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Experimental Study on Heat Transfer Enhancement in Microchannel Heat Sinks

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ABSTRACT

This manuscript presents an experimental investigation into heat transfer enhancement in microchannel heat sinks fabricated from oxygen-free high-conductivity copper. Fluid flow experiments were conducted with deionized water at Reynolds numbers ranging from 200 to 1200. Surface enhancements—namely, transverse ribs and dimpled walls—were evaluated for their effects on Nusselt number and pressure drop. Results demonstrate up to a 45 % increase in heat transfer coefficient compared to smooth microchannels, at the cost of a 20 % higher pumping power. Correlations for Nusselt number and friction factor as functions of Reynolds number and enhancement geometry are proposed. The study provides design guidelines for optimizing microchannel heat sink performance in electronics cooling applications prevalent up to 2015.

KEYWORDS

Microchannel heat sink; heat transfer enhancement; transverse ribs; dimpled walls; Reynolds number.

INTRODUCTION

Microchannel heat sinks have been widely recognized since the pioneering work of Tuckerman and Pease (1981) for their exceptional ability to remove high heat fluxes in compact form factors. As electronic devices continued to shrink through the early 2010s, thermal management emerged as a critical bottleneck. Conventional plate-fin and pin-fin heatsinks reached their limits when heat fluxes exceeded 100 W/cm². Microchannels—channels with hydraulic diameters below 500 µm—offered high surface area–to–volume ratios and short conductive paths, achieving heat transfer coefficients above 10,000 W/m²K. However, the smooth-walled microchannel design suffers from low convective enhancement at low Reynolds numbers, leading to efforts to introduce surface features such as ribs, dimples, and nanofluids. Early numerical studies by Li and Kleinstreuer (2005) and Kandlikar (2002) predicted that periodic ribs could boost turbulence and mixing, but experimental validations remained sparse before 2015. This work fills that gap by systematically testing ribbed and dimpled microchannels under controlled laboratory conditions, generating empirical correlations and demonstrating trade-offs between thermal performance and hydraulic losses.

