# Lightweight Hybrid Additively Manufactured Liquid Cooler for 10 kV SiC MOSFET Power Module

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## Abstract:

Medium-voltage silicon carbide (SiC) power modules are central to high-power-density converters for electrified transportation, aerospace propulsion, renewable energy systems, medium-voltage motor drives, and solid-state transformer in data centers. However, the elevated heat fluxes generated by medium-voltage SiC devices impose stringent thermal management requirements while system-level mass constraints increasingly motivate lightweight cooling solutions. Prior work demonstrated a multi-tier liquid cooling architecture for a 10 kV SiC MOSFET power module featuring stacked substrates and an additively manufactured metallic cooler. Building upon this platform, this work investigates a lightweight hybrid liquid cooler that replaces the aluminum manifold with a 3D-printed nylon manifold while retaining the AlSi10Mg heat transfer core. The hybrid cooler is experimentally evaluated against the original fully metallic cooler using pressure drop measurements, thermal resistance characterization, and infrared thermography. Results show that replacing the aluminum manifold with nylon reduces the cooler mass by 51% while maintaining similar hydraulic performance across the tested flow range. The thermal resistance increases moderately due to the reduced thermal conductivity of the polymer structure and reduced parasitic thermal spreading through the manifold. The results demonstrate the feasibility of hybrid polymer-metal cooling architectures for medium-voltage power electronics applications where gravimetric thermal performance is a critical design consideration, including electrified aircraft propulsion systems and mobile power converters.

**Keywords:** Liquid cooling, SiC MOSFET, additive manufacturing, hybrid cooler, lightweight thermal management, medium-voltage power electronics

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## 1. INTRODUCTION

Wide-bandgap semiconductor devices, such as silicon carbide (SiC) MOSFETs, are critical to medium-voltage power electronics systems with substantially improved switching performance, higher operating temperatures, and increased power density compared with conventional silicon-based technologies. Medium-voltage SiC devices operating at blocking voltages of 10 kV and beyond have emerged as key enabling technologies for megawatt-class electrified aircraft propulsion systems due to their ability to reduce switching losses, improve converter efficiency, and simplify power conversion architectures [1].

Nevertheless, the higher power densities associated with SiC devices impose increasing thermal management requirements. Elevated junction temperatures can degrade reliability, accelerate thermo-mechanical fatigue, and limit converter performance. Advanced liquid cooling technologies are required to dissipate large heat fluxes while maintaining acceptable temperature rise and thermal resistance under transient loads [2]. A variety of cooling mechanisms have been developed and demonstrated, including jet-impingement [3,4], micro-pin-fin cooling [5], and two-phase immersion [6], among others. Previous work by the present authors investigated a multi-tier cooling architecture for a 10 kV SiC MOSFET power module featuring stacked substrates and patterned middle-layer copper structures for enhanced partial discharge performance [5]. The study demonstrated that the multi-tier cooler achieved substantially lower thermal resistance and pressure drop compared with a conventional cold plate while maintaining compatibility with the insulation requirements of medium-voltage operation.

For aerospace application, specific power targets for electrified aircraft propulsion systems increasingly demand lightweight thermal management systems capable of minimizing mass while maintaining adequate cooling performance. Hybrid polymer-metal cooling structures provide a promising pathway toward lightweight thermal management by combining the high thermal conductivity of metallic heat transfer cores with the low density, electrical insulation capability, and electromagnetic interference (EMI) suppression of polymer/non-metal manifolds [7]. Kailkhura et al. developed an additively manufactured metal-polymer composite heat exchanger employing embedded copper conduction pathways within lightweight ABS structures for electronics liquid cooling applications [8]. Lad et al. developed additively manufactured polymer-metal coolers for discrete SiC MOSFET packages using a Nylon 12 (PA12) manifold manufactured using selective laser sintering (SLS) integrated with metallic (copper, aluminum) finned heat sinks [9]. However, existing studies have largely focused on low- to medium-voltage or generalized electronics cooling platforms. Limited work has explored lightweight hybrid cooling architectures for medium voltage SiC power modules operating at voltage levels approaching 10 kV, where thermal management challenges are compounded by stacked substrate structures, enhanced insulation requirements, and partial discharge considerations.

The present work extends the previously developed multi-tier cooling platform for a 10 kV SiC MOSFET power module by introducing a lightweight hybrid nylon-AlSi10Mg cooling architecture. The primary contribution of this study is the experimental evaluation of the thermal-hydraulic and gravimetric tradeoffs associated with replacing the aluminum manifold structure with a lightweight 3D-printed nylon manifold. The work specifically investigates: (1) the design and fabrication of a hybrid polymer-metal multi-tier cooler, (2) experimental comparison against a fully metallic baseline cooler, (3) thermal resistance and pressure drop characterization, and (4) gravimetric thermal performance implications for weight-sensitive power electronics applications.

