Comparative Heat Transfer Analysis of Optimal Electric Motor Designs with Different Winding Materials

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Abstract

This project presents a comprehensive comparative analysis of heat transfer in electric motor design through the exploration of different winding materials. The study involves a thorough examination of the thermal model, employing the MFEM framework for finite element analysis. A key modification involves the substitution of the conventional copper winding material with aluminum, silver, and magnesium and the subsequent visualization of temperature distribution using ParaView. The outcomes of this investigation reveal insights into the thermal performance of these new winding materials, with a specific emphasis on temperature variations, efficiency, and total mass in comparison to the conventional copper winding. This comparative analysis contributes valuable insights into the potential benefits and drawbacks associated with the implementation of alternative winding materials in the electric motor design.

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Introduction

Electric propulsion for aircraft is an emerging field of study that explores the possibility of achieving propulsion using either fully electric systems or hybrid electric systems, all while minimizing carbon dioxide emissions [1]. Compared with traditional aircraft, electric aircraft have several advantages, such as having simple energy management structures, low maintenance costs, and no emissions [2]. An electric motor used for aircraft propulsion typically consists of several key components that work together to generate thrust. The major parts of an electric motor for aircraft propulsion include rotor, stator, windings, power electronics, cooling, and power management, etc. [3].

According to *Toliyat et al* [4], the essence of motor winding in an electric motor for aircraft propulsion lies in its role as a critical component that generates the magnetic fields necessary for motor operation. In an electric motor, the winding is typically made of conductive materials (such as copper or aluminum) and is wound around a core [4]. When an electric current is applied to these windings, it creates a magnetic field that interacts with permanent magnets or other magnetic components in the motor, leading to the rotation of the motor shaft and ultimately providing propulsion for the aircraft [4]. The winding design and material choice are crucial factors in determining the motor's efficiency, power output, and overall performance [4]. Engineers must carefully consider these aspects to optimize the motor for the specific requirements of aircraft propulsion.

In 2023, *Babcock et al.* [5] worked on a multi-disciplinary analysis model that aimed at accurately predicting aircraft propulsive electric motor performance. The model considered losses related to frequency, flux density, and temperature and accounts for demagnetization effects in permanent magnets due to temperature changes. Efficient gradient-based optimization techniques were used by analytically computing derivatives through coupled adjoints, showcasing an improved motor efficiency in a real aerospace-grade electric motor optimization while meeting thermal and power output constraints. This paper was used as a foundation to study how the maximum temperature (and therefore heat transfer) changes with different winding materials for the optimized motor design.

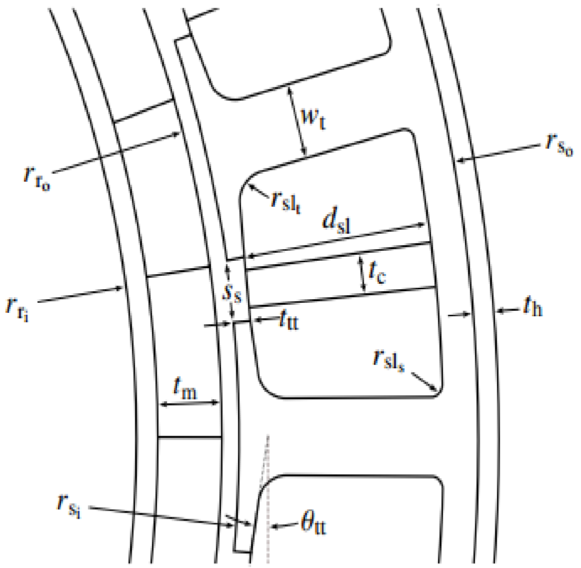
The goal of this project is to review and optimize the thermal model, if necessary, and then examine how the maximum temperature would change with different winding material and use this information to improve the optimal motor design. Copper is currently being used as the winding material in the model, but this project could reveal a new and more performant winding material. The performances of other winding materials such as aluminum, silver, and magnesium would be examined and analyzed with a focus on comparing with the existing, and widely adopted copper winding. The focus of the comparative heat transfer analysis is on winding and magnet temperatures.

