rotor end rings were made of copper supported by alloy of steel banding and Stator was vacuum impregnated with a potting resin [30]. Only sectors of rotor and stator with boundary conditions that include air temperature, heat transfer coefficients were applied to the model and after the thermal analysis period stator temperature was found to be 173˚C and the rotor temperature 108˚C [30].

Two Dimensional ,2-D Thermal analysis of Induction motor is carried out in [31] and equivalent thermal model of stator windings is established where less time and calculation of motor thermal filed is favored. Heat transfer relationship between stator and rotor is established by blocking the rotor for 10 s repeatedly. Some assumptions were used in [31] like ignorance of axial heat flow, replacement of frame by ribs with respect to heat transfer effects, heat transfer from rotor core to shaft and smaller gap between stator outer surface and inner frames. The temperature difference between the stator and rotor was found to be 13.1˚C with rotor blocking process.

Similarly, a simple, a 2-D thermal analysis for rotor and stator sector was performed as in Figure 13 to study the temperature distribution in stator and rotor. The thermal field of the stator and rotor is calculated with heat source of $10E^5 W/m^3$. Boundary temperature and temperature around the rotor core is 20˚C. It has been seen that the stator core has the highest temperature of 45˚C and rotor has temperature of 20˚C and there is temperature difference as the heat is transferring through an air gap from rotor to stator.

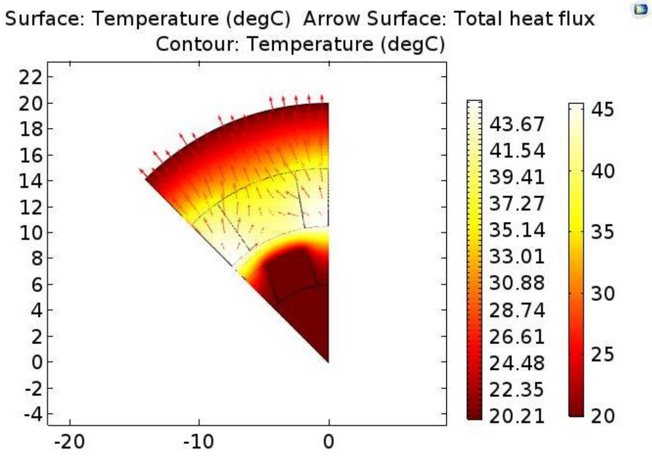


Figure 13: Stator and Rotor temperature distribution

Due to lack of thermal insulation and load rotor temperatures are acceptable. High stator core temperature occurs in the core region of by the thermal conductivity of the stator laminate, high lamination losses and end turn cooling effect of the stator conductors in the core [30].

Thermal simulations have been again performed in different 2D Finite element model to see the temperature distribution in it with the measurements and stuffs collected from Rolls Royce. In the design process of the electric motor thermal analysis is very important so to know the temperature of motor construction parts [32].

Valuable result of temperature rise in motor could be designed with FEA and with the help of it, temperature distribution in critical parts could be easily examined. Geometry of the 2D thermal model in Figure 14 consists of coil region surrounded by copper conductors with equivalent thermal conductivity. Boundary condition is Dirichlet type, where boundary temperature is specified. Here the boundary temperature between the stator and rotor frame is 20˚C. The heat source value is $10E^5 W/m^3$. Air gap is chosen to be 3 mm. In Figure 14, temperature difference between the stator windings and stator core could be seen. Highest temperature is in the stator windings surrounded by copper conductors and it is found to be 60 ˚C. The stator core part has a temperature around 30˚C to 35˚C. Air gap temperature also varies, close to stator windings it is 60˚C and close to the rotor core it is 30˚C.

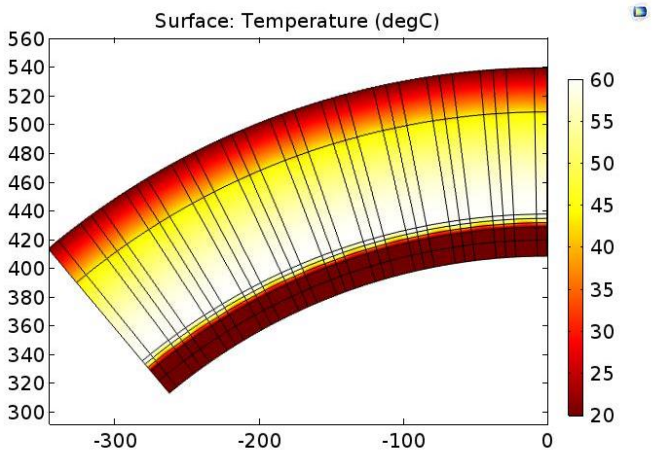


Figure 14: 2-D thermal model of stator -rotor core

Air gap convection limit heat transfer, so information of airflow in machine is important for the design purposes [33]. In [33] cylindrical geometry Couette flow is the term which is used to describe the flow between the stator and rotor surface and the flow is dominated by inertial effects and viscous effects. In disk machine air -gap flow is pumped by an outwardly imposed pressure difference and heat is naturally transferred to the fluid by forced convection at the stator surface [33].

