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An Experimental and Numerical Studies of Fin-Type Heat Sinks, Microchannel Heat Sink Its Cooling Performance and Design Consideration

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Abstract
Microchannel heat sinks (MCHS) have emerged as pivotal components in advanced thermal management systems due to their superior heat transfer capabilities. Fin-type heat sinks, essential for efficient thermal management in electronic devices, are evaluated through a series of experimental and numerical studies. This paper reviews recent advancements in the design and performance analysis of various fin-type heat sinks, including micro pin-fins of different geometries and dimensions. By comparing the heat transfer efficiency and pressure drops among different designs and operating conditions, this review aims to provide insights into optimizing fin-type heat sinks for improved thermal management.

Keywords: Microchannel heat sink, Fin-type heat sink, micro pin-fin, nanofluids, heat transfer, cooling performance, geometric parameters.

1. Introduction

Microchannel heat sinks (MCHS) are critical in managing heat dissipation in high-performance electronic devices. Their efficiency is influenced by several factors, including the channel structure, coolant type, and geometric parameters. This review collates recent advancements in the field, focusing on numerical and experimental studies that explore these variables and their impact on heat transfer performance.

Heat sinks are critical components in cooling systems for electronic devices. This paper reviews recent experimental and numerical studies on fin-type heat sinks, focusing on micro pin-fins with various geometries and dimensions. The review includes investigations on the impact of pin-fin shape, height, spacing, and operating conditions on heat transfer performance and pressure drops.

Numerical study on microchannel heat sink -

Sr no.	Author and Year	Type of cross sectional area- shape and size (µm)	Reynolds no.	Pressure drop	Material of microchannel	No. of channel/fins
1	Assel Sakanova	Cu double layer- 300 µm, 635 µm AlNe,300	100 to 300	45-250 KPa	Direct bond copper	50-150

	(2014)	µm				
2	Chien-Hsin Chen (2011)	Circular aspect ratio-2.83, Microchannel- 5x1.6 cm	150	50 Kpa	Copper	25
3	Y.L. Zhai (2015)	6 types MC per-formed- Cavities and ribs ranges from 0-7502, 0-022 respe.	300-600	10-120 Kpa	Silicon	10
4	Hui He (2016)	Rectangular – for bubble growth Aspect ratio-1/2 to 1/6	150	60 Kpa	aluminum	20
5	D.R.S. Raghuraman (2016)	Rectangular – aspect ratio 20-46	50-350	1.5-10 Kpa	Silicon	122
6	Yanlong Li (2014)	Straight channel and y- shaped bifurcation (60,90,120,180)	210-490	7 K Pa	aluminum	50
7	Assel Sa-kanova (2015)	700x85x28µm for straight and zigzag channel. wave ampli-tudes of 25 lm, 50 lm and 75 lm are considered in this study.	100-240	15-31 Psi	diamond–water, CuO–water, and SiO2–water nano fluids.	7
8	D.D. Ma (2016)	Straight channel and zigzag channel (AR-0.02-0.25)	200-800	5-45 KPa	Water	30
9	Minghai Xu (2016)	Microchannel with dimple	500	3-48 Kpa	water	9-21 dim-ples in one channel
10	Lin, chen (2014)	Double layer Micro-channel heat sink X-10 Y- 1 Z-10mm	100	100 kpa	Silicon	50-100
11	Ding Yuan (2021)	Rectangular Micro channel Width-1.5 mm, depth-0.75 mm, and Hd-1 mm with connected and rotating groove	208-430	500kpa	aluminum	20

Effectiveness of Channel Structures

- **Sandwich Structure-** Assel Sakanova (2014) demonstrated that the sandwich structure of MCHS exhibits the most effective performance in terms of heat removal and temperature uniformity. The study employed Al2O3 water-based nanofluids and observed that higher nanofluid concentrations enhanced cooling performance, with a 17.3% improvement at 5% concentration and a 10.6% enhancement at 1% concentration. Notably, selecting a smaller number of channels resulted in a significant reduction in thermal resistance.
- **Porous Medium Model-** Chien-Hsin Chen (2011) explored a nanofluid-cooled MCHS using a saturated porous medium model with the Forchheimer-Brinkman extended Darcy equation. Their findings indicated that higher volume flow rates and appropriate inertial force parameters (0.3 for 1% volume fraction and 0.1 for 2%) led to accurate predictions of cooling performance compared to experimental results.
- **Complex Channel Structures-** Y.L. Zhai (2015) introduced six novel micro heat sink designs with varying cavity and rib configurations. Among these, the micro heat sink with triangular cavities and ribs demonstrated superior performance for Reynolds numbers ranging from 300 to 600. The study highlighted the pronounced influence of Reynolds number and rib height on entropy generation and thermal transport efficiency.