Methodology

In this section, the geometric and thermal models employed within the motor modeling framework will be summarized and the underlying assumptions built into this model will be delved into.

Geometric Model

Within the scope of this research, the three-phase radial-flux inrunner permanent magnet synchronous motor (PMSM) is considered out of the various electric motor architectures being used for aerospace applications [5]. The geometry of the PMSM is characterized by the parameters listed in Table 1 and illustrated in Fig. 1. Note that the stack length, which quantifies the motor's axial depth, is not represented in Fig. 1 as it extends out of the plane of the illustration.



Parameter	Description
l_s	Stack length
d_{sl}	Slot depth
t_m	Magnet thickness
r_{r_i}	Rotor inner radius
r_{r_o}	Rotor outer radius
r_{s_i}	Stator inner radius
r_{s_o}	Stator outer radius
w_t	Tooth width
t_{tt}	Tooth tip thickness
θ_{tt}	Tooth tip angle
r_{sl_t}	Slot radius tooth
r_{sl_s}	Slot radius stator
s_s	Shoe spacing
t_c	Internal coolant duct thickness
t_h	Heatsink thickness

Figure 1: Diagram showing how geometric design parameters define the geometry for the PMSM of interest [5].

Thermal Model

The thermal characteristics of the motor will be simulated through a segmented (piecewise-continuous) approach, where the temperature distribution is modeled separately within each of the distinct components of the motor, including the stator, rotor, and windings. The temperature distributions within each component are interconnected or coupled using interface terms that consider thermal contact resistances and convective heat transfer (as necessary) [5].

To model the thermal behavior of the motor, the steady-state heat equation is used, which incorporates the divergence of Fourier's law for thermal diffusion and additional source terms to accommodate electromagnetic loss factors. This leads to the formulation of the linear diffusion equation governing the temperature field T as follows [5]:

$$-\nabla \cdot (\mathrm{K}\nabla \mathrm{T}) - q_{EM} = 0, \quad \forall\, x \in \Omega_T \tag{1}$$

where K is the thermal conductivity tensor, and q_{EM} denotes the combined heat sources due to the electromagnetic losses (DC, AC, and core losses). The set Ω_T denotes the computational domain of the thermal analysis, taken here to be a two-dimensional cross-section of the motor.

To couple the segmented temperature fields in the distinct motor components, thermal contact resistance (TCR) and internal convection (IC) interfaces were considered. Precisely, heat transfer is modeled using the TCR terms from [5]:

- the epoxy that bonds the stator and heatsink,
- the slot liner between the windings and the stator, and
- the epoxy that bonds magnets and the rotor.

Newton's law of cooling states that the heat flux across the interface between components, $K\nabla T \cdot \hat{n}$, is proportional to the temperature difference on each side of the interface, ΔT , with proportionality constant h [5]. This can be expressed mathematically as:

$$K\nabla T \cdot \hat{n} = h\Delta T \tag{2}$$

It is assumed that the thickness, t, of these thin insulating layers is constant along the interface, the proportionality constant, known in this context as the thermal contact conductance coefficient h_{TCR}, can be determined as:

$$h_{TCR} = \frac{K}{t}, \tag{3}$$

where again K is the thermal conductivity of the thin insulating material.

The motor is air-cooled by surrounding air moving around it; thus, a convection boundary condition is applied outside the motor to factor in the cooling effect of the ambient air moving around the motor nacelle. This boundary condition can be expressed as:

$$K\nabla T \cdot \hat{n} = h\left(T - T_f\right), \tag{4}$$

where h is the convection heat transfer coefficient, and T_f is the temperature of the fluid moving around the nacelle (also called the ambient temperature). In addition, a Neuman boundary condition is prescribed as

$$K\nabla T \cdot \hat{n} = q_r \tag{5}$$

along the interior of the rotor to account for the heat transfer from the rotor into the shaft.

