Cryogenic Thermal System for Coreless Axial Flux PM Machine with Litz Wire Winding for Electric Aircraft Propulsion

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***Abstract*—Electric machines for aviation demand ultra-efficient, compact designs with high specific power density, which can be achieved through advancements in both electromagnetic design and thermal management. This paper proposes and investigates an integrated thermal management approach for a coreless stator axial flux permanent magnet (AFPM) machine featuring a double-sided Halbach array PM rotor, two stators, and an aluminum nitride (AlN) cold plate positioned between the stators for direct cooling. The cold plate incorporates internal serpentine channels for liquid hydrogen circulation. The electromagnetic performance and efficiency of the machine at cryogenic temperatures are assessed using temperature-dependent data from the literature, indicating that as the temperature drops to –140°C, the remanence of the permanent magnets increases, and the resistivity of the Litz wire decreases continuously. These effects collectively enable the machine to achieve up to 99% efficiency at cryogenic conditions. To evaluate the feasibility of achieving this performance, thermal analysis is conducted using an analytically derived lumped thermal resistance network and computational fluid dynamics (CFD) simulations. The results show that the required thermal environment can be realized through precise cold plate design and stator winding manufacturing with careful potting using high thermal conductivity epoxy.**

***Index Terms*—Cryogenic, liquid hydrogen, axial flux, coreless stator, electric machine cooling, Litz wire.**

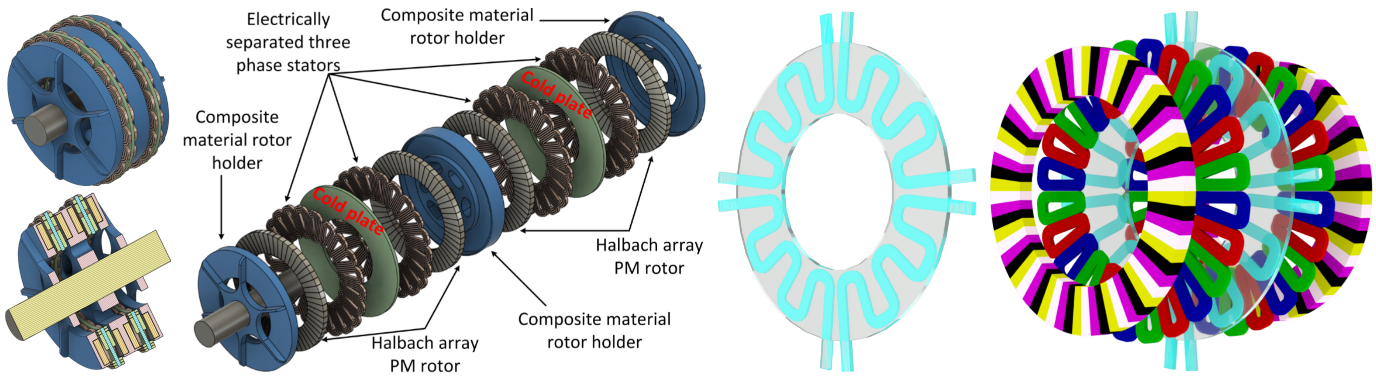
I. Introduction

A report by Roland Berger projects that without substantial progress in electrifying aviation, the industry's share of global carbon emissions could climb to 25% by 2050, assuming other sectors successfully decarbonize [1]. This necessitates a significant enhancement of the performance of electric propulsion systems to rival that of traditional internal combustion engines. This goal can be achieved through advancements in electric machine design, such as using AFPM machines, improved magnetic structural configuration like Halbach array PM rotors, and higher electric loading enabled by enhanced cooling systems [2–4].

Axial flux PM machines provide distinct benefits over traditional radial flux topologies, notably delivering higher specific power in a more compact envelope [5, 6]. Their ability to support a large number of poles contributes to reduced machine mass with increasing pole count [7]. These machines offer superior thermal management due to their geometry, which allows for more effective direct cooling strategies than radial flux designs [8, 9]. This facilitates higher electric loading and minimizes the mass of active magnetic materials. Their axial compactness allows multiple machines to be mounted along one shaft without increasing the outer diameter, thereby improving system power output and fault tolerance, which is a key advantage for aviation systems [10, 11].

Coreless stator AFPM machines are developed by removing the stator teeth and positioning the windings directly within the air-gap [12]. In this configuration, torque is generated via the Lorentz force resulting from the interaction between the magnetic field of the rotor and the current-carrying conductors [13, 14]. This configuration enables high specific power density and efficient direct cooling of the windings [15]. These characteristics make coreless stator AFPM machines particularly advantageous for aerospace propulsion systems.

