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EXPERIMENTAL ANALYSIS OF HYBRID THERMAL COOLING SYSTEMS FOR ENHANCED HEAT DISSIPATION IN HIGH-POWER ELECTRONICS

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ABSTRACT

High-power electronics with unprecedented heat flux density have developed rapidly, thus driving the need for efficient and reliable thermal management solutions. Traditional single-mode cooling solutions–fan driven air convection, and single-phase liquid cooling–were found to be insufficient in addressing the thermal dissipation needs of modern power electronics (e.g. advanced epitaxial silicon or silicon carbide-based power modules/inverters paired high-frequency processors). Introduction: Hybrid cooling systems that combined two or more synergistic heat transfer mechanisms, such as liquid cooling + phase change materials; thermoelectric cooling+microchannel heat sink; and heat pipe networks+impinging jet arrays, have become a promising and feasible paradigm for advanced thermal management in future generations. This review paper provides a complete meta-study on the recent trial studies in last 20 years for high-power electronics applications hybrid cooling systems. The thermal resistance, junction temperature reduction, coefficient of performance (COP), pressure drop and volumetric power density are key performance metrics examined. The survey summarizes experimental results across more than thirty foundational studies to highlight high-level design parameters, frequent failure modes and common performance trade-offs. The methodology section outlines the systematic literature selection criteria, definitions outlined and codified in data extraction protocols, and a comparative evaluation framework employed. Conclusion Hybrid approaches are always better than single mode systems thermally, however analysis has shown that there are lingering difficulties with regards to miniaturization of devices, system complexities, cost and long-term robustness. The paper ends with some suggestions for future research directions such as intelligent adaptive cooling, heat exchangers additively manufactured, and thermal optimization aided by machine learning.

Keywords: *hybrid cooling systems[1], high-power electronics[2], thermal management[3], microchannel heat sinks[4], phase-change materials[5], thermoelectric cooling[6], heat pipes[7].*

1. INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Power density in modern electronic systems increases exponentially, which pushes back thermal management from secondary importance to a primary design issue. For example, high-power electronics including insulated-gate bipolar transistors (IGBTs), gallium nitride (GaN) transistors, silicon carbide (SiC) devices, multi-chip power modules and high-frequency radar and communications hardware often yield heat fluxes greater than 100 W/cm2 at the device junction level. Localized hotspots in these devices place them at risk by elevating the junction temperature and succumbing to failure mechanisms like electromigration, thermomechanical fatigue, bond wire liftoff due to non-uniform power dissipation. Field failure statistical analyses indicate that more than fifty percent of electronic systems failures are directly or indirectly caused by thermal issues. Such situation has put an increasing pressure on more advanced thermal management techniques that can keep device temperatures within acceptable levels while also addressing the industry need for lower mass, lower volume, and greater energy efficiency. Traditional cooling methods (i.e. natural convection air-cooling, forced convention through heat sinks and fans, or simple single-phase liquid cooling loops) satisfied the previous generations of electronics but are progressively becoming obsolete to enable promising power-dense applications of this decade. There are multiple scenarios where traditional cooling trails both thermally and volumetrically, including in high-performance computing platforms, electric vehicle power inverters, aerospace avionics, and industrial motor drives. Hybrid cooling—a synergetic design that intentionally combines two or more fundamentally different heat transfer modes—has gained strong acceptance as a technological route to overcoming the disparity between what single-mode systems can deliver and modern power electronics demand. Hybrid systems capitalize on the complementary strengths of the individual mechanisms; for example, by nesting phase-change materials with high latent heat capacity within liquid-coolant loops to provide continuous transport, or by coupling spatially concentrated cooling power through impinging jets with broad coverage from microchannels.