These equations are discretized using the MFEM library [6] with the finite element method which results in algebraic form that is linear in T [5].

The thermal model, parameterized geometry model, and electromagnetic model are featured in a comprehensive motor code that will be built and run on a Scientific Computation Research Center (SCOREC) machine.

To achieve this through SCOREC machines, a handful of software packages were employed;

- Engineering Sketch Pad is used for the geometry,
- MFEM is used for discretization and finite element analysis (FEA),
- Adept is an algorithmic differentiation package
- MISO brings everything together in a usable PDE solver.

Geometry Selection

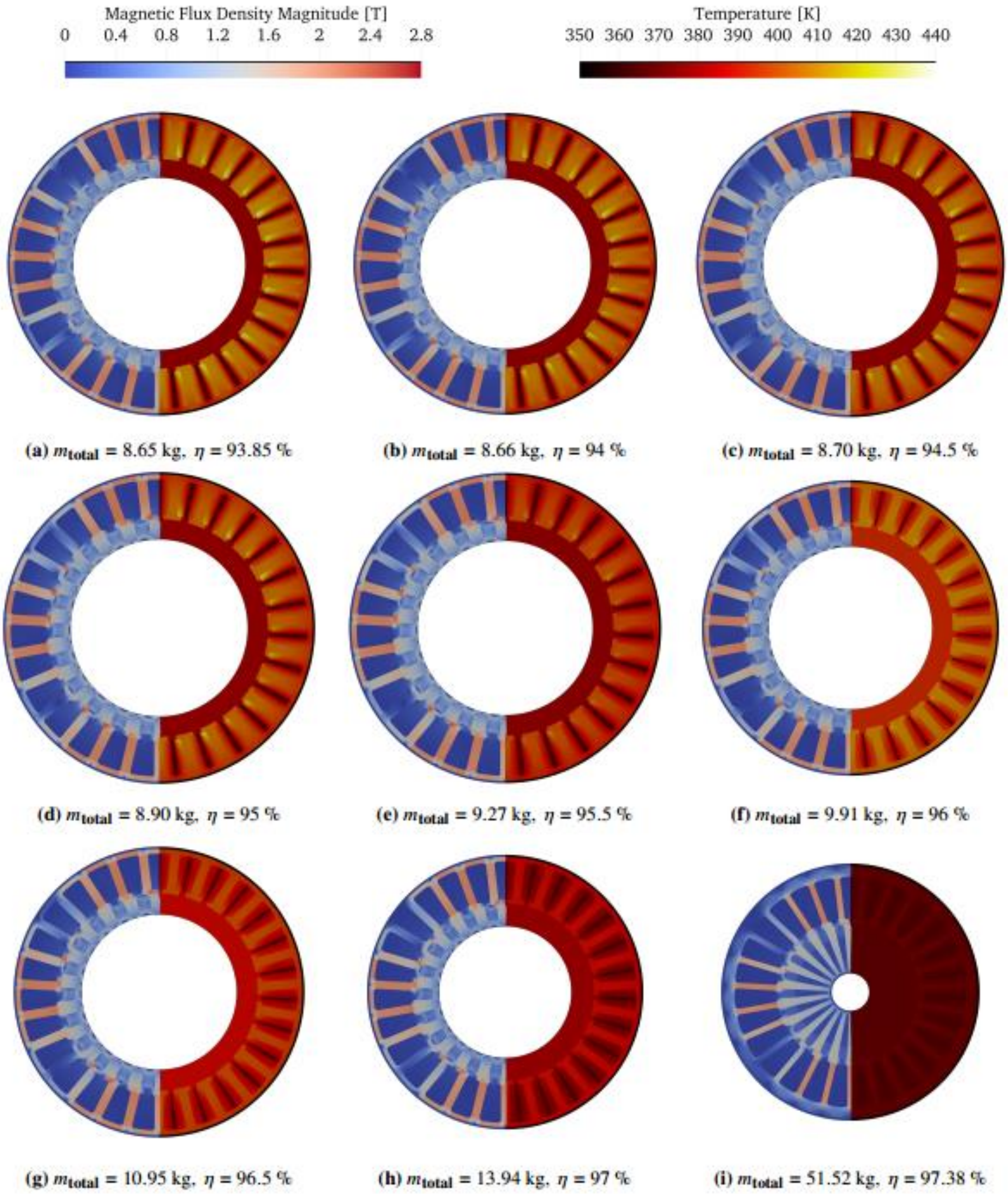


Figure 2: The magnitude of the magnetic flux density (shown on the left) and the temperature distribution (shown on the right) in each of the feedback-optimized Pareto-optimal motor geometries. All optimized designs are plotted on the same scale [5].

In the earlier work by *Babcock et al* [5], there are varieties of optimized pareto motor designs as shown in figure 2. The optimally designed electric motors have their