## 2. METHODOLOGY

**Fig. 1a** shows the baseline cooling architecture, which was previously developed for a customized 10 kV SiC MOSFET phase-leg power module employing patterned middle-layer stacked substrates for enhanced partial discharge performance [5]. The original cooler utilized a fully metallic architecture consisting of an additively manufactured (DMLS) $AlSi_{10}Mg$ heat transfer core integrated with a CNC-milled aluminum 6061-T6 manifold and fluid chamber. Direct liquid-to-baseplate cooling was implemented to eliminate thermal interface material between the cooler and the power module baseplate, thereby minimizing thermal contact resistance and improving overall heat extraction capability. The multi-tier cooler incorporated a fin-channel heat transfer structure fabricated using additive manufacturing techniques. The internal cooling geometry was designed to promote enhanced convective heat transfer while maintaining relatively low pressure drop. Multiple fluid inlet paths were implemented to improve coolant distribution and temperature uniformity across the baseplate region.

Building upon the previously developed metallic cooling platform, a lightweight hybrid cooling architecture was developed by replacing the aluminum manifold structure with a 3D-printed nylon manifold while preserving the AlSi10Mg heat transfer core. The hybrid configuration is illustrated in **Fig. 1b**. The 3D-printed (DMLS) $AlSi_{10}Mg$ heat sink serves as the primary heat transfer structure and contains the fin-channel cooling geometry directly interfacing with the power module baseplate. The 3D-printed (SLS) nylon manifold functions primarily as a hydraulic distribution structure and external housing component. Carbon-filled PA12 was selected as the manifold material due to its low density, additive manufacturability, and higher thermal conductivity than regular PA12. The reduced density of nylon substantially lowers overall system mass compared with fully metallic architectures. In addition, polymer manifolds may provide benefits for electrically isolated cooling systems in medium-voltage applications. The hybrid architecture was designed to preserve the hydraulic geometry of the original cooler as closely as possible in order to isolate the influence of material substitution on thermal and hydraulic performance. As such, changes in pressure drop are expected to primarily arise from manufacturing tolerances or surface finish variations rather than major geometric differences.

The thermal-hydraulic performance of the hybrid cooler was experimentally evaluated using an in-house liquid cooling test loop [10]. The experimental setup included a chiller for coolant temperature control, a flow control system, differential pressure measurements, thermocouple instrumentation, and infrared thermography for junction temperature visualization. The test vehicle consisted of a customized 10 kV SiC MOSFET power module mounted directly onto the cooler assembly. Infrared thermography was performed using a FLIR infrared camera to monitor temperature distribution on the power module surface during operation. The IR camera was calibrated prior to testing, and measurements were conducted under controlled lighting conditions to minimize reflection artifacts. Coolant flow rate was measured using an inline turbine flow meter, while pressure drop across the cooler was monitored using a differential pressure transducer. Flow rates spanning the operating range of the cooler were investigated to evaluate thermal resistance and hydraulic characteristics under varying convective conditions

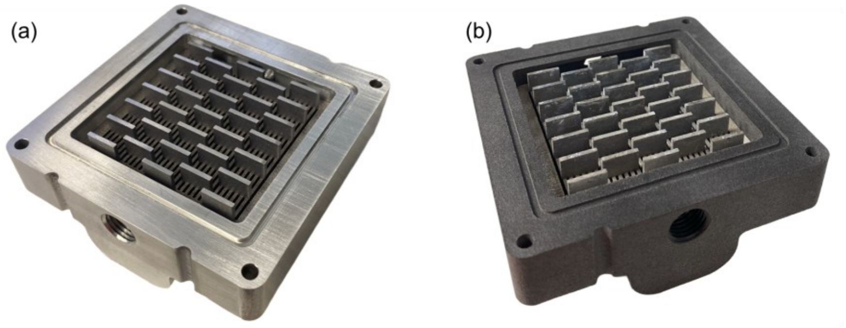

**Fig. 1.** Photographs of (a) the aluminum-$AlSi_{10}Mg$ cooler and (b) the nylon-$AlSi_{10}Mg$ hybrid cooler following the same design.