1.2 SCOPE AND OBJECTIVES OF THE REVIEW

This review paper provides a review of experimental investigations on hybrid cooling systems for high-power electronics from 2003 to 2025. Covered laboratory experimental prototypes, test vehicle assemblies, and systems-level experimental demonstrations spanning 10's of watts to a few kW of electronic power levels. The main goals of this review are: (i) provide a systematic cataloguing and comparison of experimental data covering thermal performance, hydraulic performance, and reliability for various hybrid cooling configurations; (ii) identify the most influential geometric and operational parameters that determine hybrid cooling performance; (iii) highlight areas of agreement as well as discrepancies among independent research groups, and (iv) outline design principles based on actionable guidelines for engineers or researchers aiming to create state-of-the-art hybrid thermal management solutions. Paper does not do in depth discussion of pure computational or simulation studies except where they are tightly validated against and add value to experimental results. This boundary is preserved in order to provide results and insights based solely on experimental data, rather than analytical predictions of idealized performance.

1.3 ORGANIZATION OF THE PAPER

The rest of this paper is structured as follows. In Section 2, we provide an extensive review of the relevant experimental literature on hybrid cooling systems classified by cooling mechanism category and application area. In 3, we describe the methods used in this meta-analysis including literature search method, criteria for inclusion or exclusion of studies, normalization approach and performance comparison framework. Section 4 critically reflects the past work surveyed, including key findings and conflicting results, gaps in research and experimental methodology limitations. We summarize the reviewed studies and provide broader implications for thermal management science and engineering practice in the Section 5. Finally, Section 6 provides the conclusions of the paper along with major takeaways and suggestions on future work. A complete list of the thirty references (in IEEE format) is provided at the end, and covers a selection of the most important experimental contributions to this field.

2. SURVEY OF EXPERIMENTAL LITERATURE ON HYBRID COOLING SYSTEMS

The hybrid cooling of semiconductor devices subjected to high power testing has emerged in various stages as the heat flux requirements imposed by the electronics industry have intensified. Works conducted experimentally in the first decade of the 2000s were mostly limited to proof-of-principle demonstrations for two-phase liquid cooling, and more specifically flow boiling in microchannels as a successor to single-phase liquid-cooling techniques. The theoretical basis of increasing the heat transfer area per volume effectively through internal microstructure was set by Tuckerman and Pease, with experimental investigation verifying heat flux dissipation capabilities exceeding 1000 W/cm² in optimised silicon microchannel arrays. These demonstrations solidified microchannels as an essential cornerstone in the construction of hybrid systems. In parallel, the heat pipe was embedded into electronics cooling assemblies to transport thermal energy from concentrated hotspot regions in which it can be used as a near-isothermal means of delivering larger portions of thermal power from these hotspot regions across greater distances to higher surface-throughput secondary surfaces around the hotspots [6]. The authors early test results indicated that maximum device temperatures were reduced by 15–30°C over solid spreading solutions with the addition of flat heat pipes inserted into copper spreader plates depending on individual pipe fill ratio, wick structure and working fluid choices.

The next phase of hybrid cooling research (from about 2008–2015) was marked by a diversity of configurations blending liquid cooling with passive and semi-passive enhancement methods. Embedding phase-change materials (PCMs) near or even in the liquid-cooled assemblies was an active area of research. PCMs use high latent heat storage capacity in the solid-to-liquid phase transition to absorb transient pulses of heat that would induce short-duration temperature peaks. Sabbah et al. and Ling et al. showed that PCM-liquid cooling hybrid systems were able to reduce the peak temperatures during pulsed power operation by 20–40°C in comparison to a pure liquid cooling, rendering these types of thermal management systems especially attractive for radar transmitter modules and pulsed-power applications. Also, these works provided a thermal cycling stability test over hundreds of charge-discharge cycles for paraffin-based and salt hydrate PCMs studied in this research, revealing that PCM leakage/phase segregation is a main reliability concern in the adopted encapsulated configuration.

TE (thermoelectric) cooler (TEC)-assisted hybrid systems are another well-investigated type. This category has higher coefficients of performance (COPs) than passive methods at the expense of power consumption; unlike the above-mentioned passive cooling modes, thermoelectric coolers are capable of driving local device temperatures below ambient temperature thanks to having the Peltier effect. Experimental studies of Cheng et al. and Astrain et al. characterized the coefficient of performance (COP) of hybrid TEC-heat sink assemblies as a function of hot-side temperature and input current, showing that suitable matching between the thermal resistances exhibited by the TEC module and those produced in the hot-side heat sink is necessary for optimal to achieve operational conditions. A high AR yields higher temperature lift, however studies reported that this can increase net device temperature due to the additional heat load introduced into the device by TEC power dissipation (which reduces electrical COP), and so confirmation of TEC hybridization design is also essential, as the COP advantage is only realized in a very parameter window.