applications in aircraft propulsion where power to weight ratio and overall aircraft weight are important factors. As efficiency increases, so does the total mass of the electric motor. Hence, the fourth (option d) optimal motor design, with 8.90kg mass and 95% efficiency, was chosen for comparative analysis with other winding materials.

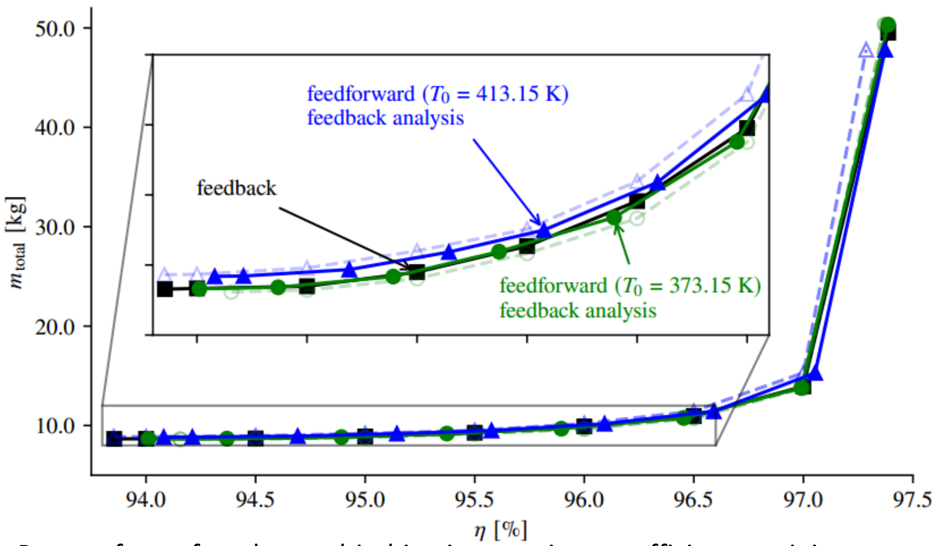


Figure 3: Pareto front for the multi-objective maximum efficiency minimum mass motor optimization problem [5].

Winding Materials Properties

The following parameters were specified for the new winding materials at 20°C (293.15K) [7], [8], [9]. The material property for copper in the earlier work [5] was retained.

Material Property/Material Type	**Thermal Conductivity (K) [W/m·K]**	**Temperature Coefficient of Resistivity ($\alpha_{\rho 0}$) [K^{-1}]**	**Electrical resistivity (ρ_0) [Ωm]**	**Density (ρ) [kg/m³]**	**Cost [$/lb]**
Copper	400	3.8×10^{-3}	1.68×10^{-8}	8960	3.7205
Aluminum	237	4.31×10^{-3}	2.65×10^{-8}	2,700	0.9745
Silver	429	3.82×10^{-3}	1.59×10^{-8}	10,490	23.976
Magnesium	156	4.86×10^{-3}	4.39×10^{-8}	1,740	5.25

Table 2: New winding materials information.