When integrated with a coreless stator architecture, the use of Halbach array PM rotors can significantly boost both efficiency and specific power in AFPM machines [16]. Studies indicate that Halbach configurations can deliver around 40% greater air-gap flux density and torque output than equivalent surface-mounted PM rotors with the same size [17]. Although these arrays are more costly and complex to manufacture, their performance benefits have led to their adoption in several electric machine designs for aerospace propulsion [18–20].



(a) (b) (c) (d)

Figure 1. Proposed coreless AFPM machine with an integrated cryogenically cooled thermal management system, illustrating (a) compact and sectional views of the double-stage design, (b) the exploded view of the full assembly, (c) the topology of the cold plate positioned between the two stators in each module, and (d) the exploded view of a single stage.

This paper explores the thermal management potential and electromagnetic performance of a coreless AFPM machine operating at cryogenic temperatures for electric aircraft propulsion. Hydrogen is used as the primary fuel source and is stored in liquid form at approximately 20 K to maximize volumetric energy density [21]. Before being supplied to fuel cells or turboelectric generators, the hydrogen is heated to around 353 K [22]. This temperature differential presents an opportunity to harness the cooling capacity of liquid hydrogen for component-level thermal management, potentially improving overall system efficiency and aircraft performance.

This paper shows that operating the coreless AFPM machine at a cryogenic temperature of -140^{oC} helps sustain high electromagnetic efficiency and prevents performance degradation under high electric loading conditions. The analysis includes an electromagnetic evaluation of the motor topology with attention to temperature-dependent characteristics, along with a thermal assessment based on the machine's geometry and power loss distribution.

The thermal modeling methodology employs a lumped thermal resistance network, derived analytically using empirical heat transfer correlations and validated through CFD simulations. The model also incorporates the impact of anisotropic thermal conductivity within the stator coil windings, considering void fractions reported in experimental investigations [23]. This integrated approach potentially enables accurate prediction of the machine's thermal behavior under cryogenic operating conditions.

II. Coreless AFPM Machine with Integrated Cryogenic Thermal Management

The proposed motor consists of two mechanically integrated stages, effectively equivalent to mounting two coreless AFPM motors on a single shaft. Example design of the motor configuration is illustrated in Figs. 1a and 1b. The electromagnetic and thermal components of a single stage are further detailed in compact and exploded views, as shown in Figs. 1c and 1d.

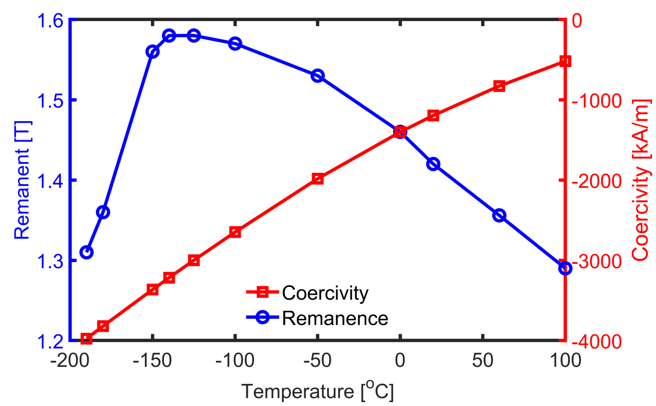
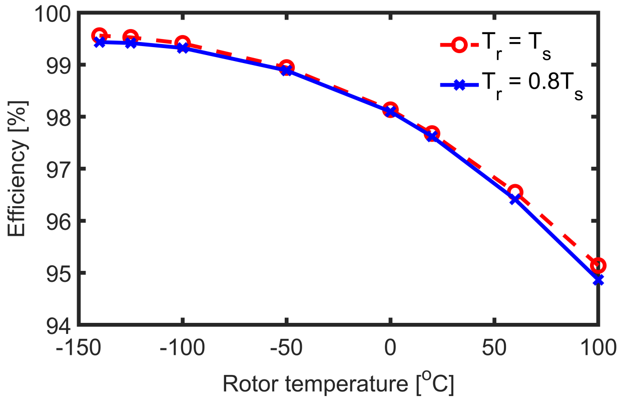


Figure 2. Remanence and coercivity curves of NdFeB 50BH at various temperatures.