In [34] a method to account heat transfer in air gap of electrical machines developed by Taylor has been mentioned which could be used to judge the flow in air gap, if it is vortex or turbulent and laminar using equation (7).

$$T_a = R_e.(l_g/R_r)^{0.5} \tag{7}$$

Where , T_a : $Taylor\ number$
R_e : $Reynolds\ number$
l_g : $air\ gap\ radial\ thickness$
R_r : $rotor\ outer\ radius$

Slotting effect on the air gap heat transfer on rotor and stator has been studied by Gazely [35]. He has found that there is increase in heat transfer for vortex flow and decrease in heat transfer for laminar flow [34].

4.5. Heat Transfer Coefficient and Thermal Resistance

Rate of heat transfer from solid to fluid or vice versa is given by equation (8), when the fluid outside the solid surface is in forced or natural convective motion [36].

$$q = hA(T_w - T_f) \tag{8}$$

Where , q : $heat\ transfer\ rate$
h : $convective\ heat\ transfer\ coefficient$

A : $area$
T_w : $soild\ surface\ tempearture$
T_f : $tempearture\ of\ the\ flowing\ fluid$

Heat Transfer coefficient is a function of geometry of the system, flow velocity, fluid properties and temperature difference and as it cannot be predicted theoretically empirical correlations are used to predict it [36]. Heat Transfer coefficient has great effect depending on the type of fluid whether laminar or turbulent. Nusselt and Prandtl numbers are used to correlate data for heat transfer coefficient.

Prandtl number [36] could physically relate the thickness of fluid layer and thermal boundary layer by equation (9),

$$N_{pr} = c_p\mu/k \tag{9}$$

Where, N_{pr} : $Prandtl\ number$
c_p : $heat\ capacity$
μ : $fuild\ viscosity$
k : $Thermal\ conductivity$

Nusselt number [36] could relate heat transfer coefficient to thermal conductivity of fluid and diameter of the section by equation (10),

$$N_{nu} = hD/k \tag{10}$$

Where, N_{nu} : $Nusselt\ number$
h : $heat\ transfer\ coefficient$
D : $diameter\ of\ the\ section$
k : $thermal\ conductivity\ of\ fluid$

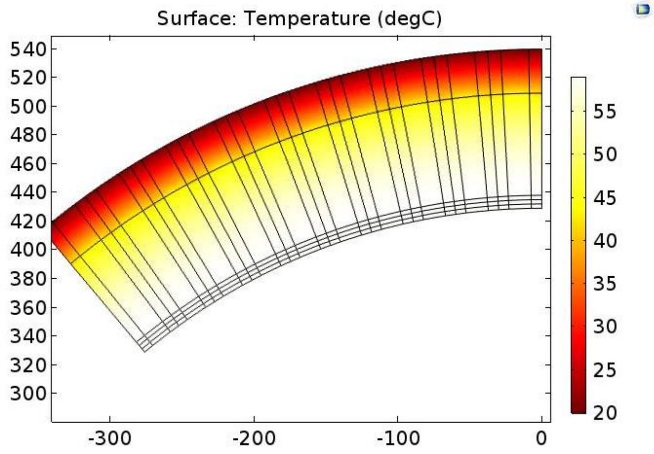


Figure 15: 2D Thermal Model with Heat Transfer Coefficient

A 2D Thermal model was created using Finite Element Analysis to estimate the temperature distribution in convective cooled surface by applying heat transfer coefficient. Boundary temperature between the stator and rotor frame is 20˚C. The heat source value is $10E^5W/m^3$. A convective heat transfer coefficient of $21.2\ W/(m^2K)$ was applied to the convection cooled surface. The result of simulation is as shown in Figure 15 in which the temperature varies from 20˚C to 59˚C. Temperature distribution between convection cooled surface is graphically represented in Figure 16.

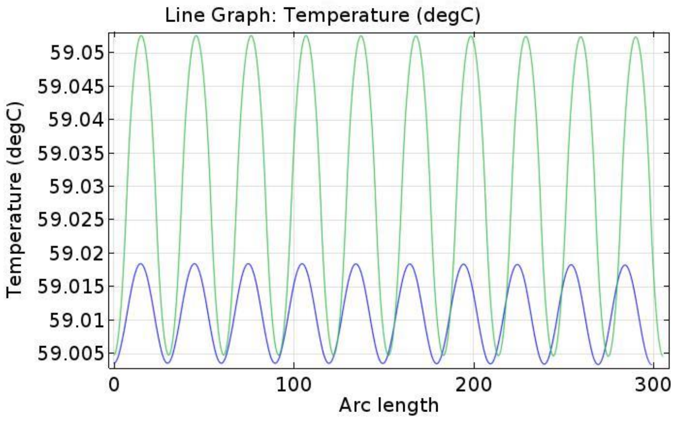


Figure 16: Graphical Representation of temperature distribution in convection cooled surface

With the help of single thermal resistance convection heat transfer can be modelled between a solid surface and cooling fluid [37]. Convection Thermal Resistance is defined by equation (11), as,

$$R_{convection} = {}^{1}/_{hA} \tag{11}$$

Where; $R_{convection}$: $Thermal\ resistance$
h : $convection\ coefficient$
A : $surface\ area$

Convection coefficients between stator and air gap and between rotating rotor and air gap has to be assessed because in these two main parts losses are generated [37].