Results and Discussion

The performance parameters of interest for the comparative analysis are efficiency, total mass, maximum magnet temperature and the maximum winding temperature. The simulation results are summarized in the table below.

Material Type	Efficiency [%]	Total Mass [kg]	Thermal Management System Mass [kg]	Maximum Magnet Temperature [K]	Maximum Winding Temperature [K]
Copper	95.0	8.90	3.20	377.47	430.18
Aluminum	93.86	8.35	3.61	379.26	425.69
Silver	95.09	9.10	3.17	377.40	432.14
Magnesium	90.78	9.37	4.78	385.51	452.22

Table 3: Simulation result summary of copper and the new winding materials

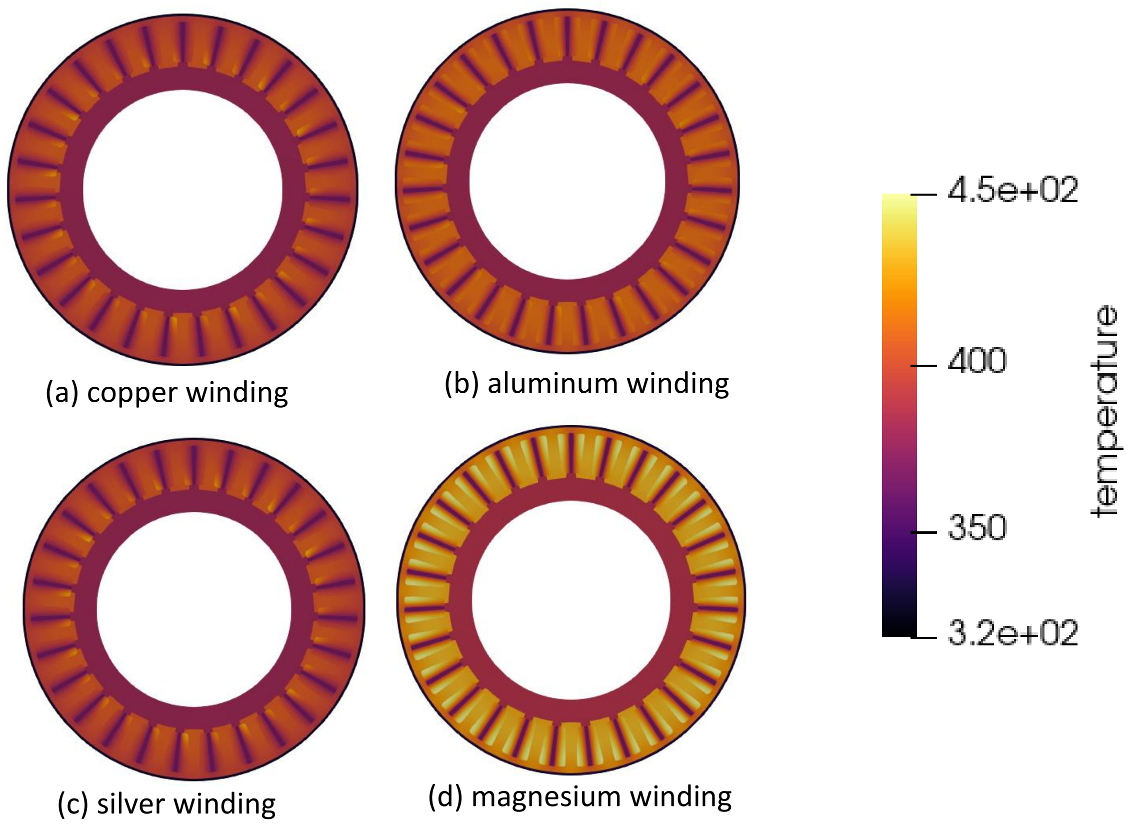


Figure 4: Motor temperature distribution with different winding materials

Analyzing the simulation results, the comparative evaluation of different winding materials reveals distinctive temperature profiles. Notably, aluminum exhibits the lowest maximum winding temperature of 425.69K. Due to its lower density in comparison to copper and silver, aluminum possesses a reduced thermal mass. While this characteristic might limit its heat conduction capacity, it also allows aluminum to experience quicker heating and cooling cycles. Consequently, this property contributes to aluminum demonstrating the lowest maximum winding temperature among the considered winding materials. Copper winding exhibits a little higher maximum winding temperature at 430K, along with a temperature distribution akin to silver. In contrast, magnesium winding exhibits a contrasting scenario, registering the highest temperatures among the considered