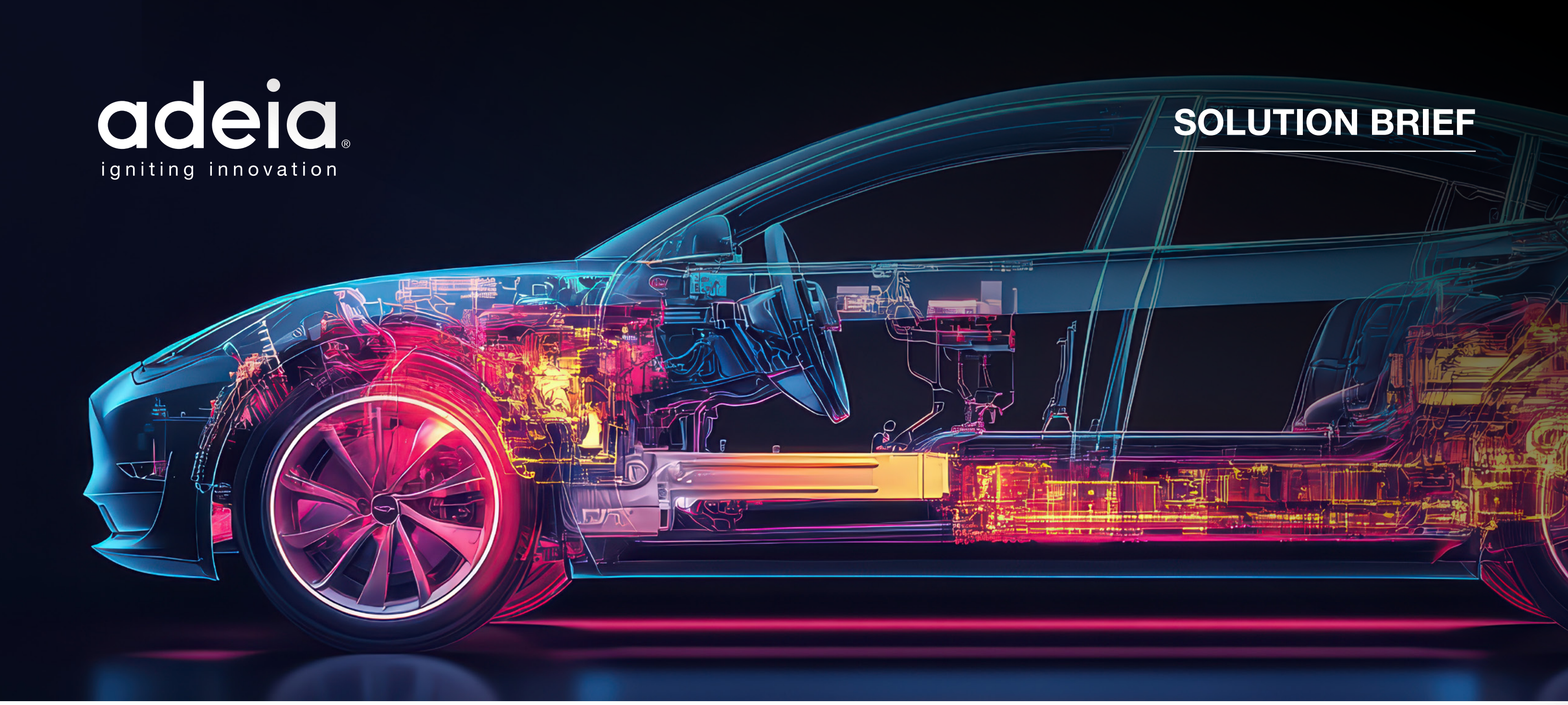


Automotive Thermal Cooling

For decades, automotive thermal management focused primarily on engines, passenger comfort systems, and a relatively limited number of electronic components.

That model is changing rapidly.