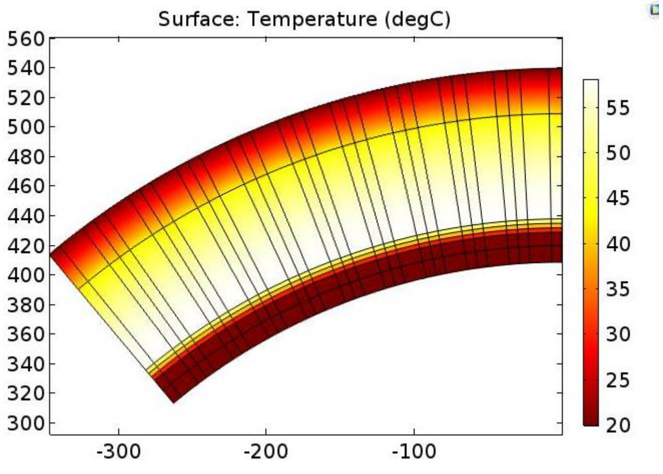


Figure 17: 2D Thermal Model with Thermal Resistance

A 2D Thermal Model with thermal resistance has been modelled in Figure 17 to see the temperature distribution in convection cooled surface and in this model the Heat transfer coefficient has been replaced by resistance. In this model the heat source value is $10E^5 W/m^3$.Boundary temperature between the stator and rotor frame is 20˚C. Thermal resistance in thin layers is $0.00625\ Km^2/w$. It could have been seen from simulation result that temperature in thin layer varies from 30˚C to 45˚C.

As in [37] it is cumbersome to model heat transfer in end winding space and the geometry of the end winding is complex. Evaluation of cooling fluid velocity and convective heat transfer is difficult. So it could be concluded that to show significant effect on the flow region the work done here could be used and expanded further in future.

5. COOLING OF MACHINES

Thermal point view is focused mainly on winding and the cooling of electrical machines. Here is this section an overview of cooling permanent magnet machine and cooling of ship propulsion pods is focused. In [38] heating of machine is defined as function of losses within it that are developed as heat and cooling is defined as a function that facilities for heat dissipation to outside media like oil, air or solids.

In [39], Normal design of machines regarding to cooling is given by equation (12),

$$\theta_t = \theta_v + \theta_s + \theta_m \tag{12}$$

Where, θ_t : $hot\ spot\ tempearture\ rise$

θ_v : $difference\ in\ tempearture\ between\ hot\ spot\ and\ dissipating\ surface\ over\ which\ air\ flows.$

θ_s : $dissipating\ surface\ and\ cooilng\ air\ temperature\ differnce.$

θ_m : $cooling\ air\ tempearture\ rise$

Machine temperature rise was a matter for speculation one time, as during machine construction it did not receive much attention as now and to dissipate losses from the machine, efficient cooling methods were taken into account [39].

5.1. Cooling of Permanent magnet machines

Different arrangements of cooling can be used depending on the size and type of enclosures of the machine. Permanent magnet machines can be divided into two categories from cooling viewpoint [12].

a) Machines with self-ventilation
b) Machines with external ventilation

a) Permanent Magnet Machines with Self Ventilation

Cooling air is generated by rotating disc, PM channels or fan like devices integrated with rotating part of the machine with self-ventilation. One of the greatest advantage from cooling perspective is the self-ventilation capability of the Permanent magnet machines [12].

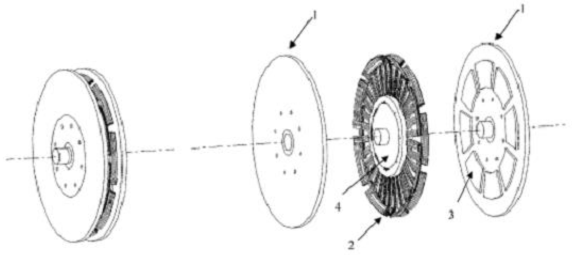


Figure 18: Exploded view of Permanent Magnet machine [12].

By examining the machine structure in Figure 18 it could be revealed that as the rotor disc rotates an air stream will be drawn through the air inlet holes into the machine and forced outwards into the radial channel. Permanent magnets act as impeller blades and the fluid behavior of the machine Is much like that of a compressor or centrifugal fan [12].

b) Permanent Magnet Machines with external Ventilation

Cooling medium is circulated by means of external devices like fan or pump in machines with external ventilation. The necessity of external devices is because, loss per unit heat dissipation area increases linearly with power ratings [12]. Some cooling techniques with the use of fans and pumps are explained below.

External Fans

In order to bring out the heat generated in the stator windings of large permanent magnet machines it may require the need of large amount of air flow per unit time [12].