materials. Specifically, it presents a maximum magnet temperature of 385.3K and a notably increased maximum winding temperature of 452.22K. This disparity portrays the thermal performance differences between copper, silver, and magnesium windings, emphasizing the critical role of material selection in influencing the temperature characteristics of electric motor components.

The propensity of copper and silver to yield lower temperatures than magnesium in the winding can be attributed to their inherent characteristics, particularly their low electrical resistance. This characteristic translates into lower resistive losses as current flows through the winding, thereby mitigating temperature increases. This phenomenon is underpinned by the lower resistivity and thermal coefficient of resistance values exhibited by copper and silver when compared to aluminum and magnesium. Furthermore, the superior thermal conductivity of copper and silver, 400W/mK and 429W/mK respectively, in contrast to other materials, plays a pivotal role. Materials with higher thermal conductivity possess enhanced capabilities for conducting and dissipating heat efficiently. Consequently, the heightened thermal conductivity of copper and silver facilitates superior heat dissipation, contributing to the reduction of winding temperatures. The intricate interplay of electrical and thermal properties emphasizes the significance of material selection in optimizing the thermal performance of electric motor components.

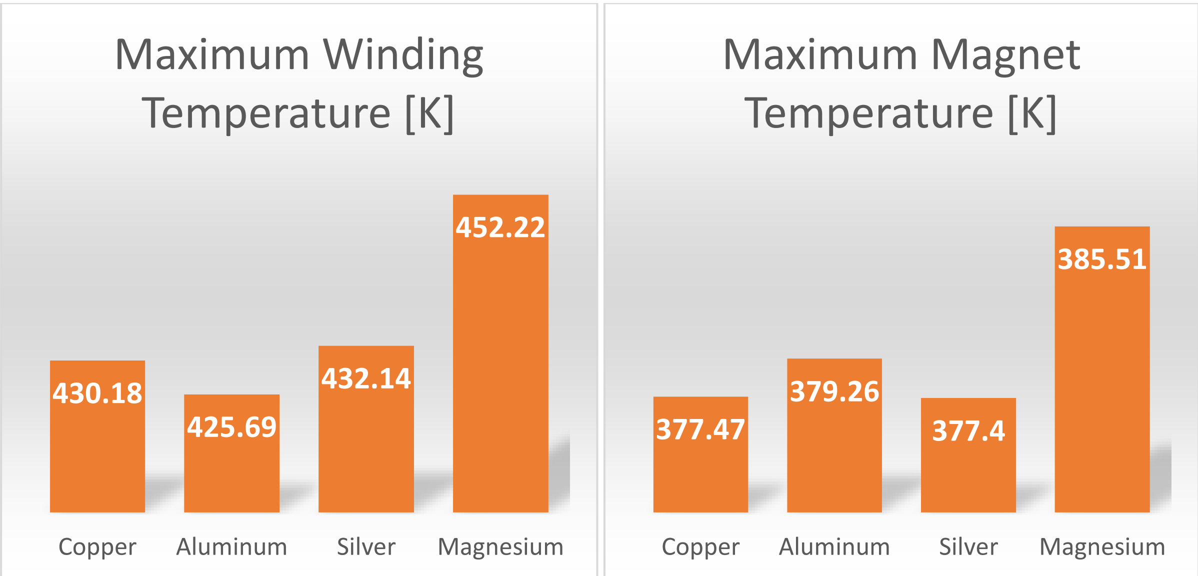
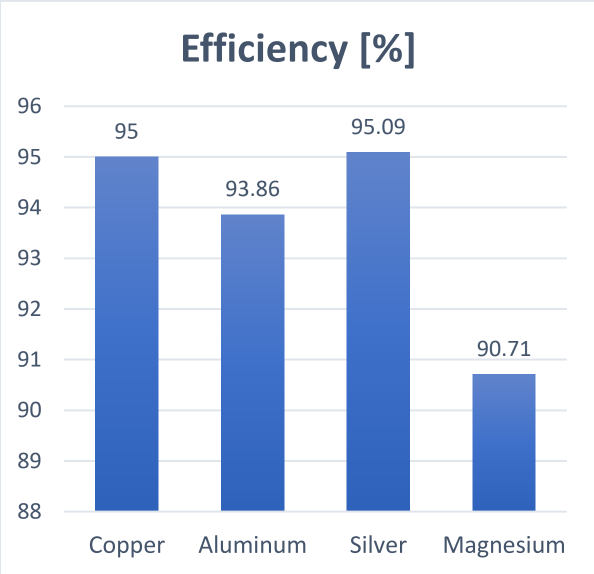