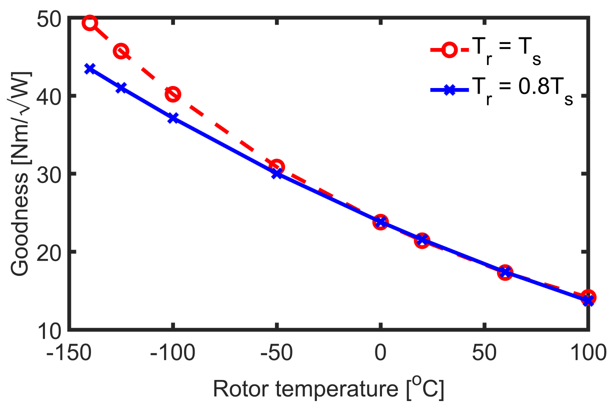
Each stage incorporates a double-sided Halbach array PM rotor with a 90-degree Halbach arrangement, two PMs per pole, and two similar coreless stators. In order to enhance fault tolerance capability, the stators are electrically independent and connected to separate power converters. The stator coils are fabricated using rectangular Litz wire and potted with a high-thermal-conductivity epoxy to enhance thermal performance.

Achieving the required high specific power density (kW/kg) for this application necessitates high current loading, making thermal management critical. The coreless stator configuration and axial flux construction can enable direct and effective cooling of the stator coils. This paper introduces and evaluates a cold plate design with serpentine channels for the thermal management of the proposed motor.

The cold plate is positioned between the two stators of each stage, resulting in two similar cold plates in the complete motor assembly. The selected material for the cold plate must exhibit poor electrical and magnetic conductivity to minimize eddy current losses and magnetic flux disruptions while offering high thermal conductivity to efficiently dissipate



(a)



(b)

Figure 3. Efficiency (a) and Goodness (b) under two scenarios: (1) equal rotor and stator temperatures, and (2) rotor temperature at 80% of the stator temperature, evaluated across a range from high to cryogenic temperatures.

heat from the stator coils. Additionally, compatibility with additive manufacturing techniques, such as 3D printing, enhances fabrication precision and ease. Aluminum Nitride (AlN) was chosen as the optimal material based on these criteria and is used for thermal analysis throughout this study.

The proposed electric motor concept is part of a project to develop a 112-passenger blended-wing regional jet powered by on-board liquid hydrogen. The liquid hydrogen will also be a coolant for superconducting cables running through the aircraft, providing a readily available cryogenic resource near the motor and drive systems. This paper explores the potential performance benefits of integrating a cryogenic thermal management system into the coreless stator AFPM motor design.

The magnetic behavior of Neodymium Iron Boron (NdFeB) magnets at cryogenic temperatures has been experimentally studied in [24]. The results for a NdFeB 50BH grade magnet are presented in Fig. 2. These magnets exhibit a negative temperature coefficient of remanence, approximately -0.1%/K near room temperature, indicating that the magnetic field increases as temperature decreases. However, below a critical temperature of about 140 K, spin reorientation causes the magnetic field to decline, reversing the trend.

Table I

SUMMARY OF HEAT TRANSFER MODES, HEAT FLOW CALCULATIONS, AND CORRESPONDING THERMAL RESISTANCES.

Heat transfer mode	Heat flow calculation	Thermal resistance
Conduction	$Q = KA\frac{\mathrm{d}T}{\mathrm{d}x} \approx KA\frac{\Delta T}{t}$	$R_{\text{cond}} = \frac{L}{KA}$
Convection	$Q = hA\Delta T$	$R_{\text{conv}} = \frac{1}{hA_s}$

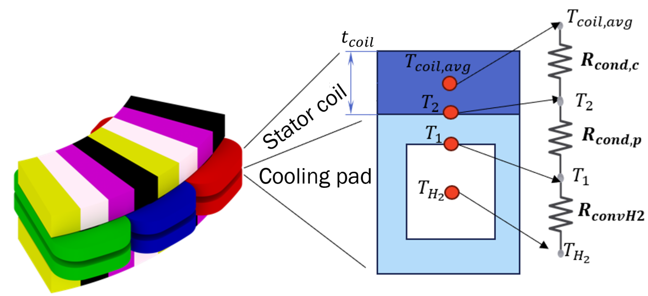


Figure 4. Geometry of the AFPM motor and its corresponding simplified thermal circuit.

The resistivity of aluminum and copper Litz wires at cryogenic temperatures was experimentally measured in [25], showing a substantial decrease in resistivity as temperature drops. While aluminum exhibits higher resistivity than copper at near-room temperatures, the results reveal that aluminum's resistivity declines more quickly with temperature drop. Below approximately 77.9 K, aluminum achieves a lower resistivity than copper. This characteristic is advantageous for electric machines designed for electric aircraft propulsion, as aluminum's mass density is about one-third that of copper, leading to a significant improvement in specific power density.

