2026 Volume: 02 Issue: 11 www.ijrpa.com ISSN 2456-9995 Review Article

International Journal Research Publication Analysis

Page: 01-12

THERMAL PERFORMANCE ENHANCEMENT OF MICROCHANNEL HEAT SINKS USING HYBRID PIN-FIN AND WAVY CHANNEL GEOMETRIES: A CRITICAL REVIEW

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Article Received: 11 October 2026

Article Revised: 01 November 2026

Published on: 20 November 2026

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DOI: https://doi-doi.org/101555/ijrpa.1905

ABSTRACT

Microchannel heat sinks are widely investigated for removing concentrated heat from compact electronic and electro-mechanical systems. Combining wavy passages with internal pin fins can create secondary motion, repeatedly disturb boundary layers, and improve temperature uniformity, but may also produce a substantial pressure-drop penalty. This critical narrative review examines the historical development, governing transport mechanisms, reported numerical and experimental findings, and design methodology for hybrid wavy–pin-fin microchannel heat sinks. Direct hybrid studies are compared against foundational microchannel, wavy-channel, and pin-fin investigations using thermal resistance, Nusselt number, pressure drop, pumping power, and matched operating constraints. Recent work demonstrates useful geometric synergy, yet maximum heat-transfer coefficients do not necessarily occur at minimum thermal resistance or maximum system-level efficiency. The review proposes a reproducible conjugate-heat-transfer CFD and multi-objective optimization framework, identifies limitations in cross-study comparisons, and outlines validation priorities. No original experiments or simulations are claimed.

KEYWORDS: microchannel heat sink; wavy channel; pin fin; conjugate heat transfer; pressure drop; pumping power; thermal–hydraulic optimization.

1. INTRODUCTION

Increasing electronic heat flux, nonuniform hotspot loading, and smaller packaging volumes create severe thermal-management demands. The seminal silicon microchannel work of

Tuckerman and Pease [1] established that compact liquid-cooled passages can remove exceptionally high heat fluxes. However, reducing hydraulic diameter alone is not sufficient: developing thermal fields, entrance losses, substrate conduction, manifold maldistribution and viscous losses determine the attainable temperature rise [2–6]. Subsequent geometry modifications seek to improve convective exchange without requiring unacceptably high flow rate or pumping power.

Wavy channels introduce periodic curvature, which can generate transverse secondary flows and promote cross-sectional mixing [7]. Micro pin fins interrupt the stream, increase wetted area, cause separation and wake reattachment, and redistribute coolant [8]. In hybrid geometries, the two mechanisms interact: a pin placed at a favorable phase of the wall wave may intensify local convection, while excessive obstruction can lead to poor hydraulic performance. The engineering objective is to reduce chip maximum temperature and thermal resistance under realistic flow and pressure budgets—not simply to maximize Nusselt number [9–15].

2. Historical Development and Importance

Microchannel research evolved from etched silicon heat sinks in the early 1980s [1] to reliable conjugate simulations, experimentally validated thermal–hydraulic correlations and practical electronic packaging [2–6]. The early emphasis was on passage dimensions, channel aspect ratio, developing laminar flow and pressure-drop measurement [3–6]. Later studies examined intentionally disturbed flows: pin-fin banks [8], sinusoidal channels [7] and locally optimized hotspot coolers [11]. Recent advances in microfabrication and numerical optimization have made integrated waviness, curved or streamlined pins, secondary channels and perforated inserts feasible [12–18].

The importance is practical as well as academic. Thermal stress and junction-temperature nonuniformity can shorten device service life. More even coolant distribution and reduced hotspots may improve reliability, whereas high pumping power may compromise energy efficiency or require larger auxiliary hardware. Hybrid geometries are therefore most attractive when they improve a specified system constraint, such as maximum wall temperature at fixed pumping power, rather than an isolated heat-transfer indicator. Application-scale differences also matter: a micron-scale water-cooled chip cannot be directly ranked against a millimeter-scale air-cooled EV battery duct at much higher Reynolds number [12,15].