Figure 5: Graphs showing the variation of temperature with different winding materials.

Copper and silver, which results in lower temperature in the winding is a result of their low resistance to the flow of current which results in resistive losses and thus temperature increases. This stems from their lower resistivity and thermal coefficient of resistance values when compared to the values for aluminum and magnesium. In addition to this, the higher thermal conductivity of copper and silver aid better conduction and dissipation of heat. Materials with higher thermal conductivity dissipate heat better thus reducing the temperature of the winding.

Resistivity also plays an important role in the overall efficiency of the motor since efficiency is a factor of electrical power input and mechanical power output. With lower resistance to the flow of current through the windings, current flows better through the winding which results in higher electrical power input and thus increased efficiency. This describes why silver is more efficient than copper and appears to be the material with the highest efficiency (95.09%). Conversely, magnesium and aluminum less efficiency could be attributed to their higher resistive values.



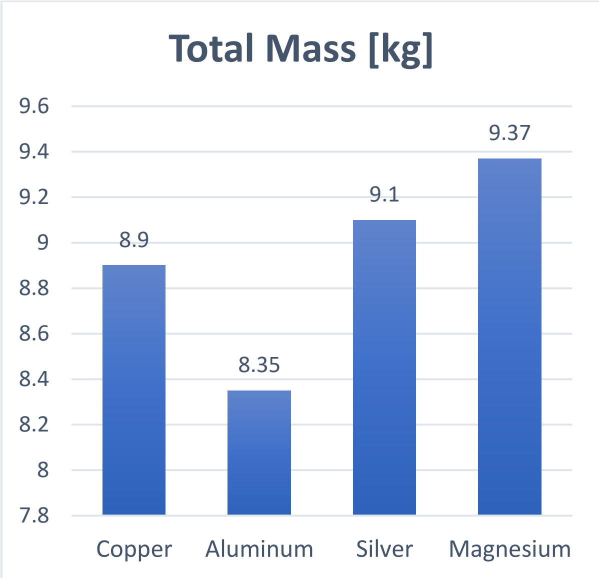


Figure 6: Graphs showing efficiencies and total masses based on different winding materials.

With low density and lowest winding temperature presented by aluminum, it yields the lowest total mass of 8.35kg and thermal management system (TMS) mass of 3.62kg while copper results in 8.9kg total mass and TMS mass of 3.20kg. This shows how well the density of aluminum has impacted the total mass. Even though silver is the most efficient and thus possesses the least TMS mass of 3.17, the high total mass exhibited by silver winding which is greater than the masses from copper and aluminum winding is a result of silver's high density. While magnesium has the lowest density of 1,740kg, it would have yielded the lightest motor total mass. Conversely, due to its comparative poor performance which leads to the highest estimated TMS mass of 4.78kg, magnesium winding ultimately turns out to be the heaviest motor.