Electrification, advanced driver-assistance systems, autonomous-driving technologies, and increasingly powerful onboard computing platforms are introducing unprecedented thermal demands throughout the vehicle. Batteries, traction inverters, charging systems, lidar sensors, cameras, and AI processors all generate heat that must be managed within increasingly compact spaces. At the same time, automakers are adopting higher-voltage architectures and wide-bandgap semiconductors to improve efficiency, reduce charging times, and increase vehicle performance. These technologies deliver significant benefits but also create new thermal-management challenges that conventional cooling approaches were not designed to address. The result is that thermal management is evolving from a supporting engineering discipline into a foundational technology that affects vehicle performance, reliability, safety, charging speed, and range. Adeia is developing advanced thermal-management technologies designed to address these emerging challenges across batteries, power electronics, sensors, and computing platforms.

Thermal Demands Are Increasing Faster Than Cooling Capabilities

The challenge facing automotive thermal-management engineers is not simply that electronic systems are generating more heat. Equally important is where that heat is being generated and how concentrated it has become. Historically, many vehicle systems operated at relatively modest heat fluxes that could be managed using remote cooling approaches such as air cooling or liquid cold plates. Today's emerging technologies are fundamentally different. Advanced processors, AI accelerators, wide-bandgap power electronics, and next-generation sensing systems increasingly generate heat within highly localized regions, creating thermal hotspots that can exceed the capabilities of traditional cooling architectures.

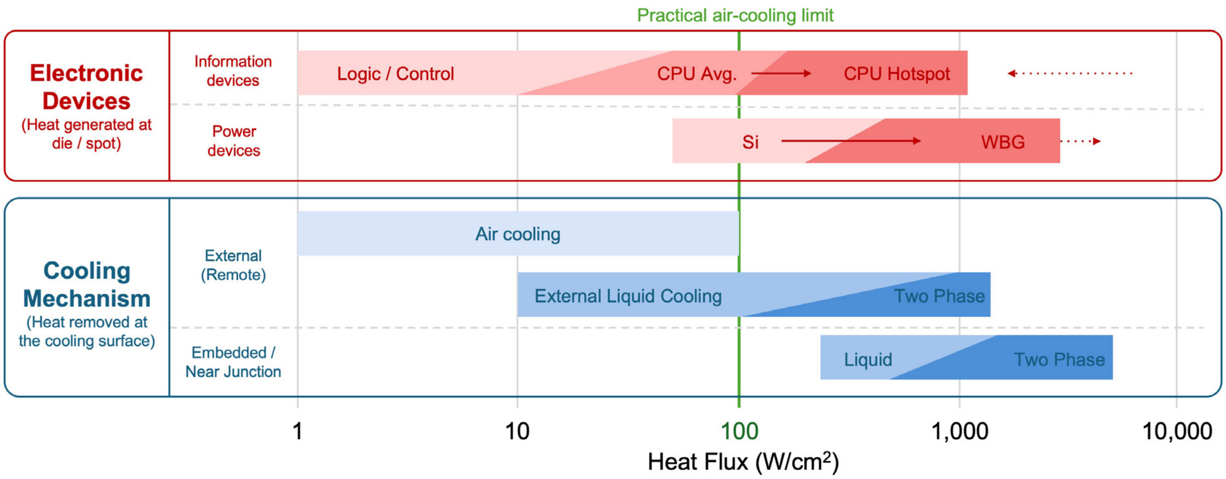


Figure 1. *Increasing heat fluxes are driving a transition in thermal-management technologies. As electronic systems continue to increase in power density, conventional air-cooling approaches become increasingly difficult to implement, while liquid cooling must move closer to the source of heat generation. Future automotive electronics may require embedded cooling architectures and phase-change heat-transfer mechanisms capable of managing localized thermal hotspots within compact packages.*

Figure 1 illustrates this trend. As electronic devices evolve toward higher power densities, heat generation continues to move toward increasingly demanding operating regimes. Conventional air-cooling approaches become impractical beyond certain heat-flux levels, while traditional liquid-cooling solutions often struggle to efficiently remove heat from highly concentrated hotspots located deep within compact packages. At the same time, cooling systems are being pushed closer to the source of heat generation. Rather than removing heat remotely from an external surface, future thermal-management solutions may increasingly rely on embedded cooling architectures that operate near the semiconductor junction, motor winding, or other critical heat-generating regions. These approaches reduce thermal resistance between the heat source and coolant, enabling substantially higher heat-removal capability within the same package volume.