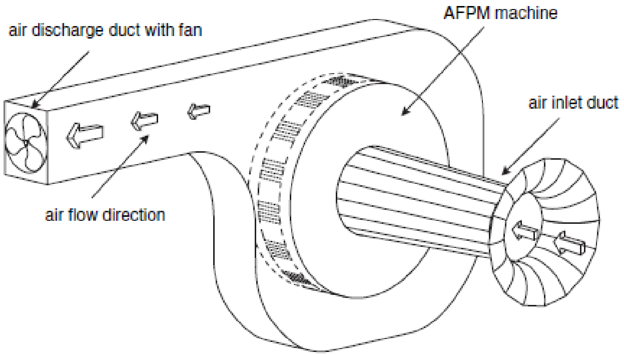


Figure 19: Permanent Magnet machine with external air Cooling [12]

An air blast or suction fan could be used as shown in Figure 19 depending on the operating condition and to direct the air flow in both cases intake or discharge ducts are needed. This cooling arrangement helps to avoid recirculation of hot air as the inlet air temperature has a significant effect on the machine arrangement [12].

A shaft integral fan could be used as a good option in high speed permanent magnet machines as shown in Figure 20. The rotor hub of permanent magnet machine serves as both cooling fan and supporting structure for the rotor discs. It could also be seen that as the machine operate in both directions of rotations the blades of the hub are not curved [12].

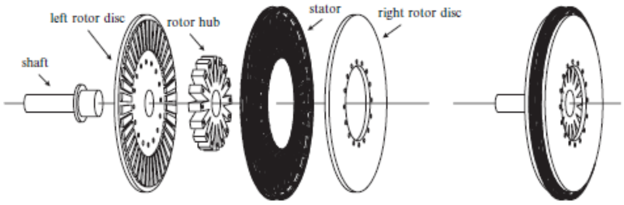


Figure 20: Permanent Magnet machine with shaft integral fan [12]

Heat Pipes

Heat from permanent magnet machine could be removed by means of heat as shaped in Figure 21.

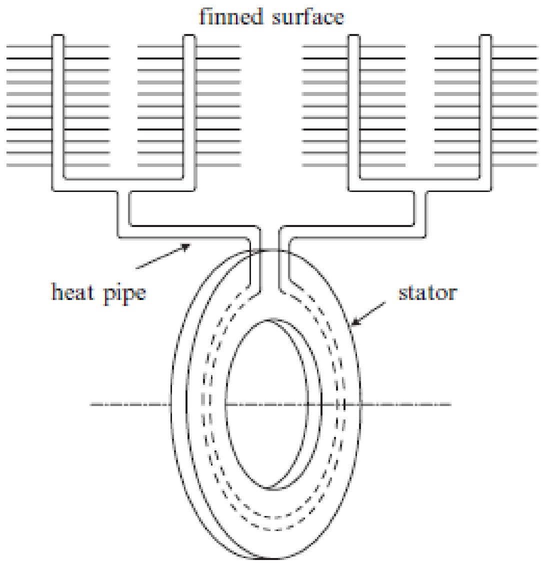


Figure 21: Permanent Magnet Machines cooled by heat pipe [12].

A Heat pipe has three different sections 1) an evaporator or heat addition region, 2) a condenser or heat rejection region, 3) adiabatic or isothermal region. When heat is added the working fluid in the wicking structure is heated until it evaporates. Due to high temperature and pressure in evaporator region the vapor's flow to cooler condenser region and there the vapor condenses dissipating its latent heat of vaporization. The liquid is pumped back to evaporator due to capillary forces in the structure. So if the heat source is below or above the cooled end the heat pipe could transfer heat [12].

In Figure 21, air moving over the fins cools the finned surface and heat transferred to the atmosphere. Heat loss removed by heat pipe is given [12] by equation (13).

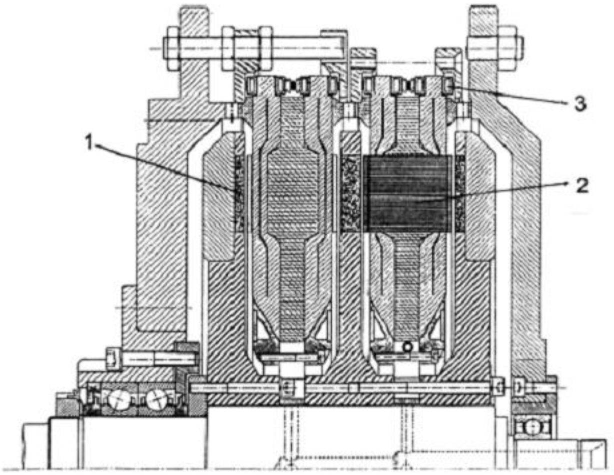
$$\Delta P_{hp} = \frac{\vartheta_{hot}-\vartheta_{cold}}{\frac{1}{h_{hot}A_{hot}}+\frac{1}{h_{cold}A_{cold}}+\frac{1}{h_{fin}A_{fin}\eta_{fin}}} \tag{13}$$