Geometric Parameter Effects

- **Bubble Growth Analysis-** Hui He (2016) developed an analytical model to predict pressure fluctuations in rectangular microchannels through bubble growth stages. The model revealed that microchannels with higher aspect ratios had better heat removal capabilities, whereas lower aspect ratios led to rapid pressure drops.
- **Aspect Ratio Impact-** D.R.S. Raghuraman (2016) investigated rectangular MCHS with varying aspect ratios. The study found that MCHS with an aspect ratio (AR) of 20 had a higher pressure drop compared to AR 30 and 46.66. However, AR 46.66 required more pumping power due to a larger mass flow rate.
- **Y-Shaped Bifurcation-** Yanlong Li (2014) conducted 3D numerical simulations on Y-shaped bifurcation microchannels. The study found that the pressure drop increased with the angle between the bifurcation arms and the inlet Reynolds number. The configuration with a 180° angle exhibited the smallest pressure drop among the studied angles.

Advanced Heat Transfer Techniques

- **Wavy Channel Structures-** Assel Sakanova (2015) also explored wavy channel structures combined with nanofluids. Their study showed that wavy channels with wave amplitudes of 25 µm, 50 µm, and 75 µm, and wavelengths of 250 µm and 500 µm, improved heat transfer. Among the nanofluids tested, diamond-water nanofluid provided the highest heat transfer coefficient and the lowest thermal resistance.
- **Zigzag Microchannel-** D.D. Ma (2016) examined the impact of geometric parameters on fluid flow in zigzag microchannels. The study found that the pressure drop decreased with increased porosity and enhanced fluid disturbance due to the zigzag cavity, except for specific Reynolds number conditions.
- **Dimpled Channels-** Minghai Xu (2016) analyzed dimpled channels with various geometric parameters. The results indicated that increasing dimple depth reduced pressure drop, with the optimal

depth being 0.1 mm. However, changes in dimple depth had minimal impact on heat transfer performance.

- **Grooved Microchannels-** Ding Yuan (2021) investigated the performance of smooth and grooved microchannels. The study found that pressure drop in microchannels with connected grooves was significantly higher (84.3% increase) compared to smooth channels, attributed to vortices induced by the grooves.

Experimental study on microchannel heat sink -

Sr no.	Author and year	Type of cross sectional area- shape and size (µm)	Working medium	Reynolds no.	Pressure drop	Material of microchannel	No. of channel/fins
1	Guodong Xia (2012)	Straight channel and staggered complex coggurated channel	Di water	611	12-24 Kpa	Silicon wafer	30
2	Abhilash K. Tilak (2022)	novel Inverted T-shaped with Semi-Circular Ends at Base (ITSCEB) microchannel heat sink (MCHS)-23x60x7mm	water	200-1400	0.2-0.12 bar	copper	13
3	Ganesan Narendran (2022)	Curved Double layered microchannel heat sink	nanofluid	600-2000	6.3-10.2 Kpa	Aluminum	12
4	Mohammad Ataei (2020)	Rectangular(32x50mm) Minichannel heat sink	Al2o3/TiO2- water nano fluid	400-1000	2-3Kpa	Aluminum	10
5	Reza Bahoosh (2021)	Rectangular(1x1.2x1.091mm) Minichannel (25x50mm)-helix angle-45,60,90o	Water – AL2O3 nanofluid	113-478	2Kpa	Aluminum	36

6	Bo Sun (2022)	Rectangular (w-200 µm,h-800 µm) Dh-320 µm	Deionized water	150-750	133.48 Kpa	Copper	20

Comparative Performance of Microchannel Designs

- **Channel Configurations-** Guodong Xia (2012) conducted experiments comparing the performance of heat sinks with I-type, rectangular header, and staggered complex corrugated channels (CMCHS) against a regular microchannel heat sink (RMCHS). The study showed that the measured pressure drops agreed well with theoretical values, with deviations of less than ±3.5% for heater film temperature and ±7.2% for channel pressure drops. The CMCHS exhibited a higher pressure drop than the RMCHS, attributed to vortex formation, boundary layer interruption, and fluid stagnation at low flow rates.
- **Novel Microchannel Designs-** Abhilash K. Tilak (2022) investigated the Inverted T-shaped with Semi-Circular Ends at Base (ITSCEB) microchannel design compared to a conventional rectangular MCHS. Using water as the coolant, they found that the ITSCEB design resulted in a pressure drop 4.6% to 21.7% higher than the rectangular design despite similar hydraulic diameters.

Effects of Coolants and Fabrication Techniques

- **Nanofluids in Microchannels-** Ganesan Narendran (2022) studied the thermal performance of Ti64 microchannels with different nanofluids. The Ti64 3D printed microchannel with GO-0.12% nanofluid showed a 75.4% higher pressure drop compared to Ti64 heat-treated microchannels. Surface imperfections from fabrication processes significantly influenced the pressure drop.
- **Hybrid Nanofluids-** Mohammad Ataei (2020) examined an aluminum minichannel heat sink using various coolants, including distilled water and nanofluids. The hybrid Al2O3/TiO2-water nanofluid resulted in a lower pressure drop compared to TiO2-water nanofluid. At a Reynolds number of 400, the pressure drop increase was 25.90% for hybrid nanofluid, 29.54% for TiO2 nanofluid, and 20.45% for Al2O3 nanofluid.
- **Cylindrical Minichannels-** Reza Bahoosh (2021) investigated cylindrical minichannels with helical structures and secondary branches using water-Al2O3 nanofluid. The study found significant enhancements in the Nusselt number with helical minichannels compared to straight ones, with improvements of 31.1% and 51.3% at helix angles of 60 and 45 degrees, respectively. The maximum Nusselt number enhancement for nanofluids was 14.3% for a 0.1% volume fraction.