3. Review Methodology

A structured narrative search was performed using title and topic combinations including "wavy microchannel", "pin-fin microchannel", "hybrid microchannel", "thermal resistance", "pumping power", "conjugate heat transfer" and "thermal-hydraulic optimization". Priority was assigned to directly relevant peer-reviewed studies, experimentally verified modeling papers, and foundational works necessary for interpreting micro-scale measurements. The main evidence groups were: (i) straight-channel baselines; (ii) wavy-only passages; (iii) pin-fin-only passages; and (iv) combined wavy–pin-fin architectures. Review papers and standard heat-transfer texts were added for context and definitions. This is not an exhaustive PRISMA systematic review; reported percentages are retained only in their original comparison context.

Comparisons emphasize Reynolds-number range, fluid, thermal boundary condition, baseline geometry, pin/wave dimensions and whether experimental validation was performed. Metrics reported without a common denominator—particularly Nusselt number, surface temperature, thermal resistance and total pressure loss—are treated as complementary rather than interchangeable. Published thermal enhancement factors may use different normalization conventions, so the stated definitions must be inspected before any cross-paper ranking.

4. Literature Survey and Critical Synthesis

Tuckerman and Pease [1] demonstrated the potential of high-performance silicon microchannels; Qu and Mudawar [2] later combined water-flow experiments with three-dimensional numerical analysis and quantified both heat transfer and pressure loss for rectangular passages. Kandlikar and Grande [3] and Morini [4] reviewed the underlying scale effects and experimental disagreements; Lee and Garimella [5] clarified the impact of entrance-region heat transfer and aspect ratio, while Steinke and Kandlikar [6] emphasized careful separation of frictional pressure drop from minor losses. Together, these works define the control conditions needed before asserting that a complex channel outperforms a straight one.

Sui et al. [7] investigated three-dimensional wavy microchannels and explained enhanced mixing through curvature-induced secondary flow. Unlike a pin-fin approach, waviness can produce periodic lateral transport without necessarily imposing repeated bluff-body blockage. Nevertheless, wave amplitude, wavelength and channel dimensions govern both mixing strength and frictional penalty. The design implication is that aggressive waviness may be

unfavorable under a constrained pump, even if it offers higher local Nusselt number. These conclusions provide a physical basis for subsequent hybrid geometries.

Peles et al. [8] experimentally examined flow over a micro pin-fin bank and developed a simplified thermal-resistance description. Pin fins create larger area and wake-driven mixing, but they also alter the pressure field; the heat sink must be assessed as a complete substrate–fluid system. Bhandari et al. [9] synthesized micro pin-fin design changes and emphasized that pitch, shape, height and configuration must be considered jointly. Ansari and Kim [11] subsequently explored a hybrid microchannel/pin-fin hotspot cooler with stepped pins; their numerical evidence supports targeting local thermal nonuniformity rather than distributing the same disturbance everywhere, although flow and manufacturing penalties require separate assessment.

A 2023 investigation of a MEMS-based water-cooled heat sink with wavy channels and pin fins [10] combined mathematical modeling with experimental validation at Reynolds numbers of 250–1500. The authors reported lower thermal resistance for the modified arrangement than for a straight-channel baseline, alongside greater pumping-power demand. This is particularly valuable as direct evidence of the intended hybrid mechanism. It is also a caution: a thermal-resistance improvement cannot be declared system-optimal without specifying the allowed pumping power and inlet/heat-flux conditions.

Gönül [12] examined streamlined micropins in convergent–divergent wavy microchannels and reported a maximum Nusselt-number improvement of about 4.79 times relative to the straight-channel reference, accompanied by a pressure-drop increase of about 9.87 times for the reported comparison. The magnitude of the two changes demonstrates a central limitation of thermal-only optimization. Higher wave amplitudes and smaller wavelengths increased heat transfer, but the desirable pin height was not simply “the largest possible.” The useful contribution is the coupled geometry map, which should be assessed using fixed pumping power and maximum chip-temperature constraints.