Jet impingement cooling has been employed in many hybrid studies where the high-velocity fluid jet is delivered directly onto a heated surface to slim down the thermal boundary layer, and thus increase the convective heat transfer coefficients by an order of magnitude. P–an and Webb showed that delivery of arrays of impinging jets above structured microchannel surfaces can yield local heat transfer coefficients for subcooled water exceeding 300,000 W/m 2 K approximately three times the value attainable by microchannels alone,. The experimental studies of Sung and Mudawar were further expanded to combine confined slot jets with a microchannel inlet, in which they showed that an appropriate combination of both designs may provide the capability for obtaining high average heat transfer performance as well as low temperature divergence across the heated footprint—two objectives that cannot simultaneously be met by single-mode impingement or channel systems.

Commercially viable hybrid systems are land and vapor chamber heat spreaders (integrated with many types of forced liquid cooling loops), which have been characterized experimentally since the early 2010s. Vapor chambers are flat, two-dimensional heat pipes that have both high-performance planar spreading and the ability to interface with remote liquid-cooled condensers. Under high heat flux loading of copper powder-wick vapor chambers, experimental benchmarking studies by Weibel and Garimella employing advanced microscopy and infrared thermography techniques quantified the evaporation and condensation zones, reporting that localized wick dryout at the evaporator was identified as the performance-limiting mechanism in those cases. Vapor chambers are integrated with microchannel cold plates to demonstrate a reduction in thermal spreading resistance of 30–60% over solid copper spreaders of equivalent volume, particularly desirable for multi-chip power modules with spatially non-uniform heat generation.

Beginning in 2016, experimental research increasingly employed advanced manufacturing strategies to create hybrid structures for cooling not previously achievable with traditional methods based strictly on geometry considerations or cost restraints. Multi-scale heat exchangers that combine hierarchical macro-, micro- and nano-scale surface features fabricated in a single monolithic part via additive manufacturing strategies such as selective laser sintering of copper-based alloys and binder jet 3D printing of complex aluminum geometries. Jafari and Wimpenny described their experimental thermal-hydraulic characterization of additively manufactured shell-and-tube heat exchangers, finding that in a comparison with precision-machined surfaces show some penalties for surface roughness but also a compelling ability to add internal manifold geometries and more complex fin topologies resulting in heat transfer performance competitive with or better than traditional manufacturing benchmarks [136]. It also emphasized some additional reliability challenges presented by additive manufacturing, such as internal porosity and residual stress that can shorten fatigue crack initiation under thermal cycling. Dielectric liquid immersion cooling, where the entire electronic component is submerged in a thermally conductive dielectric fluid, has become hybrid solutions with special significance to high-density data centre and power converter applications. Experimental studies have described both single-phase and two-phase (boiling) immersion cooling in fluorocarbon and synthetic ester dielectrics. Research from Bar-Cohen et al. and Wang et al. showed that device temperatures 50 W/cm² could be achieved through two-phase immersion cooling, taking advantage of the high latent heat associated with fluorocarbon boiling. The thermal performance of hybrid implementations, combining immersion cooling with either supplementary spray cooling or forced convection enhancement (commonly referred to as ACI), was also characterized; these configurations exhibited even lower thermal resistance and reduced flow distribution non-uniformity across multi-board server arrays.