The magnetic properties of the permanent magnets and the resistivity characteristics of copper Litz wire, as reported in [24] and [25], were utilized to evaluate the electromagnetic performance of the proposed coreless stator AFPM machine. The results, shown in Fig. 4, consider two scenarios: one where the stator and rotor operate at the same temperature and a more realistic scenario, based on literature, where the rotor temperature is approximately 80% of the stator temperature.

The motor's rated output power during takeoff is 2 MW, distributed as 1 MW per stage in the proposed configuration. Efficiency and Goodness—the torque ratio to the square root of losses—were analyzed across a broad temperature range, from 130 K to 370 K, under constant power conditions. The results demonstrate a notable increase in both efficiency and Goodness at lower temperatures. Notably, efficiencies exceeding 99%, comparable to those of power electronic systems, are achievable at cryogenic temperatures.

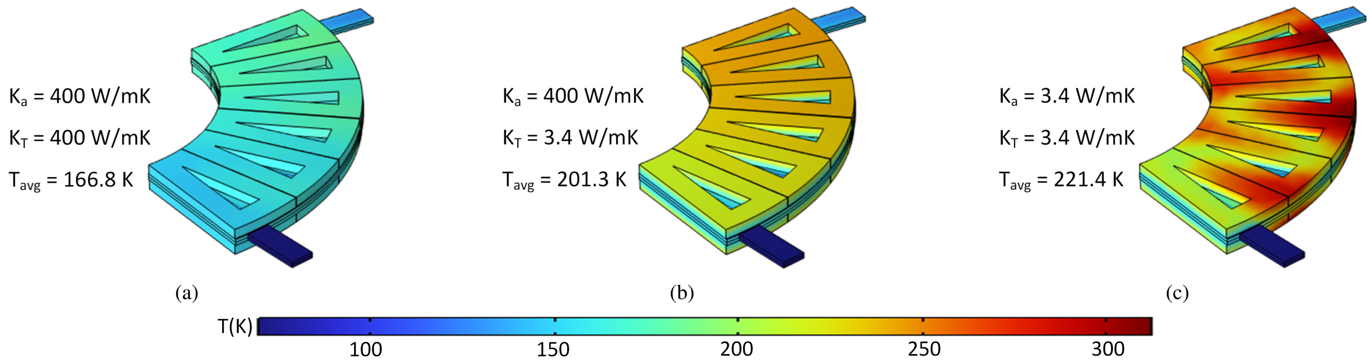


Figure 5. Simulation results for non-isotropic thermal conductivity when (a) k_T = k_A = 400 W/mK, (b) k_T = 3.4 W/mK and k_A = 400 W/mK, and (c) k_T = k_A = 3.4 W/mK.

III. Thermal Analysis

Electric aircraft powered by liquid hydrogen as fuel can leverage its cooling potential to enhance system performance. This integration enables thermodynamic calculations to be closely aligned with motor design, optimizing thermal management. This section investigates the thermal performance of a proposed coreless AFPM machine, focusing on efficient heat dissipation from the stator coils. The cooling system incorporates a cold plate that absorbs heat from stator losses. Two complementary methods are employed to evaluate the effectiveness of this cooling structure: lumped thermal circuit analysis and computational fluid dynamics (CFD) simulations. These approaches aim to determine the cooling requirements necessary to manage the machine's heat losses and provide a detailed visualization of its thermal behavior.

A. Calculation Tools

The lumped thermal circuit is an analytical technique that simplifies complex geometries into a one-dimensional heat flow model based on the energy balance equation. This approach translates heat transfer through conduction, governed by Fourier's law, and convection, governed by Newton's law of cooling, into equivalent thermal resistances. Table I presents the conversion of heat transfer equations into thermal resistance values [26]. The schematic in Fig. 4 illustrates the heat flow path, in which the heat generated in the stator coils is transferred through the cold plate and cooling channels, ultimately carried away by the working fluid. This method enables preliminary calculations and assists in determining the primary sizing of the cold plates.

Following the preliminary calculations using the lumped thermal circuit, a 3D CFD analysis was conducted. This approach not only determines the average temperature but also provides a detailed visualization of the entire model. The simulation utilizes the turbulence k-ϵ model, a turbulence solver with relatively high accuracy in heat and fluid flow simulations. The material setup for the CFD analysis mirrors that of the lumped thermal circuit, incorporating a heat source from the stator coil, with heat removal facilitated by the working fluid.

