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Mass-Specific Thermal Optimization of a Heat Sink for rotating 80kW SiC Dual Inverter Exposed to Extreme Conditions

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***Abstract*—The scope of this study encompasses the design of a heat sink for rotating power electronics operating under conditions of significantly elevated temperature within a rotating actuator system which integrates two 40kW SiC inverters for fault-tolerant operation. The primary objective is to identify optimal parameters for designing the rotary heat sink, ensuring efficient heat dissipation while adhering to weight limits and considering space envelope and coolant air constraints. The thermal efficiency of the designed heat sinks is accessed in terms of mass-specific heat transfer coefficient through the computational fluid dynamic analysis. The findings demonstrate that the augmented fin height and thinner fin dimensions lead to enhanced performance. Notably, a larger gap between fins augments the thermal performance of the heat sink under rotation. Conversely, an opposing trend manifests when the heat sink is stationary.**

Keywords— Rotating power electronics, rotary heat sink design, Mass-specific heat transfer coefficient, extreme conditions

I. INTRODUCTION

While the passive rotating diode-bridge rectifier has been operational since the 1960s in brushless excitation systems [1], the recent shift to active rotating power electronics marks a transformative trend in electrical machine applications [2]–[4].This shift introduces challenges from high heat-generating components, necessitating efficient thermal management for sustained reliability. Cooling active rotating power electronics is complex due to limited space for conventional methods, mechanical strains affecting system integrity, and considerations regarding heavier heat sinks. Optimal coolant selection must balance operational and environmental needs. Prioritizing energy-efficient cooling is crucial, alongside meticulous design for coolant circulation in rotating components.

Rotary-finned heat sinks offer a promising thermal management solution for active rotating power electronics, leveraging centrifugal forces to enhance convective heat transfer [5], [6]. Though extensive research on electronic cooling exists [7], the challenges associated with the thermal management of rotating power electronics under high-temperature conditions remain largely unexplored. This paper addresses the knowledge gap through a problem-specific parametric study on a rotary actuator heat sink, aiming to achieve optimal thermal performance while minimizing added system weight. The primary objective is to identify optimal parameters for designing the rotary heat sink for the power electronics embedded within a rotating actuator system. This system integrates two 40kW SiC inverters for fault-tolerant operation.

II. PROBLEM DESCRIPTION AND MODELLING

A. Physical Model

In an assembly featuring a rotary actuator containing high-power electronics generating an 800W heat load, an aluminium radial heat sink is employed to manage heat dissipation. Operating within an elevated-temperature environment, the heat sink faces incoming hot air at 120°C through an axial inlet with a flow rate of 0.14 kg/s. Once the heat is effectively dissipated from the heat sink, the heated coolant air exits the system via a radial outlet, as depicted in Figure 1.

For the parametric study, the variation of fin height (f_h), thickness (f_t) and spacing (f_s) is investigated while adhering to the manufacturing constraints of f_h to f_t ratio < 5.

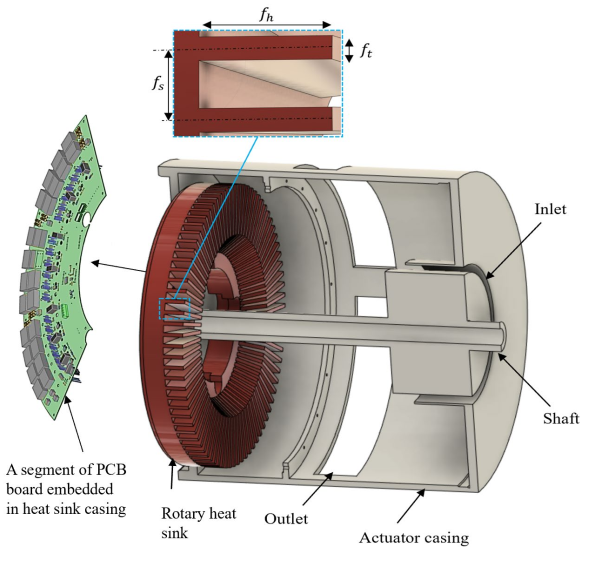


Fig. 1. Physical model of the rotary actuator (sectional view of the actuator casing).

B. Computational Model

The computational domain consists of a segment of the physical domain, containing a single fin of the heat sink. Figure 2 depicts the implemented boundary conditions (BC) within this computational domain.

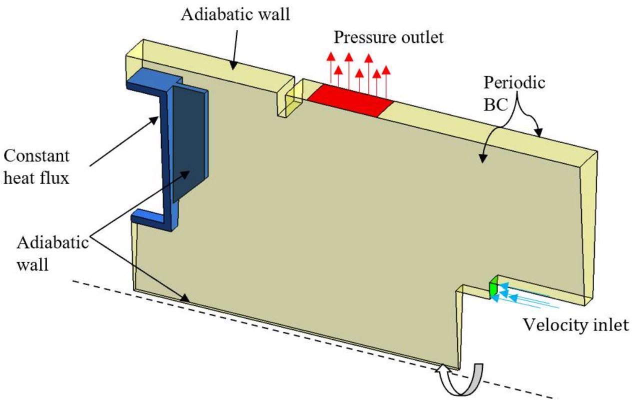


Fig. 2. Schematic of the computational model.