Where, ΔP_{hp} : $heat\ loss\ removed\ by\ the\ heat\ pipe$
ϑ_{hot} : $average\ tempearture\ of\ elements\ suronding\ heat\ pipe\ in\ stator.$
ϑ_{cold} : $average\ tempearture\ of\ air\ cooling\ the\ finned\ surface.$
h_{hot} : $convective\ heat\ tarnsfer\ coefficient\ in\ stator.$
h_{cold} : $convection\ heat\ transfer\ coefficent\ in\ the\ finned\ area.$
A_{hot} : $exposed\ area\ of\ heat\ pipe\ in\ stator.$
A_{cold} : $exposed\ are\ of\ heat\ pipe\ in\ finned\ area.$
h_{fin} : $convection\ heat\ transfer\ coefficent\ of\ fins.$
η_{fin} : $efficiency\ of\ finned\ surface.$
A_{fin} : $area\ of\ the\ finned\ surface.$

Direct Water cooling

Large power permanent magnet machines make use of forced water circulation to cool the stator windings directly depending on the conditions at the site of operation. For forcing water circulation, it makes use of external water pump. Figure 22 shows longitudinal section of water cooled double disc motor. In Permanent magnet machines with internal iron core stator cooling channel is positioned around the outer periphery of the stator disc as the heat transfer area is the largest here [12].

Permanent magnet machines with coreless winding the space between the two active sides of each coil is utilized for placing cooling duct, as the windings coils have rhomboidal shape. As the water is forced to pass through the coils as shown in Figure 23 heating due to eddy current and I^2R losses in the winding is removed. [40]



1- Permanent magnet, 2 – Stator core, 3- Stator winding

Figure 22: Permanent Magnet Machine with Water cooling System [12].

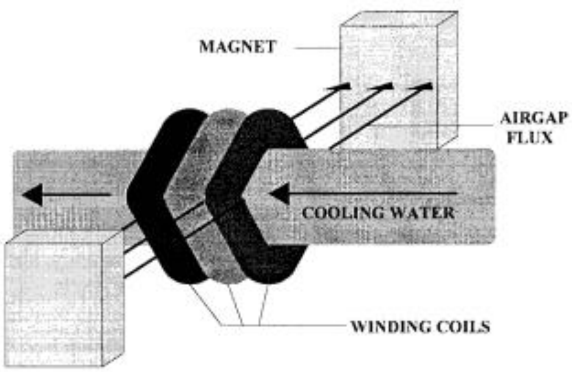


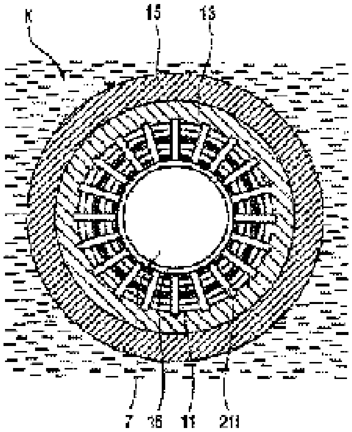
Figure 23: Cooling arrangement of Permanent magnet Machines with coreless winding [40].

5.2. Cooling of Ship Propulsion pods

Throughout the commercial marine industry integrated electric ships are becoming common. Cruise ships, product carriers, ferry's, shuttle tankers, icebreakers and offshore oil exploration platforms are all built with integrated electric power system. Podded propulsor in which the motor mounted in azimuthing pod below the stern of a ship is the latest trend in the market. Advantages of podded propulsors like improved ship efficiency, complete elimination of propulsion shaft, maneuverability and possibility of locating propulsion motors outside the skin of the ship all make them more popular [41]. Cooling of the motors in these ship propulsion pods is discussed in this section.

a) Cooling of Stator and Rotor

In the invention of propulsion system of ship related to Figure 24 consists of a rotor winding subjected to intense cooling which is directly or indirectly coupled to cooling device and the stator winding surrounding the rotor. Here water is the cooling agent. Cooling channels are extended in radial and axial directions to ensure the efficient cooling of windings. To provide the flow of large cooling agent an expansion of supporting teeth in radial direction is needed. For cooling the outer casing cooling coils are mounted outside the housing [42].



k- coolant water, 15-outer casing of machine, 13- iron yoke
7-rotor,16-air gap,11-stator winding,
211 -support teeth

Figure 24: Expanded view of transverse section of propulsion unit of a vessel [42].

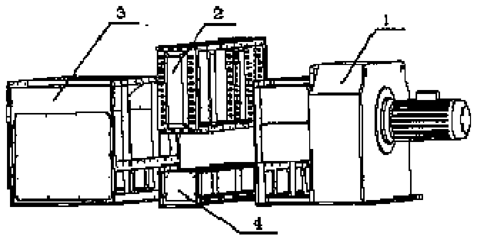
b) Ventilation cooling device for ship propulsion motor

Ventilation cooling device for ship propulsion motor shown in Figure 25 consists of a cooler, a diversion tank and ventilation set. Diversion tank connected to ship propulsion motor is also communicated with the air cooling loop of the motor. At the bottom of the cooler a base tank for the flow connection and diversion is arranged. Cooling device have staggered V plate which could separate water in the air. So as to ensure safety requirements of the ship propulsion motors ventilation cooling device can be connected through same connection mode or separated optionally to from integral ventilation cooling device for ship propulsion motor [43].