Addressing these challenges will likely require more than incremental improvements to conventional cooling hardware. Future thermal-management systems must remove heat more efficiently, operate closer to the source of heat generation, and adapt to changing operating conditions across a wide range of vehicle subsystems.

Adeia is developing several technologies designed to support these next-generation requirements. These include architected thermal structures that enable new cooling geometries, embedded evaporative cooling approaches that bring heat removal closer to critical components, and adaptive thermal-management concepts that actively respond to changing thermal loads.

Architected Thermal Structures Enable New Cooling Approaches

Many advanced thermal architectures have been proposed over the years, but their practical implementation has often been limited by manufacturing complexity. Geometries that offer exceptional heat-transfer performance frequently contain intricate three-dimensional features that are difficult to fabricate using conventional manufacturing methods, particularly at the microscale dimensions required for high-performance cooling applications.

Adeia has developed fabrication technologies that enable the production of complex microscale thermal structures based on triply periodic minimal surface (TPMS) geometries. These structures consist of continuous three-dimensional networks that can be engineered to create large surface areas, interconnected transport pathways, and precisely controlled thermal architectures within compact volumes.

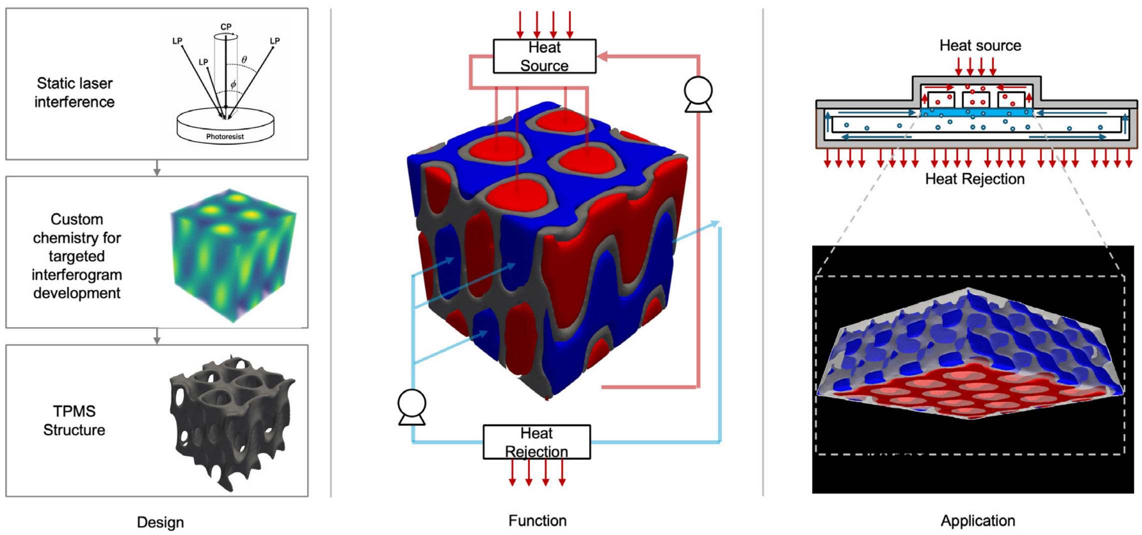


__Figure 2.__ Adeia has developed fabrication technologies that enable complex microscale thermal structures based on triply periodic minimal surface (TPMS) geometries. These architected structures create multiple continuous domains within a compact volume, enabling advanced heat-exchanger and vapor-chamber architectures that would be difficult to manufacture using conventional approaches. By expanding the range of manufacturable thermal geometries, these technologies provide new opportunities for integrated cooling solutions in high-power automotive electronics and electrified vehicle systems.

Figure 2 illustrates how these fabricated TPMS structures can be adapted for multiple thermal-management applications. The geometry naturally partitions space into separate but continuous domains, enabling the creation of compact heat exchangers in which hot and cold fluids remain isolated while exchanging heat across a large interfacial area. Similar architectures can also support advanced two-phase cooling concepts, including vapor chambers and evaporative cooling systems.

By enabling the fabrication of thermal structures that would be difficult or impossible to produce using conventional approaches, Adeia's technology expands the design space available to thermal engineers. For example, advanced vapor-chamber architectures fabricated using these techniques could help mitigate dryout limitations at high heat fluxes, extending the operating range of air-cooled systems before more intrusive liquid-cooling architectures become necessary.