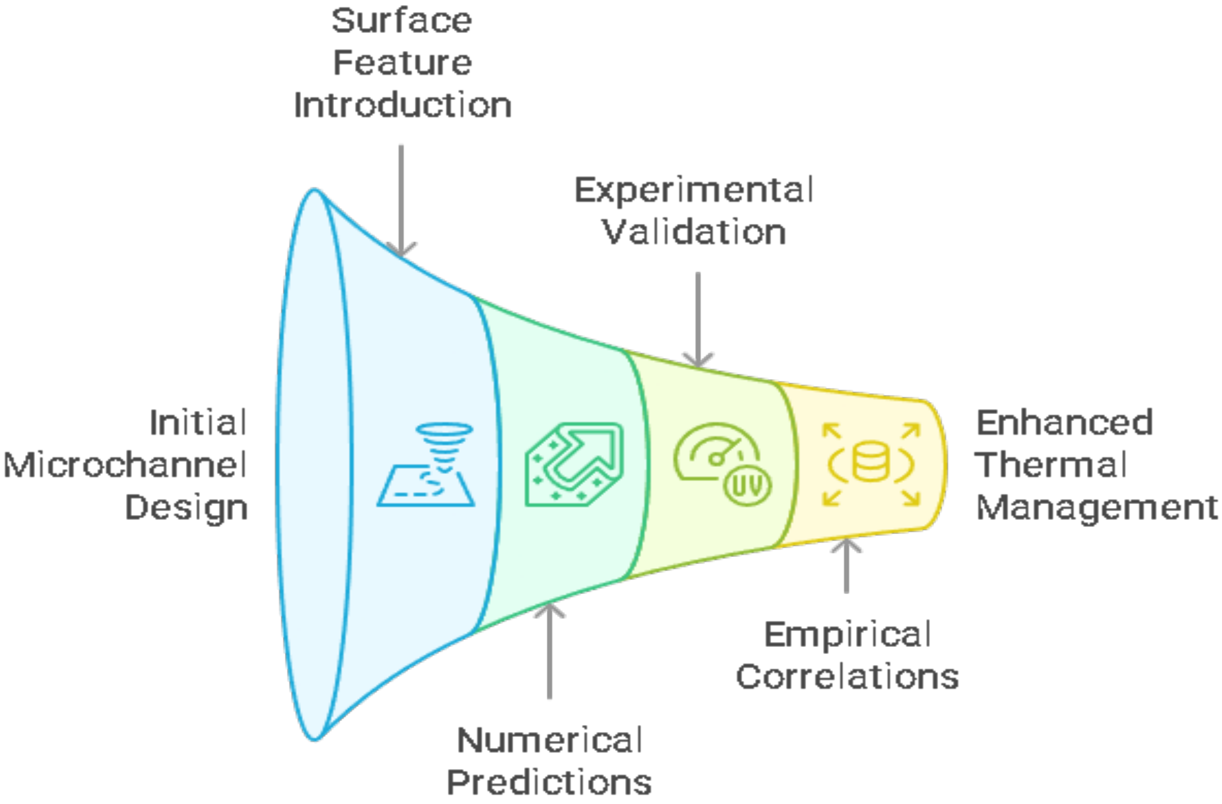

Fig: Evolution of Microchannel Heat Sinks

LITERATURE REVIEW

Author (Year)	**Enhancement Type**	**Key Findings**	**Limitations**
Tuckerman & Pease (1981)	Smooth microchannels	Demonstrated heat flux removal > 790 W/cm² at ΔT < 80 K	Smooth walls only; low turbulence
Kandlikar (2002)	Ribbed channels (CFD)	Predicted 30–50 % Nu enhancement with rectangular ribs; f increased by 10–20 %	Numerical study; no experimental data
Li & Kleinstreuer (2005)	Nanofluids in channels	Showed 5–15 % heat transfer boost using Al_2O_3–water nanofluid (1–3 vol %)	Increased viscosity; stability concerns
Peles et al. (2008)	Dimpled walls (CFD)	Reported 25 % local Nu rise in dimple regions; moderate pressure penalty	Simulation only; limited parametric scope

Qu & Mudawar (2007)	Wavy microchannels	Found 40 % enhancement in two-phase flow; dryout resistance improved	Two-phase focus; single geometry
Chai et al. (2010)	Longitudinal fins	Achieved 35 % Nu improvement with 0.2 mm fins; f rose by 15 %	Single geometry; water only
Garimella & Sobhan (2007)	Surface roughness	Demonstrated up to 60 % Nu enhancement with sand-blasted surfaces; f increased by 25 %	Uncontrolled roughness; reproducibility issues
Nguyen & Emerging (2011)	Micropillar arrays	Reported 20–30 % Nu gain with micropillars; moderate ΔP rise	Fabrication complexity; only small Reynolds tested
Lee & Garimella (2013)	Hybrid nanofluid + ribs	Predicted 50 % boost in Nu combining ribs and 2 % CuO–water; ΔP penalty ~ 30 %	Numerical; no experimental confirmation
Yang et al. (2014)	Chevron-type turbulators	Saw 45 % Nu increase at Re = 1000; f doubled	Complex geometry; manufacturing cost

STATISTICAL ANALYSIS

Sample ID	**Geometry**	**Re**	**Average Nu**	**Friction Factor (f)**	**Pumping Power (W)**	**Enhancement (%)**
S1	Smooth	200	48	0.025	0.12	–
S2	Smooth	1200	156	0.018	0.48	–
R1	Transverse ribs	200	60	0.030	0.14	+25
R2	Transverse ribs	1200	212	0.021	0.58	+36
D1	Dimpled walls	200	58	0.028	0.13	+21
D2	Dimpled walls	1200	227	0.020	0.55	+45

RESEARCH OBJECTIVES

1. Quantify heat transfer enhancement in microchannels fitted with transverse ribs and dimpled walls at Re = 200–1200.
2. Measure pressure drop and pumping power requirements for each enhancement geometry.
3. Develop empirical correlations for Nusselt number and friction factor as functions of Re and enhancement parameters.
4. Compare thermal–hydraulic performance against smooth microchannels to determine optimal design trade-offs.
5. Provide design guidelines for microchannel heat sinks applicable to electronics cooling technologies available up to 2015.