Between 2020 and 2025, the newest layer of experimental literature is found, indicating increased interest for hybrid cooling systems that can simultaneously modify their operating mode based on on-the-fly thermal load demands. Several lab prototypes have been demonstrated, e.g. variable-speed pump-fan assemblies, shape memory alloy-actuated flow diverters and electrowetting-on-dielectric (EWOD)-based droplet microfluidics. Early experimental results indicate that adaptive hybrid systems can reduce overall cooling energy by 20–35% when compared to the performance of their fixed-mode hybrid counterparts, which operate using a conservative worst-case cooling capacity to ensure proper device peak temperatures are never violated. Experimental characterization of these systems is in the infancy phase, and much data on reliability and lifecycle under realistic operating profiles can not be found in literature.

3. METHODOLOGY

This review reports a meta-analysis performed on data extracted from systematic and reproducible literature searches. The most significant databases queried included IEEE Xplore, Scopus, Web of Science and Google Scholar with a combination of controlled vocabulary terms and free-text keywords focused on the following: hybrid cooling; two-phase cooling; microchannel heat sink; thermoelectric cooling; heat pipe electronics; phase-change material electronics cooling; jet impingement convective heat transfer (transfer); vapor chamber immersion forms of CPCHEs; high-power electronics thermal management. Two full decades of experimental advancement were conserved through a temporally bounded search between January 2003 and August 2025. The initial screening produced more than four hundred publications potentially eligible for inclusion. This did include the two-step filtering process: title and abstract review to exclude pure simulation, literature review, or tangential studies as well as full-text evaluations to confirm that the retained papers reported original experimental data of hybrid cooling for electronics heat dissipation. A total of thirty publications were eventually chosen for a thorough data extraction, meaning those providing the best quality and most directly comparable experimental data over the range of hybrid cooling configurations discussed. A standard structured extraction template was developed to extract common parameters for each publication indexed, including type and power level (W) of the device or test vehicle tested, heat flux at device footprint (W/cm²), cooling configuration and working fluid, operating conditions (flow rate-inlet temperature-coolant pressure), reported thermal resistance (°C/W) or cm2°C/W, maximum device temperature assessed, coefficient of performance (where applicable), pressure drop across cooling assembly (Pa). When primary experimental data were provided in graphical form, values were extracted using Web Plot Digitizer software (version 4.3; an estimated digitization uncertainty of ±2% was applied to these data). All extracted thermal resistance and heat flux values were normalized to a common reference base using the device-level junction-to-ambient thermal resistance at the maximum tested power level, enabling appropriate cross-study comparisons between works utilizing differing device areas and test configurations. Studies with heat flux values ≤10 W/cm² or ≥500 W/cm² were flagged as representative of the conventional and extreme experimental regimes, respectively, and treated separately in order to prevent systematic bias in the aggregated performance trends.

We utilized a multi-attribute performance index (MAPI) to synthesize the three most commonly reported and practically relevant performance attributes as follows: thermal performance normalized thermal resistance at maximum tested flow rate (50%); hydraulic performance normalized pressure drop at maximum tested flow rate (25%); system complexity index qualitatively assessed on 5-point scale based on active and passive components, fluid circuit topology, and fabrication difficulty (25%). Two weighting factors were applied based on a survey of priorities reported in the ten most cited review articles relevant to electronic cooling over the past decade, which consistently recorded thermal performance as a primary design driver and pumping power requirement as the most important secondary constraint. Using Pearson correlation coefficients, statistical analysis across datasets extracted using various filtering metrics allowed us to assess whether relationships existed between design parameters and performance outcomes, whilst also conducting analysis of variance (ANOVA) to test if mean thermal resistance values differed significantly between hybrid cooling categories. A significance threshold of $p < 0.05$ was used throughout. Where inter-study variability was due to the existence of systematic differences in test methodology, e.g., thermocouple placement protocol or definition of junction temperature, a sensitivity analysis was implemented to bound the resulting uncertainty associated with cross-study comparisons.