c) Cooling of immersed hull fixed ship electric motor

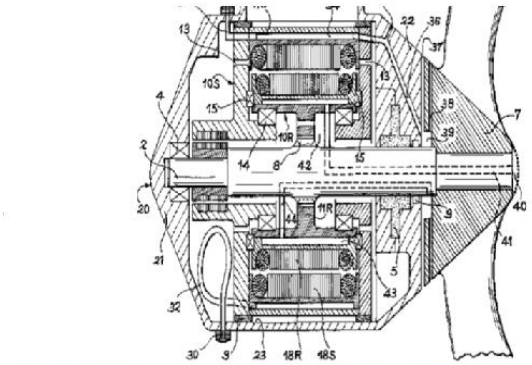
The invention in Figure 26 is connected to field of ship particularly propellers placed under water or beside the hull of submarine vessel. An auto cleaning filter is fitted to the cooling system which has water inputs. The input is connected to motor stator and cooling case which is connected to pump.

Cooling system consists of nacelle fixed to ship hull, propeller mounted on shaft, propulsion motor placed in nacelle and pump integrated in propeller hub with parts connected to channels in cooling case [44].



1- Ventilation unit, 2-coolers, 3-Diversion box, 4-Staggered base boxes

Figure 25: Marine propulsion motor ventilation schematic Structure of a cooling device [43].

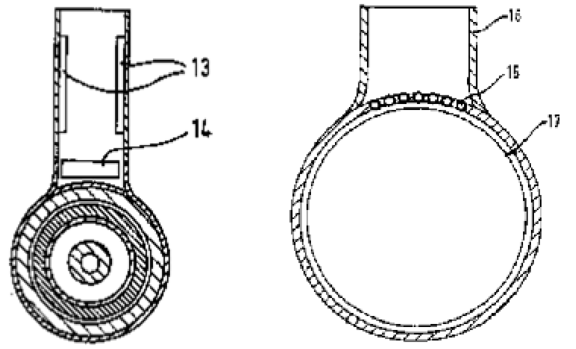


10 -stator ,10S- cooling casing, 20- a nacelle, 10- electric propulsion motor , 2-shaft, 7-propeller hub, 11S,11R- cooling casings of the motor

Figure 26: Propeller submerged vessel with cooling system [44]

d) Cooling device for Electric Motor Pod

Objective of invention in Figure 27 is to is to offer cooling of the motor like coil winding heads, when the electric propulsion pod is in tropical waters with high water temperatures. Heat is rejected from propulsion pod and access shaft and the presence of access shaft in heat rejection from motor attains the effect that, cooling of the motor is not restricted to surface of the propulsion pod only. Convective cooling surface is arranged in the shaft of the motor which helps in transfer of heat from centre of motor to cool ends. At the transition between the propulsion pod and access shaft cooling ducts are provided through which water flows and have a conical configuration to avoid blocking due wreckage of ship [45].

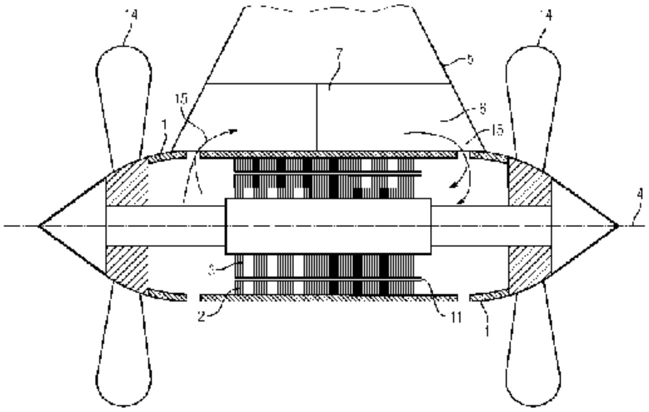


13,14 - cooling elements 15-coolent tubes, 16-shaft,17-propulsion

Figure 27: Cooling Surface arrangement and Cooling ducts Between propulsion pod and shaft [45]

e) Closed Cooling circuit cooling of Electric Pod Drive

Cooling of electric pod propulsion in Figure 28 relates to propulsion pod of ship consisting of a pod housing, one arranged in the gondola housing electric motor having stator and rotor and one to a gondola shaft by which the pod housing is rotatable. Electric motor is disposed in the cooling channels, which extend into interior of hull (water tight body of ship) and heat exchangers are there for cooling the cooling channels. Separate cooling modules consisting of fans and air or water coolers are there in the hull and the cooling air is directed through the cooing channels in the shaft to drive motor. Closed cooling circuit is applicable to only ship hull rotatable propulsion pod [46].