The conjugate heat transfer problem is numerically solved using the finite-volume based CFD code, Ansys Fluent, incorporating the k-ω SST turbulence model to accurately capture the flow and heat transfer behaviour [8]. The computational model's validity is established by comparing the computed local heat transfer coefficient results with experimental data of Ref. [9], with a maximum deviation of 6.92%, indicating satisfactory agreement within an acceptable range [9].

III. RESULTS AND DISCUSSION

The thermal performance of the heat sink is analysed through mass-specific heat transfer coefficient ($h_m = Q/(m_s\left(T_b - T_f\right))$) [10]. Herein, the symbols T_b, T_f, Q, and m_s represent the heat sink's base temperature, the incoming air temperature at the inlet, the heat load, and the heat sink's mass, respectively.

Figure 3 illustrates the variation of h_m for heat sinks with variable fin configurations under stationary and rotational conditions (denoted with S and R). Results demonstrate that irrespective of the fin configurations, the heat sink featuring rotary fins consistently demonstrate markedly enhanced h_m in comparison to the heat sink with stationary fins. It is due to the effects of centrifugal forces, which lead to thinner boundary layers and elevated heat transfer coefficients when contrasted with stationary flow setups [5], [6].

Considering the impact of fin dimensions on h_m, the findings reveal that increasing the f_h and reducing f_t leads to an improvement in h_m. A larger gap between fins proves advantageous when the heat sink rotates, augmenting the heat dissipation capability. In contrast, a contrary trend becomes apparent when the heat sink is held stationary. This is also evident from Fig. 4 which shows distribution of temperature across the heat sink fin surfaces under static and rotating conditions for two different fin spacing dimensions. This observation underscores the complexity of heat transfer dynamics, indicating that achieving a larger effective surface area does not necessarily guarantee enhanced heat transfer performance. The intricate interplay between heat sink surface area and flow distribution must be considered.

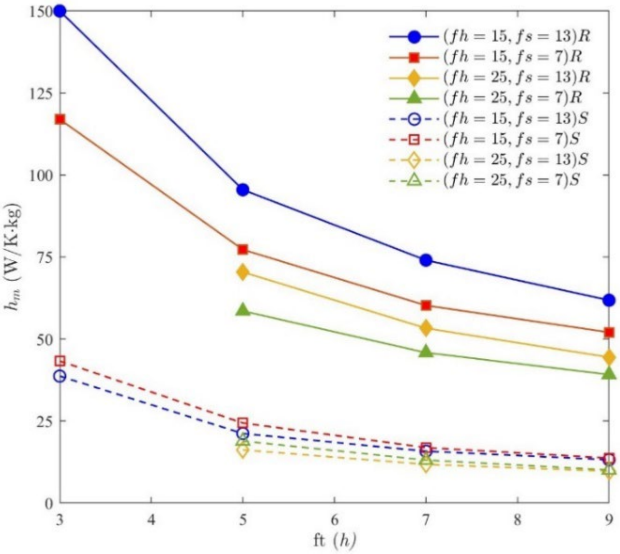
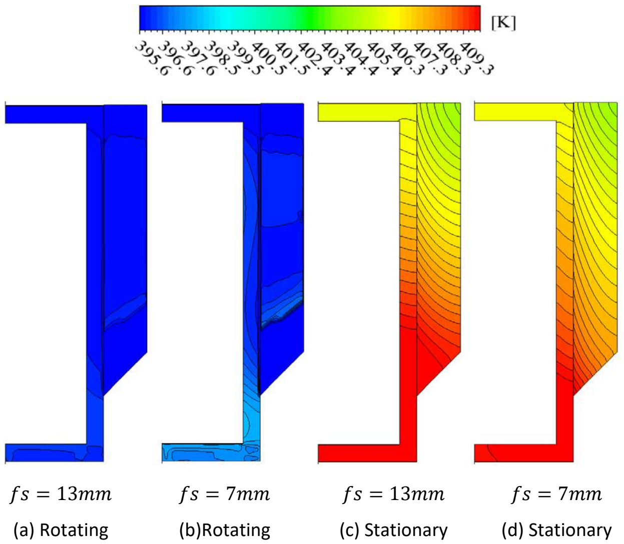


Fig. 3. Effect of fin parameters (f_t, f_h, and f_s) variation on the h_m of the heat sink for rotating (R) and stationary (S) conditions (all fin dimensions are in mm).



$fs = 13mm$ (a) Rotating

$fs = 7mm$ (b)Rotating

$fs = 13mm$ (c) Stationary

$fs = 7mm$ (d) Stationary

Fig. 4. Thermal contour distributions across the heat sink fin surfaces under static and rotating conditions for $fs = 7mm$ and $fs = 13mm$.

IV. CONCLUSION

This study has explored the mass-specific thermal performance of a rotary heat sink designed for power electronics within a high-temperature rotary actuator system. Study findings conclude that enhancing fin height and reducing fin thickness improves heat sink performance. The larger gaps between fins prove advantageous during heat sink rotation. This indicates that achieving a larger effective surface area does not necessarily guarantee enhanced heat transfer performance. The intricate interplay between heat sink surface area and flow distribution must be considered.

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