Capillary-Driven Cooling for High-Power Electric Machines

As electric-vehicle powertrains continue to evolve, thermal management is becoming an increasingly important factor in motor performance, efficiency, and power density. Many emerging motor architectures concentrate heat generation within densely packed winding regions where delivering coolant uniformly can be difficult. In these systems, thermal performance is often limited not by the ability of the coolant to absorb heat, but by the ability to distribute coolant effectively throughout the motor.

Adeia is developing cooling architectures that leverage capillary forces and phase-change heat transfer to improve coolant distribution within electric machines. Rather than relying exclusively on externally driven flow, these concepts use engineered cooling structures to generate localized capillary pumping forces that help transport liquid coolant directly toward high-heat-flux regions.

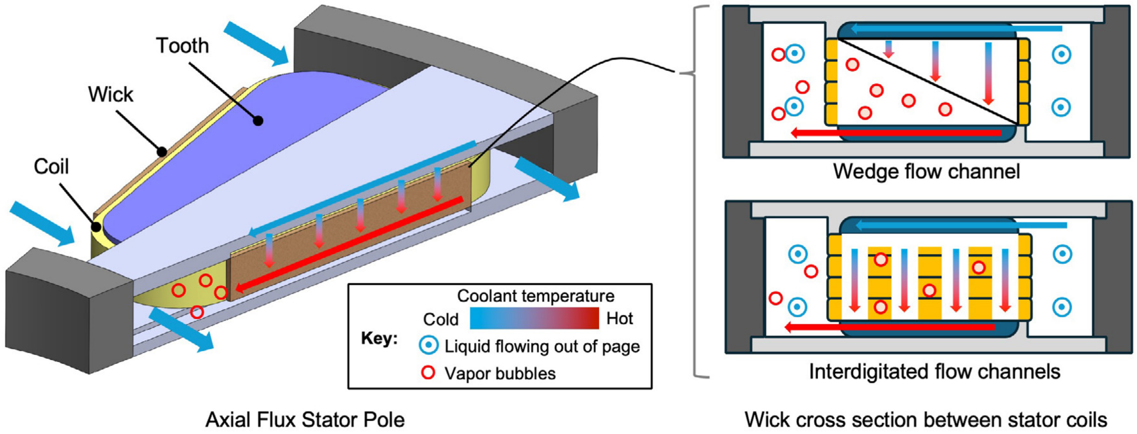


Figure 3. *Capillary-driven evaporative cooling concept for high-power electric machines. Embedded cooling structures distribute liquid coolant throughout the motor while capillary forces continuously replenish evaporating regions located near heat-generating windings. This approach has the potential to improve coolant distribution, enhance temperature uniformity, and increase heat-removal capability within compact motor architectures.*

As illustrated in Figure 3, coolant is distributed through embedded cooling pathways located adjacent to motor windings. As heat is absorbed, the liquid undergoes a phase transition, removing thermal energy through evaporation. Capillary forces generated within the cooling structure continuously replenish liquid to the evaporating regions, helping maintain cooling performance even in locations that can be difficult to reach using conventional flow-distribution approaches.