## 3. RESULTS & DISCUSSION

One of the primary motivations for the hybrid cooler design is the reduction of thermal management system mass. The mass of the $AlSi_{10}Mg$ heat sink core is measured to be 95.8 g. The aluminum chamber and the nylon chamber are measured to be 402.8 g and 150.7 g, respectively. Thus, replacing the aluminum manifold with a nylon manifold reduced the overall cooler mass by approximately 51% relative to the fully metallic baseline configuration. This substantial reduction in mass is particularly relevant for electrified aircraft propulsion systems and mobile power electronics platforms, where thermal management systems contribute significantly to overall converter weight.

Next, we examine the influence of the nylon manifold on the thermal hydraulic performance of the cooler. **Figure 2** compares the pressure drop characteristics of the fully metallic cooler and the hybrid nylon-AlSi10Mg cooler as a function of flow rate. The results indicate that replacing the aluminum manifold with nylon produces minimal change in hydraulic performance across the investigated flow range. The similarity in pressure drop behavior can be attributed to the preservation of the internal flow geometry and hydraulic pathway. Since the dominant flow resistance originates from the fin-channel heat transfer structure rather than the external manifold material itself, the hydraulic losses remain largely unchanged despite the material substitution. This observation suggests that lightweight polymer manifolds may be implemented without substantially compromising pumping power requirements, provided that the hydraulic geometry is preserved.

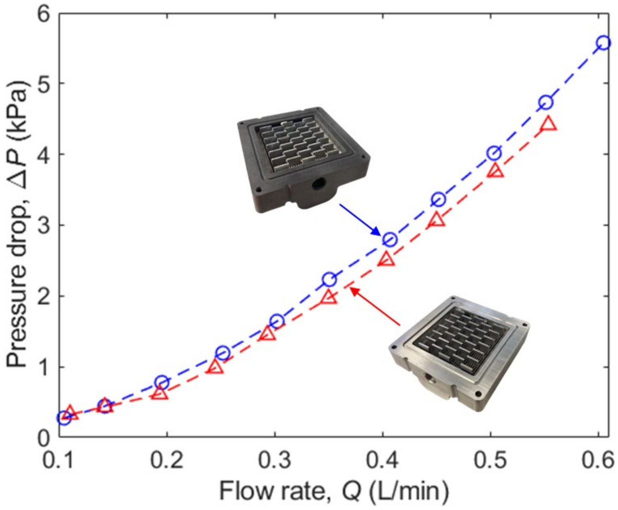

**Fig. 2.** Comparison between the aluminum-$AlSi_{10}Mg$ multi-tier cooler and the nylon-$AlSi_{10}Mg$ hybrid cooler for pressure drop versus flow rate.

**Figure 3** compares the thermal resistance of the fully metallic cooler and the hybrid cooler over a range of coolant flow rates. As expected, thermal resistance decreases with increasing flow rate due to enhanced convective heat transfer and reduced coolant-side thermal resistance. The hybrid cooler exhibits moderately higher thermal resistance compared with the fully metallic architecture. Several physical mechanisms are likely to contribute to this increase. First, the lower thermal conductivity of nylon reduces parasitic heat spreading through the manifold structure. Second, the polymer manifold alters conjugate heat transfer pathways within the cooler assembly. Third, differences in thermal contact behavior and structural compliance between the polymer and metallic components may contribute additional thermal resistance. Overall, the nylon- $AlSi_{10}Mg$ hybrid cooler exhibits a 23% - 34% higher thermal resistance compared to the full metallic cooler in the flow rate range of 0.1 – 0.6 L/min. Despite the thermal penalty, the hybrid cooler maintains acceptable thermal performance while significantly reducing system mass.

**Figure 4** presents infrared thermographs of the 10 kV SiC MOSFET power module cooled using the fully metallic cooler and the hybrid nylon-metal cooler at a flow rate of 0.55 L/min. The thermographs reveal the temperature distribution and hotspot characteristics of the power module during operation. The hybrid cooler exhibits elevated temperatures and less uniform thermal spreading relative to the fully metallic configuration. These observations are consistent with the measured increase in thermal resistance and reduced conductive spreading associated with the lower thermal conductivity polymer manifold. Nevertheless, the hybrid cooler maintains effective heat removal capability and prevents excessive hotspot formation within the investigated operating range.