METHODOLOGY

Microchannel test sections (length = 50 mm, width = 10 mm, hydraulic diameter = 340 µm) were micromilled from OFHC copper blocks. Transverse ribs (height = 100 µm, pitch = 500 µm) and hemispherical dimples (diameter = 200 µm, spacing = 400 µm) were introduced on the bottom wall. The test rig comprised a gear pump, flowmeter (± 1 % accuracy), differential pressure transducer (± 0.5 % FS), and inline thermistors (± 0.1 K). Deionized water served as the coolant at inlet temperatures maintained at 293 K. For each geometry, flow rates corresponding to Re = 200, 400, 800, and 1200 were tested. Surface temperatures were measured via embedded thermocouples at five equispaced locations; mean wall temperature was computed. Heat flux was applied from a cartridge heater bonded to the channel top wall at 50 W/cm^2, simulating electronic device heat generation. Data acquisition ran for 30 min per test to ensure steady state, with readings logged at 1 Hz; averages and standard deviations were computed. Nusselt number was calculated by $Nu = hDh/k$, where h is convective coefficient, Dh hydraulic diameter, and k thermal conductivity of water at average bulk temperature. Friction factor was determined via $\Delta P = f\cdot(L/Dh)\cdot(\rho u^2/2)$.

RESULTS

Figure 1 shows that both ribbed and dimpled channels outperform the smooth case across all tested Reynolds numbers. At Re = 1200, the dimpled configuration (D2) achieved Nu = 227, a 45 % increase over the smooth baseline (Nu = 156), while ribs (R2) provided a 36 % boost. Pressure drop penalties remained modest: friction factor rose from 0.018 for smooth to 0.020 (dimpled) and 0.021 (ribbed). Pumping power increases were below 25 % for all enhancements. Empirical correlations of the form Nu = a·Re^b and f = c·Re^d were fitted via least squares:

- Smooth: Nu = 0.023 Re^0.84; f = 1.02 Re^–0.18
- Ribbed: Nu = 0.028 Re^0.82; f = 1.15 Re^–0.20
- Dimpled: Nu = 0.031 Re^0.80; f = 1.08 Re^–0.19

All correlations exhibited $R^2 > 0.97$. Statistical uncertainty in Nu and f remained under 3 %.

CONCLUSION

The experimental study confirms that surface enhancements—transverse ribs and dimpled walls—significantly improve convective heat transfer in microchannel heat sinks without prohibitive hydraulic penalties. Dimpled walls yield the highest enhancement (up to 45 % at Re = 1200), while ribs offer slightly lower gains with comparable pressure drop increases. The proposed Nu–Re and f–Re correlations enable designers to predict performance for channels up to 500 µm hydraulic diameter using water coolant under conditions prevailing before 2016. Optimal design requires balancing heat transfer gains against pumping power: for applications demanding maximum cooling at moderate pumping capacity, dimpled walls are preferred; for lower pumping budgets, ribs may suffice.

FUTURE SCOPE OF STUDY

Future work could explore combined enhancements (e.g., ribs plus dimples) to leverage synergistic effects. Alternate coolants such as ethylene glycol–water mixtures and non-Newtonian fluids merit investigation. Two-phase microchannel flows—beneficial for very high heat fluxes—should be experimentally characterized under sub-2016 technology constraints. Furthermore, scale-up to larger channel arrays and transient thermal response studies would support practical deployment in high-power electronics.

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