Examining and assessing the temperature distribution in an electric motor holds significance due to the safety implications associated with overheating. Elevated temperatures create potential safety hazards, such as insulation breakdown (as we could have in the slot liner between the stator slot and the winding), that may result in short circuits or electrical faults. These issues can lead to damage to the motor itself, connected equipment, and even pose the risk of fire.

High temperature in different motor components have different. For example, high temperatures in a permanent magnet can lead to demagnetization which reduces the magnetics strength and thus results in reduction of the motor performance. High temperatures have the potential to diminish the magnetic flux produced by the magnets, thereby influencing the overall efficiency and power output of the motor. The permanent magnet used in this work is neodymium magnet (NdFeB) and according to *Wallscheid* [10], the maximum reasonable temperature of use for NdFeB magnet is 150-230 °C (i.e. 423.15K -

503.15K) which is higher than the predicted magnet temperatures estimated for all materials considered.

Conclusion

Considering the combination of performance results such as efficiency, temperatures, weight, and cost, copper is generally a well performant winding material which is evident by its wide adoption for winding globally. However, in this study, aluminum and silver perform better in some areas. On one hand, silver is 0.09% more efficient than copper but it’s about seven times more expensive than copper and results in heavier motor which makes it challenging to consider silver over copper. On the other hand, aluminum winding yields lighter motor mass and lower maximum winding temperature but less efficient than copper winding by 1.14%.

Recommendation

While this study has focused on winding temperatures, magnet temperatures, efficiency, total mass and cost of materials, there are other areas that should be further investigated which are:

- study of the impact of the winding materials on stator temperature,
- investigation of the thermal expansion and structural impact.
- Investigation of resistive losses from aluminum, silver, and magnesium windings, and
- assessing the impact of different winding materials on the motor's electromagnetic performance.

References

[1] Samith Sirimanna *et al.*, “Comparison of Electrified Aircraft Propulsion Drive Systems with Different Electric Motor Topologies,” vol. 37, no. 5, Jun. 2021.

[2] T. Zhao, S. Wu, and S. Cui, “Multiphase PMSM With Asymmetric Windings for More Electric Aircraft,” vol. 6, no. 4, pp. 1592–1602, Dec. 2020.

[3] Paul C. Krause, Oleg Wasynczuk, and Scott D. Sudhoff, “Analysis of Electric Machinery and Drive Systems,” 1995.

[4] Hamid A. Toliyat, Subhasis Nandi, Seungdeog Choi, and Homayoun Meshgin-Kelk, “Electric Machines: Modeling, Condition Monitoring, and Fault Diagnosis,” *CRC Press*, Mar. 2017.

[5] Tucker Babcock, Bryan McKeever, and Jason E. Hicken, “Multi-Disciplinary Design Optimization of an Electric Motor Considering Thermal Constraints,” *AIAA AVIATION*, Jun. 2023.

[6] T. Kolev and V. Dobrev, “Modular Finite Element Methods (MFEM).” USDOE, Jun. 21, 2010.

[7] Daily Metal Prices, “Popular Metal Prices,” [online] Available at: https://www.dailymetalprice.com/ [Accessed December 6, 2023].

[8] All About Circuits, “Temperature Coefficient of Resistance,” [online] Available at: https://www.allaboutcircuits.com/textbook/direct-current/chpt-12/temperature-coefficient-resistance/ [Accessed December 6, 2023].

[9] “The Engineering ToolBox (2003). Resistivity and Conductivity - Temperature Coefficients Common Materials.,” [online] Available at: https://www.engineeringtoolbox.com/resistivity-conductivity-d_418.html [Accessed December 3, 2023].

[10] Oliver Wallscheid, Tobias Huber, Wilhelm Peters, and Joachim B ¨ocker, “Real-Time Capable Methods to Determine the Magnet Temperature of Permanent Magnet Synchronous Motors — A Review,” *IEEE*, 2014.