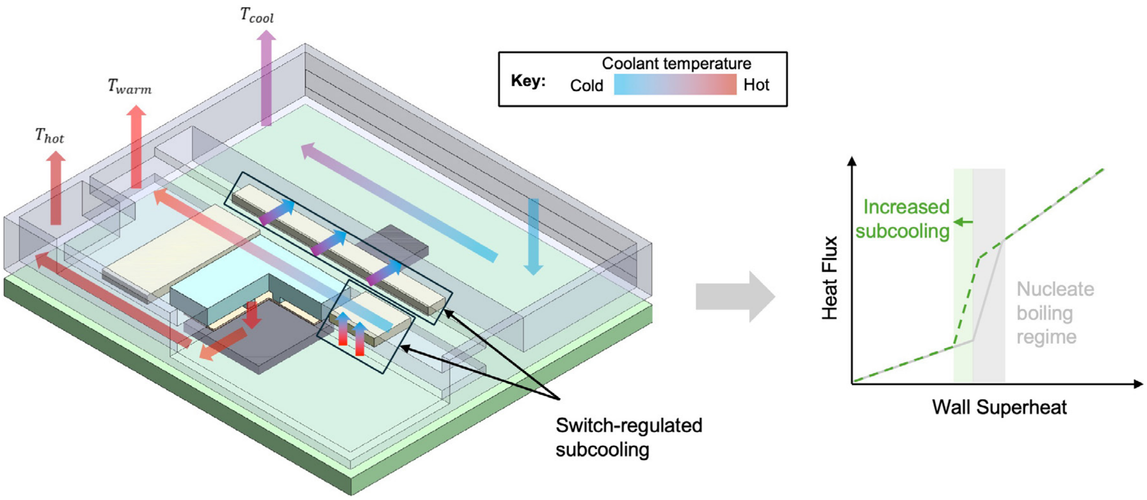
This combination of capillary-driven transport and evaporative cooling has the potential to improve temperature uniformity throughout the motor while supporting higher heat-removal capability within a compact package. More broadly, the concept demonstrates how future thermal-management systems may increasingly leverage passive physical mechanisms to improve coolant delivery and thermal performance without adding significant system complexity. Such approaches may support higher continuous-power operation and improved power density without significantly increasing motor size, coolant flow requirements, or pumping power.

Adaptive Thermal Control Through Thermal Switching

As vehicle electronics become increasingly integrated, thermal-management systems must often satisfy the needs of components with very different operating requirements. Power electronics, processors, sensors, memory devices, and communication hardware may all share the same package or cooling infrastructure, yet each can exhibit different thermal sensitivities and optimal operating temperatures.

For many advanced electronic devices, maintaining a stable and uniform temperature can be just as important as maximizing heat-removal capability. Temperature fluctuations can affect performance, reliability, and operational consistency, particularly in systems that rely on precise electronic or sensing functions. In two-phase cooling systems, operation within the nucleate boiling regime is often desirable because it provides highly effective heat transfer while maintaining relatively uniform surface temperatures.

At the same time, trends in electronic packaging are placing increasingly diverse components in close proximity. While this integration creates new thermal-management challenges, it also creates opportunities to design cooling systems with spatially varying thermal characteristics. Different regions of a cooling structure may be optimized to support different heat loads, operating temperatures, or thermal-response requirements.



Heterogeneous electronics cooler

Expanded nucleate boiling regime

Figure 4. *Future thermal-management systems may require not only efficient heat removal but also precise control of temperature across increasingly integrated electronic packages. The illustrated concept uses thermal switches to regulate interactions between adjacent cooling regions, enabling local control of subcooling and phase-change behavior. Such approaches could help maintain temperature-sensitive components within narrow operating ranges while simultaneously supporting high-performance cooling elsewhere in the system.*

Adeia is developing thermal-management architectures that leverage these spatial variations through the use of integrated thermal switches. As illustrated in Figure 4, thermal switches positioned between adjacent cooling regions can dynamically regulate coolant conditions, including local subcooling levels and phase-change behavior. By controlling the interaction between neighboring thermal zones, these structures may help maintain more stable operating temperatures across sensitive devices while preserving high heat-transfer performance where it is needed most.

Rather than treating a cooling system as a uniform thermal resource, this approach enables cooling performance to be tailored locally within the package. Such capabilities may become increasingly important as future vehicle electronics continue to integrate diverse functions within compact, high-power assemblies.

Conclusion

The future of automotive thermal management will likely require more than larger heat sinks and more powerful pumps. As vehicle systems become increasingly electrified, software-defined, and power dense, cooling technologies must evolve alongside them.

The examples presented here demonstrate a subset of Adeia's ongoing work in thermal management. Although these technologies address different challenges, they share a common objective: bringing thermal management closer to the point of heat generation while enabling greater control over how heat is transported, distributed, and regulated within increasingly complex systems. Together, they highlight opportunities to improve heat transfer, coolant distribution, and thermal control across increasingly demanding automotive applications.

As vehicle systems continue to increase in complexity and power density, thermal management will become an increasingly important enabler of performance, reliability, efficiency, and functionality. Adeia continues to develop a range of technologies designed to address these challenges, spanning advanced materials, thermal architectures, phase-change cooling, and adaptive thermal-control systems.

adeia®
igniting innovation