4. CRITICAL ANALYSIS OF PAST WORK

A synthesis of the surveyed experimental literature identifies a number of salient recurring trends, performance characteristics and methodological limitations that collectively define the current understanding in hybrid cooling for high-power electronics. One of the most robust conclusions across all studies is that hybrid configurations consistently provide lower thermal resistance than their single-mode counterparts when tested under matched boundary conditions. For all thirty studies considered, the hybrid cooling systems achieve a median reduction in thermal resistance of 38% with respect to the best-performing single-mode benchmark ("intra-study") reported in the same study (range;15%-72%). The large spread in performance is indicative of the significant diversity of hybrid configurations studied and highlights how critical system-level design choices are. Studies at the higher end of the performance range largely included those wherein jet impingement was combined with microchannels or phase-change was coupled to liquid cooling operating under pulsed load conditions while the lower end corresponded to studies in which one constituent cooling mode was near its optimal condition operating independently conditional on hybrid addition providing only relative marginal incremental improvement.

A significant point worth noting about TEC-assisted hybrid systems is that a considerable portion of the publications surveyed provide COP results obtained from operating conditions that would not correspond to realistic electronics cooling OPs. In particular, a number of studies used input current and temperature differentials which were low enough to be conducive to good TEC performance but poorly represent those present in real power module assemblies where high heat flux and significant thermal resistance dictate the conditions. However, when these TEC hybridization studies are compared with those which reported COP under realistic electronics-relevant conditions (htr ≥ 50 W/cm², hot side temperature > 60 °C), the measured COP values fall well below unity (<0.5 in most of the cases) reflecting that more than two watts of additional heat is being coupled into the assembly for each watt pumped by the TEC. This restricts the conditions under which TEC hybridization provides a net thermal advantage (a nuance not always front and center in the source publications). This result has major engineering implications, supporting the notion that TEC hybridization should be reserved for applications in which only small (5–15°C) temperature modulations are required at moderate heat flux levels rather than as a general strategy with extreme heat flux. This lack of consistency in method for the treatment of pressure drop and pumping power constraints is particularly prevalent across hybrid cooling experimental studies. Overall, 65% of the papers reviewed gave detailed thermal performance data but offered partial or no hydraulic performance characterization. Fumbling the announcement of such is critical since the power required to pump coolant through micro-scale hybrid heat exchangers can represent a non-negligible fraction of the total system power consumption in battery or portable applications. While only a few studies reported complete thermal and hydraulic data, all such studies consistently showed that the most thermally-enhanced hybrid configurations imposed the largest pressure drops; specifically, microchannel-jet impingement hybrids produced 2–5 times greater pressure droppings than a comparable microchannel-only configuration at equivalent flow rates. The trade-off between thermal-hydraulics is poorly quantified over the wider literature base, hindering legitimate multi-objective comparisons of configurations.

The most substantial gap recognized through experimental literature reviewed is the availability of long-term performance and reliability data. Of the thirty studies that were analyzed, only eight reported any variation of thermal cycling or accelerated lifetime testing, and in these cases the number of cycles to failure or performance degradation threshold typically does not exceed five hundred cycles, which is seven orders of magnitude lower than would be experienced in practice over twenty year operational lifetimes common in automotive power electronics or industrial motor drives. PCM-integrated hybrid systems studies routinely identified void formation, phase segregation and microencapsulation failure as the major long-term degradation mechanisms but systematically characterized parametric data towards enabling quantitative lifetime prediction models for reliable system longevity were rarely reported in the literature. Likewise, but quite rarely with the rigor necessary for predictive reliability modeling, studies of vapor chamber integration reported moderate performance degradation attributed to non-condensable gas accumulation and wick partial dryout during protracted operation at high-flux.

Another aspect which exhibits significant inconsistency in the reviewed literature is experimental characterization of temperature uniformity across the cooled device footprint. Others focused on characterizing spatial temperature distributions using infrared thermography or various embedded thermocouple arrays to obtain rigorous measurements of mean performance versus non-uniformity. Others used single-value measurements at an nominally representative location which is insufficient to capture the critical spatial temperature gradient patterns in power modules that could impact overall device reliability, especially for multi-die power modules where various die can see substantially different temperatures within a package. All studies with full spatial characterization demonstrated that hybrid cooling configurations introduce new non-uniformity patterns, compared to single-mode systems in relation to the flow distribution at manifold inlets or non-uniform phase-change front propagation in PCM regions. Some of these spatial effects were observed to partially offset the measured improvements in thermal resistance at the hotspot location, a key caveat not captured with studies using point-based thermal characterization.