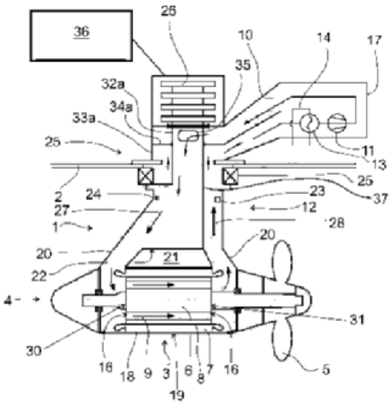


1- a pod housing, 2- stator, 3- rotor, 4- axis of rotation
5- pod shaft, 6- shaft channel,7- recooling element

Figure 28: Electric pod drive for ship with closed cooling Circuit [46].

f) Closed cooling circuit with gas

Pod propulsion unit in Figure 29 has a pod housing organized below the hull of a ship. The propeller motor has a stator, rotor, gas channels extending through rotor and a gap between rotor and stator which forms the part of the closed cooling gas circuit. For circulating gas in the cooling gas circuit the pod propulsion unit has a fan and for exchanging thermal energy between the liquid and gas flowing in the closed liquid and gas circuit respectively, it has a heat exchanger. Liquid in the closed cooling circuit is sea water and the circuit has one inlet and outlet option for it [47].



1-pod housing ,2-hull of the ship, 3-an electric propeller motor ,4-motor gondola
6-rotor ,7-stator ,8- annular gap,9- gas channels,10- closed cooling gas circuit
11-fan, 13-heat exchanger ,17-cooling unit, 27- feeding duct, 28-return duct
30-first motor end face,31-second motor end face

Figure 29: Pod propulsion unit of a ship with closed cooling Circuit with gas [47].

g) Cooling of motor with ring like duct

The inventions as shown in Figure 30 is the arrangement and configuration of cooler in electromotive drive system of ship. Cooler consists of an annular duct below the ship and the duct is provided with opening for inlet and outlet of coolant inside the shaft. Using seawater, heat exchanging element re-cools the coolant. Cooling fins are extended to annular duct and joined to wall. Heat that is generated in the coil ends, stator irons, copper windings which cannot be directly dissipated through housing are removed with the additional cooler which is configured by cooling pipes from annular cooling duct to the coil ends of stator [48].

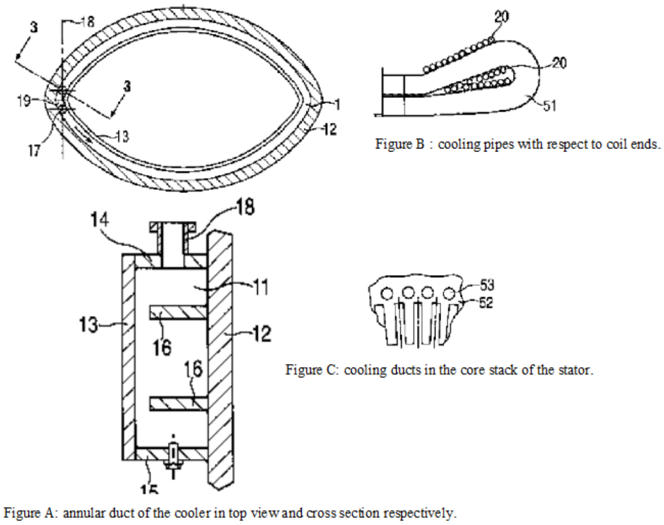


Figure B : cooling pipes with respect to coil ends.

Figure C: cooling ducts in the core stack of the stator.

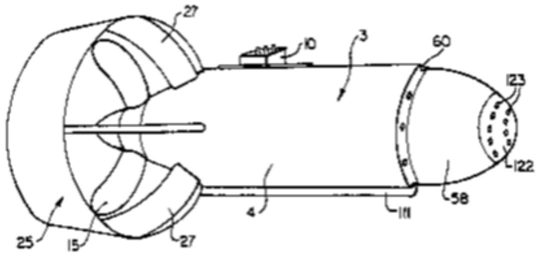
Figure A: annular duct of the cooler in top view and cross section respectively.

1-ship hull, 3-tubular housing, 11-cooling duct,12-wall.13-innerwall
14 and 15- upper and lower transverse wall, 16-cooling fins
17 and 18 -inlet and outlet opening for liquid cooling, 19-separate wall
20-cooling pipes, 51-coil ends of stator, 52-coil stack of stator,53-cooling ducts

Figure 30: Cooling of electromotive drive system for ship [48]

h) Cooling of submersible electric propulsor

Invention in Figure 31 describes closed cooling system for submersible propulsor unit having housing that contains submersible rotor and stator. Motor cooling is effective as the proplusor unit has a torpedo like housing assembly which contains motor in its interior. Water cannot penetrate and short circuit the electrical winding as the stator and rotor are canned. During the operation heat generated by the motor is removed by the ambient water surrounding the housing as it freely circulates between stator and rotor. The liquid cooling medium is closed, it is a solution of ethylene glycol and it is circulated through heat exchanger within the housing assembly [49].



3-a torpedo-like housing assembly ,4-main body member,10- terminal assembly 10
23-a shaft seal ,25-shroud assembly 27-four struts ,15-propeller ,11-shaft,
58-front support member ,60-bolts

Figure 31: Closed cooling system for submersible propulsor unit [49].