B. Results and Discussion

The analysis begins with the stator coil, which employs the Litz wire. Litz wire consists of sealed copper strands, which can result in potentially high axial thermal conductivity, such as (k_a) of 400 W/mK, equivalent to pure copper. However, void gaps between the strands can act as thermal insulators in the transverse direction, significantly reducing the transverse thermal conductivity (k_t). Woodworth *et al.* reported a transverse thermal conductivity of 3.4 W/mK [23].

The impact of transverse thermal conductivity in the stator coil was analyzed under three distinct scenarios. The first scenario assumes uniform thermal conductivity of k_T = k_A = 400 W/mK, equivalent to pure copper. The second scenario incorporates reduced transverse thermal conductivity, k_T = 3.4 W/mK, due to void gaps in the coil while maintaining k_A = 400 W/mK. The final scenario represents significantly degraded thermal conductivity in all directions, with k_T = k_A = 3.4 W/mK. The simulations were performed with a flow velocity of 10 m/s, a reference pressure of 10 bar, and a heat loss of 13.17 kW.

The temperature distribution of the stator coils is depicted in Fig. 5. The optimal temperature required to achieve maximum electromagnetic efficiency is attainable in the ideal case. However, this scenario assumes a perfectly constructed winding with no voids between layers of the Litz wire and perfect potting using a highly thermally conductive epoxy. In contrast, the other two cases exhibit higher average temperatures, exceeding the threshold necessary to achieve approximately 99% electromagnetic efficiency under the simulated flow velocity and pressure conditions.

To determine the required transverse thermal conductivity and inlet velocity necessary to achieve the desired average temperature, a parametric study was conducted to evaluate the combined effects of these parameters, with the results presented in Fig. 6. The findings indicate that increasing both the flow velocity and the transverse thermal conductivity

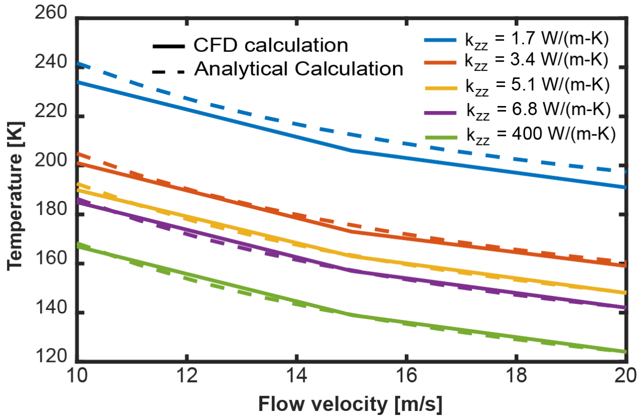


Figure 6. Average stator coil temperature for different thermal conductivities and varying flow velocity.

results in a lower temperature of the cooling pads. According to the calculations, the target temperature can be approached with a transverse thermal conductivity of at least 6.8 W/mK and a flow velocity of 20 m/s, which are potentially achievable.

Improvements to the cooling system can be pursued through three main strategies: reducing losses in the electric motor by decreasing electric loading and compensating with increased magnetic loading, enhancing the coolant's convective heat transfer by raising the fluid pressure, and optimizing the cold plate design to expand the heat transfer area. The analysis confirms that achieving a high-efficiency AFPM machine within the specified low-temperature range is feasible, though further experimental validation is necessary.

IV. Conclusion

A thermal management concept for cooling a coreless stator AFPM machine at cryogenic temperatures has been introduced, featuring a cold plate positioned in the airgap and in direct contact with the stator coils. The cold plate incorporates serpentine channels for coolant flow and is made of Aluminum Nitride, a material with low electrical conductivity and magnetic permeability but high thermal conductivity. The electromagnetic performance of the machine at cryogenic temperatures was assessed using the cryogenic properties of the PMs and copper Litz wire based on existing literature. The calculations demonstrate that at -140°C, the machine achieves an efficiency greater than 99% due to the enhanced magnet remanence and improved conductivity of the copper Litz wire.

Thermal analysis was conducted to evaluate the feasibility of the proposed cooling concept and determine the required specifications for the cooling system. The results indicate that the target temperature can be achieved with a transverse thermal conductivity of at least 6.8 W/mK and a flow velocity of 20 m/s. While these conditions are achievable, they require precise coil manufacturing to minimize voids between the Litz wire layers and potting using high thermal conductivity epoxy.

Acknowledgment

University of Kentucky student's research has been supported by the National Aeronautics and Space Administration (NASA) University Leadership Initiative (ULI) award #80NSSC22M0068. The support of ANSYS Inc., University of Kentucky the L. Stanley Pigman Chair in Power endowment is also gratefully acknowledged. Any findings and conclusions expressed herein are those of the authors and do not necessarily reflect the views of the sponsor organizations.

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