5. DISCUSSION

The reviewed body of experimental evidence establishes that hybrid cooling systems are a technically validated and practically viable solution class for high-power electronics thermal management. What should be noted, however, is that translation of laboratory-scale experimental demonstrations into scalable and economically-viable high-throughput product implementations remains a challenge not yet comprehensively covered by the literature. The most significant of these challenges is the ongoing conflict seen between maximization of thermal performance and system-level packaging constraints, such as volume, weight, cost and reliability. The top performing hybrid configurations identified in this review—jet impingement with microchannels, and vapor chamber combined with microchannel cold plates—obtain their thermal performance benefits at the cost of a relatively substantial increase in fabrication complexity and cost compared to conventional solutions. Adoption in cost-sensitive mass-market applications will remain capped until the manufacturing processes and supply chain economics for these advanced cooling structures mature enough to lower unit costs into the range of what they need in order to displace incumbent technologies.

Results from the meta-analysis also point out an opportunity for the field to establish consolidated experimental reporting guidelines. The current status, where thermal resistance definitions, test vehicle geometries and boundary condition specifications as well as reliability test protocols differ significantly from study to study, severely limits the capability of the research community to make some confidence level cross-study comparisons and construct reliable performance prediction models. The utility of the experimental data produced by different research groups and facilities would be greatly enhanced if standardized test vehicle designs like those used to characterize liquid cooling at a single-phase (e.g., JEDEC thermal characterization standards) could be developed for the dielectric-enhanced, two-phase heat transfer systems envisaged. The thermal management research community should prioritize the development of such standards. Second, the chronic underreporting of hydraulic performance data in hybrid cooling studies is an identifiable and correctable shortcoming that future authors should remedy by establishing minimum reporting standards across thermal and hydraulic performance at multiple operating points.

Looking into the future, a possible way to go is the merging of hybrid cooling system design with more advanced technologies such as sensing, actuation and machine learning. Real-time thermal load prediction and adaptive cooling mode switching achieve nearly optimal thermal management (here peak device temperature and average cooling energy consumption) in a variety of operational scenarios with significant joint (>20%) reductions. The experimental investigations described in this review paper show that adopting adaptive hybrid architectures results in 20–35% cooling energy savings. As GaN and SiC based wide-bandgap power semiconductor devices continue their market penetration into power electronics as well as drive required heat fluxes to even higher limits, the capacity for hybrid cooling systems to judiciously adjust thermal tonnage in response to a dynamic thermal load will prove indispensable. This experimental knowledge base, which is reviewed here, provides the necessary empirical foundation on which intelligent adaptive systems will be designed and tested.

6. CONCLUSION

This review paper has offered a systematic meta-analysis on experimental studies concerning hybrid cooling study of high-power electronics, synthesizing results from thirty carefully selected publications and covering a two-decade research span. The key takeaway is that hybrid cooling methodologies consistently and effectively outperform single-mode combined thermal management strategies in thermal performance, with a median reduction of 38% in the thermal resistance compiled from published literature. Vapor chamber-integrated microchannel cold plates and jet impingement with microchannels are flexible and emerged as the top hybrid configurations. Nevertheless, the review did reveal significant gaps and limitations in the existing literature, including inadequate reporting of hydraulic performance, sparseness of long-term reliability data, inadequacies relating to spatial temperature non-uniformity characterization during hybridization studies as well as limited practical applicability for TEC-based hybridization at high heat fluxes. From a methodolgical perspective, the lack of or limited standardized experimental reporting protocols throughout the field is a critical barrier to confident cross-study comparison and model development. Future research needs to focus on multi-objective characterization in thermal, hydraulic and reliability domains; the design of unified test vehicle standards; and experimental validation of intelligent adaptive hybrid cooling systems with such capabilities where the system can optimize its operating mode during runtime based on real-time load variations. Further development of hybrid cooling technology is thus needed to keep achieving the scalable performance for high-power electronics in applications from electric vehicles to high-performance computing and aerospace systems.

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