Performance of Segmented and Large-Scale Heat Sinks

- **Segmented Finned Microchannels-** Yogesh K. Prajapati (2022) studied segmented finned microchannels under single-phase flow and flow boiling conditions. The pressure fluctuations during single-phase flow were moderate to high, with an average pressure drop of 2320 Pa at a heat flux of 57.4 kW/m^2 and a mass flux of 324.5 kg/m^2.
- **Large-Scale Microchannel Heat Sinks-** Bo Sun (2022) proposed a large-scale microchannel heat sink optimized for high heat flux cooling. The design, based on the Li-Peterson model, had channels with widths of 0.2 mm and heights of 0.8 mm. The study showed that pressure drop increased with Reynolds number, reaching a maximum of 114.87 kPa at a heat flux of 500 W/cm^2 and Reynolds number of 726.

Experimental and numerical study on Fin type heat sink -

Sr no.	Author and Year	Type of cross sectional area- shape and size (µm)	Working medium	Reynolds no.	Pressure drop	Material of microchannel	No. of channel/fins
1	Bo Sun (2015)	Cicular- micro pin fin Circular c/s- 2215 mm2 And aerofoil fin shape	Water	2000	15 Kpa	aluminum	94
2	Haleh Shafeie (2013)	microchannel heat sink and PFHS pin fin heat sink. heights of 90, 180, and 500 µm for the channels are examined with D-80 µm.	Water	1000	5-50 Kpa	aluminum	18
3	Ramendra Singh Niranjan (2022)	Square micro pin fin heat sink	Air	4500-6000	25Kpa	aluminum	6
4	Fadi Alnaimat (2021)	Square pin fin heat sink(50x50x3), fin- 0.5x2mm	Di water	80-470	40Kpa	copper	25

Numerical Analysis of Fin-Type Heat Sinks

- **Geometric Variations-** Bo Sun (2015) conducted a numerical study analyzing the thermal performance of four different micro pin-fin cross-sections: conventional circular, hydrofoil, modified hydrofoil, and symmetric convex lens shapes. The micro pin-fins had a height of 250 mm, side wall thickness of 60 mm, and top and bottom wall thickness of 40 mm, with a diameter of 173 mm. Using silicon as the substrate material and water as the coolant, the study found that the hydrofoil-shaped pin-fins exhibited a 3.2% improvement in the ratio of convection to total heat load compared to the conventional circular cross-section.

Experimental Analysis of Micro Pin-Fin Heat Sinks

- **Performance of Different Heights-** Haleh Shafeie (2013) investigated water-cooled pin-finned heat sinks placed on a 1 cm x 1 cm substrate. The study compared pin-finned microchannel heat sinks (MCHSs) and pin fin heat sinks (PFHSs) with varying pin-fin heights. It was observed that the 500 µm height channel outperformed other shorter channels in heat transfer capabilities. Additionally, PFHSs demonstrated lower power drops compared to MCHSs.
- **Effect of Fin Heights and Spacing-** Ramendra Singh Niranjan (2022) analyzed the heat transfer

performance of heat sinks with square micro-pin fins under forced convection. The study revealed that increasing the height of the pin fins and the Reynolds number led to a higher dimensionless heat transfer coefficient (Nusselt number). Conversely, an increase in fin spacing resulted in a lower Nusselt number. Heat sinks with larger pin fin heights had lower thermal resistance but experienced higher pressure drops. Compared to plate fins, micro pin fin heat sinks offered approximately 10% better cooling performance.

- **Thermal Resistance and Reynolds Number-** Fadi Alnaimat (2021) conducted an experimental study on square pin-fin heat sinks with different sizes of copper pin-fin cross-sections (2-mm and 500-µm fins). The investigation covered Reynolds numbers from 80 to 470 and heat fluxes between 21.9 and 46.7 W. The results indicated that thermal resistance decreased with increasing Reynolds number. Notably, heat sinks with micrometer-sized pin-fins (500-µm fins) exhibited lower thermal resistance at low Reynolds numbers compared to heat sinks with millimeter-sized pin-fins (2-mm fins).

5. Conclusion

This review paper provides a comprehensive analysis of experimental and numerical studies on fin-type heat sinks and microchannel heat sinks, highlighting the impact of pin-fin geometry, Structural configuration, coolant type, height, geometric parameters, fabrication methods and spacing on heat transfer performance and pressure drops. The findings underscore the importance of optimizing fin designs and operating conditions to achieve effective thermal management in electronic systems.

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