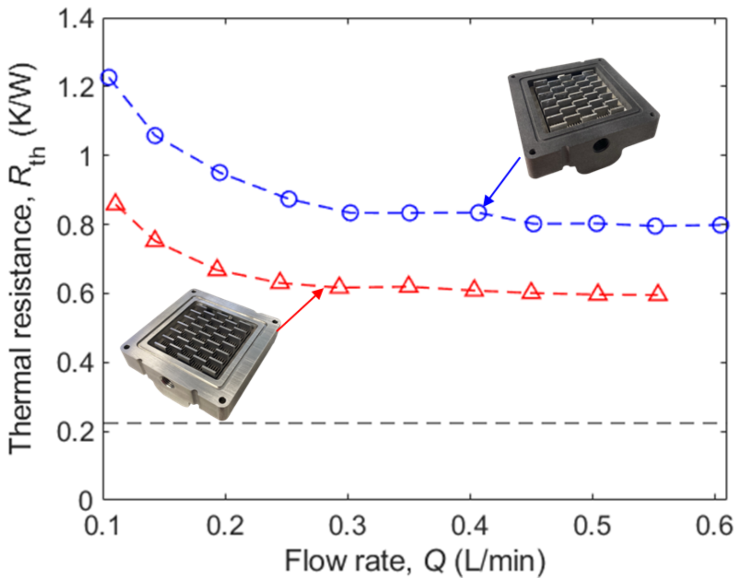

**Fig. 3.** Comparison between the aluminum-AlSi$_{10}$Mg multi-tier cooler and the nylon-AlSi$_{10}$Mg hybrid cooler for thermal resistance versus flow rate.

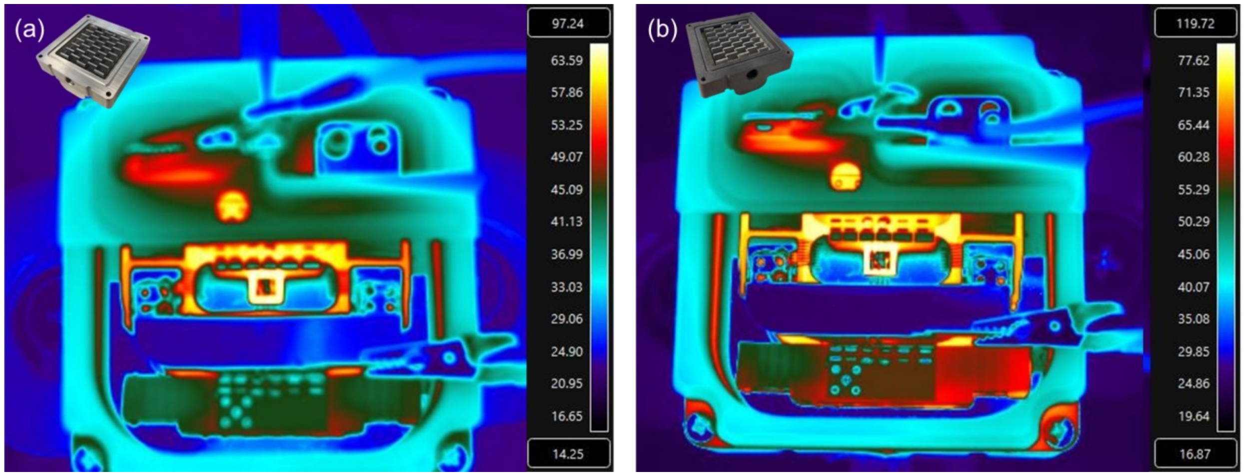

**Fig. 4.** Thermographs of the 10 kV SiC MOSFET power module cooled using (a) the aluminum-AlSi$_{10}$Mg multi-tier cooler and (b) the nylon-AlSi$_{10}$Mg hybrid multi-tier cooler at a flow rate of 550 mL/min.

## 4 CONCLUSION

This work investigated a lightweight hybrid nylon-AlSi10Mg multi-tier liquid cooler for a 10 kV SiC MOSFET power module. Building upon a previously developed additively manufactured metallic cooling platform, the present study evaluated the thermal-hydraulic and gravimetric implications of replacing the aluminum manifold with a lightweight 3D-printed nylon manifold. Experimental results demonstrated that the hybrid architecture reduced cooler mass by approximately 51% while maintaining similar pressure drop characteristics relative to the fully metallic baseline cooler. The thermal resistance increased moderately due to the reduced thermal conductivity of the polymer structure and altered thermal spreading pathways. Infrared thermography confirmed effective heat removal capability despite the thermal performance penalty. The results demonstrate the feasibility of hybrid polymer-metal cooling architectures for medium-voltage power electronics applications where lightweight thermal management is an important design consideration. The study highlights the potential of combining additive manufacturing with hybrid material architectures to achieve improved gravimetric thermal performance for electrified transportation and aerospace applications. Future work will investigate topology-optimized lightweight cooling structures, reinforced polymer materials, dielectric coolant compatibility, and integrated thermo-mechanical optimization for next-generation medium-voltage power electronics systems.

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### Data Availability

The cooler design files and the thermal testing data are publicly available through Dyrad under a CC0 public domain dedication at https://doi.org/10.5061/dryad.2rbnzs84t.

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