A 2025 numerical investigation of double-layer wavy microchannels [13] examined 28 configurations with circular pins and secondary passages, reporting that the combined geometry could produce the lowest thermal resistance in selected comparisons, while the highest reported performance-evaluation criterion occurred for a secondary-channel-only configuration. This distinction is important: the geometry maximizing a ratio-type metric can differ from the geometry minimizing thermal resistance. The paper also demonstrates that adding another enhancement feature is not automatically beneficial. Compound wavy

porous/solid passages [14] provide a related route, with different hydraulic and modeling assumptions.

Kaewchoothong and Gonsrang [15] assessed staggered pins with wavy walls for EV battery cooling at substantially higher Reynolds numbers than in many liquid microelectronics studies. The reported wavy configurations increased Nusselt number by 7.6–41.8%, with a 27.9–65.1% pressure-drop rise, and moderate waviness offered the better thermal enhancement factor. Their related 2026 curved-fin study [16] addressed turbine cooling; both reinforce the importance of pin shape–wave phase interaction. Mohammadbeigi et al. [17] showed that multivariable pin-fin optimization can be approached through structured design-of-experiments and multi-criteria ranking, while recent comprehensive reviews [18,19] highlight the need for independent validation and manufacturability checks.

5. Recommended Numerical Investigation Methodology

A defensible original numerical study should build four matched geometries: straight microchannel, wavy-only channel, straight channel with pins, and hybrid wavy channel with pins. The same footprint, substrate thickness, coolant, imposed heat flux, inlet temperature, and specified total mass flow or pumping-power budget should be used; hydraulic diameter and minimum flow area must be disclosed rather than assumed equal. Design variables may include wave amplitude A, wavelength λ, pin diameter d, pin pitch Sx and Sy, pin shape and wave-to-pin phase. A factorial or response-surface screening study can identify interactions before a Pareto optimization stage. A fifth alternative with reduced pin density may test whether selective placement is better than full coverage.

For incompressible, single-phase laminar cooling, solve continuity, momentum and fluid energy equations simultaneously with conduction in the solid substrate (conjugate heat transfer). Choose turbulence treatment only if justified by the flow state and disturbances; Reynolds number alone does not prove classical turbulent behavior in strongly perturbed microgeometry. Represent fluid properties as temperature dependent where variations are significant. Use a physically justified no-slip boundary, impose uniform heat flux or measured hotspot maps, and specify thermal losses, inlet manifold assumptions and outlet pressure. Compare grid-independent maximum wall temperature, mean heat-transfer coefficient, Δp, Nu, friction factor, thermal resistance $R_{th} = (T_{wall,max} - T_{in})/Q$ and pumping power $P_{pump} = \Delta p \times \dot{V}/\eta_{pump}$, with consistent definitions.

Validation should begin against straight-channel experiments or a published benchmark under matched conditions and then compare a modified geometry with experimental data if

available. At least three progressively refined meshes are advisable, with near-wall refinement around the pins and wave crests and transparent discretization uncertainty. The parameter study should include heat flux, flow rate, geometric variables and coolant temperatures. A robust multi-objective search can minimize maximum chip temperature and pumping power simultaneously; report the Pareto front, non-dominated candidate coordinates, sensitivity to property/roughness uncertainty and feasibility under fabrication limits. If a thermohydraulic performance factor is used, state its exact mathematical definition and whether equal mass flow, equal pressure drop or equal pumping power was enforced.

6. Discussion and Comparative Analysis

Table 1. Selected published evidence. The "up to" percentages are conditional findings, not pooled enhancement estimates; test conditions and baselines differ.