6. DISCUSSION

Thermal analysis of Electrical machines is gaining much importance as the Electromagnetic analysis of the machine in the past few years as its very important while designing electrical machine. Here in this thesis the topic Thermal analysis of Permanent Magnet Machines using double layer winding was given by Rolls Royce. It has been done in cooperation with NTNU under the supervision of Robert Nilssen. Number of meeting and discussion were carried out between the supervisor and engineers in Rolls Royce to proceed on with the thesis work along with me. Firstly, the discussion went on with the selection of tool for doing the thermal analysis. Number of tools like Lumped parameter, Computer fluid dynamics (CFD), Finite Element analysis (FEA) and MotorCad were in picture. Finally, it was decided to go with Finite Element analysis because it was much more compatible for evaluating thermal behavior of electrical machines.

Discussion focused on modelling important parts of machine from thermal point of view was on the stator winding and cooling system. Big competence was required for modeling the end windings, so it was decided to focus on simplified winding models and modelling them in Finite Element analysis. Simplified Models like conductors with different shapes and size in a rectangular slot were analyzed to study the temperature distribution in it. Equivalent thermal conductivity model was made which further helped in 2D Modelling of stator and rotor. Temperature distribution in the machine with the effect Heat transfer coefficient and Resistance was analyzed which would further help in including flow analysis in the end windings of machine in future. While doing the winding analysis, due to lack of time the fluid flow, required to cool the windings was not included but the work done could be further extended to include it.

Focusing on cooling part of the machine it was decided to include different aspects of cooling in Permanent Magnet machines and Ship propulsion pods, as Rolls Royce is focusing of motors in ship propulsion pods.

7. CONCLUSION

In this thesis Thermal Analysis of Electrical machines and different cooling aspects of Permanent Magnet machines and ship propulsion pods have been discussed.

Literature reviewing about the Thermal analysis papers gives a better understanding of thermal performance of machine. With the help of the method Finite Element Analysis (FEA) it was successfully possible to study the temperature distribution in different parts of the machine. Arrangement of conductors in a slot of a machine in different patterns like two turn profiles, four turn profiles etc helps in better understanding of temperature distribution in slot of machine and which could further be used while selecting conductors pattern while designing the machine. Equivalent thermal conductivity model gives knowledge about the thermal conductivity at different temperatures which was further helpful in designing 2D thermal models of stator and rotor. Thermal models with Heat transfer coefficient and resistance effect helps in the further study of fluid flow analysis of the machine. Cooling of Permanent magnet machines and Ship Propulsion pods was successfully studied with patents which helps to know different patterns of cooling which could be used while the designing process.

It could be concluded that knowledge about the geometric considerations of machine, insulation and material properties is not enough for the thermal study of the machine. Cooling of the windings and parts of the machine has to be considered to complete the thermal analysis of electrical machine so as to ensure a successful machine design.

8. FUTURE SCOPE

Modeling of end winding and heat transfer in electric machines was bit complicated. For including fluid flow and convective heat transfer it requires more competence and time. So it could be concluded that to show the fluid flow analysis and the effect of flow region, work done here could be used further in future 3D models as shown in Figure 32 to show the flow analysis in it.

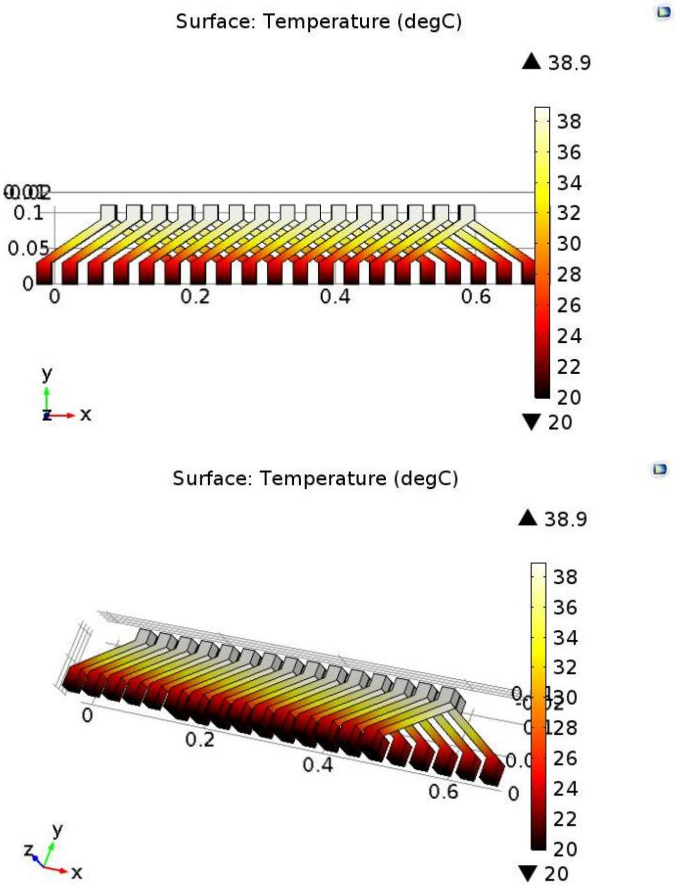


Figure 32: 3D Thermal Model of End Winding

9. ACKNOWLEDGEMENT

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