Evidence / configuration	Reported benefit or physical result	Critical qualification
Straight microchannels [1,2,5]	High area density; validated cooling baseline	Entrance, manifold, substrate and friction losses matter
Wavy-only channels [7]	Curvature-induced secondary flow and mixing	Wave amplitude/wavelength control hydraulic cost
Micro pin-fin bank [8,9]	Area and wake-driven convection	Pressure loss and fin effectiveness must be included
Wavy + pins, MEMS [10]	Lower thermal resistance than straight baseline	Pumping power higher; water, Re 250–1500
Wavy + streamlined pins [12]	Nu up to 4.79× against chosen reference	Δp up to 9.87×; not system-optimal by Nu alone
Double-layer hybrid [13]	Combined features can minimize Rth	Best PEC from different feature combination
Wavy + staggered pins [15]	Nu gain 7.6–41.8% in cited air-cooled cases	Δp rise 27.9–65.1%; distinct scale/Re

Table 2. Minimum comparison protocol proposed for geometry-optimization studies.

Metric / design issue	Suggested harmonized reporting	Reason
Rth and Tmax	Same footprint, heat flux, Tin, Q and sensor plane	Directly captures chip protection
Nu, h and area	State characteristic length and wetted-area definition	Avoids artificial area-related advantage
Δp and Ppump	Include minor losses, volumetric flow and efficiency	Recognizes auxiliary electricity
Geometry	A/λ, d/Dh, pitch ratios, blockage and roughness	Enables reproducibility
Model credibility	Mesh study, benchmark, uncertainty and regime	Prevents mesh-driven optima
Manufacturability	Feature tolerance, fouling, cleaning and cost	Links CFD to practical use

Collectively, the literature indicates that hybrid geometry can offer meaningful thermal gains through interaction between transverse secondary flows and localized pin wake structures. Yet three comparisons are often conflated: higher heat-transfer coefficient at equal flow rate, lower maximum temperature at equal pumping power, and higher thermal performance factor under a particular published formula. These are not equivalent optimization goals. Pin-array orientation relative to the wavy wall, nonuniform heating, coolant maldistribution and substrate conduction can reverse apparent rankings. Further, studies of air-cooled EV channels should not be directly generalized to water-cooled silicon microchannels. A rigorous review therefore places hydraulic and reliability constraints alongside reported Nu gains.

7. Outcomes, Research Gaps and Future Directions

The principal synthesis is that a hybrid pin–wavy architecture is most compelling when designers identify where secondary-flow acceleration and wake mixing overlap beneficially without excessive blockage. The available studies substantiate the feasibility of this strategy [10,12,13,15,16], but they do not establish a universal optimal wave amplitude, pitch or pin shape. Direct gaps include consistent fixed-pumping-power comparisons, quantified wave-to-pin phase interactions, systematic uncertainty reporting, experiment-backed multi-parameter optimization, manufacturing roughness, blockage and fouling, and transient nonuniform heat-flux tests. Machine-learning surrogates may accelerate parameter sweeps, but they should be physically checked and tested beyond training geometries [18,19].

Future investigations should explicitly test the hypothesis that spatially selective pin placement within a wavy channel outperforms uniform pin distributions for hotspots at a fixed pump budget. A reproducible study would archive CAD dimensions, mesh quality criteria, temperature-dependent properties, reference conditions, pressure-flow curves and data reduction, then report several Pareto candidates rather than a single chosen design. An experimental prototype should verify wall-temperature uniformity and full-system pressure loss, including manifolds. This integrated approach is more useful for device design than reporting only percentage Nu enhancement.

8. CONCLUSION

Hybrid pin-fin and wavy microchannel heat sinks combine complementary enhancement mechanisms—curvature-driven secondary motion and fin-induced wake/boundary-layer renewal. The reviewed studies suggest important opportunities to reduce hotspot temperature and thermal resistance, but improved heat transfer commonly comes with increased flow

resistance. The strongest design basis is a calibrated conjugate CFD framework evaluated against a straight-channel reference at matched thermal load and pumping constraints, supported by experimental evidence and transparent uncertainty analysis. Generalizable future progress is likely to come from optimized pin placement, phase-controlled hybrid geometries, manufacturability-aware design and standardized thermohydraulic reporting rather than adding flow obstacles indiscriminately.

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