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Numerical and Experimental Analysis of Hybrid Micro-Baffle Heat Sinks Employing Multi-Walled Carbon Nanotube (MWCNT) Water-Based Nanofluids for High-Flux Thermal Management

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ABSTRACT

Modern power electronic devices, high-frequency radar modules, and concentrated photovoltaics generate extreme localized heat fluxes exceeding $250\ W/cm^2$*. Standard microchannel cooling systems often encounter thermal saturation along the length of the channel, leading to non-uniform temperature profiles and high thermal stresses across chip substrates. This paper presents a comprehensive computational and experimental study of a hybrid microchannel heat sink (HMHS) equipped with micro-baffles operating with multi-walled carbon nanotube (MWCNT) water-based nanofluids (*0.05 *vol% to* 0.3 *vol%). The angled micro-baffles periodically break the hydrodynamic boundary layer and induce secondary convective mixing. Conjugate heat transfer simulations, validated against experimental measurements, demonstrate that using a* 0.2 *vol% MWCNT-water nanofluid at* $Re = 1100$ *reduces total thermal resistance by* 39.5% *compared to pure water in smooth channels. The average Nusselt number increases by* 54.8%*, accompanied by a* 16.2% *pressure drop penalty. The maximum temperature variation across the substrate is limited to* $3.2\ K$*, mitigating localized thermal hot spots. Detailed parametric analyses, boundary dynamics, limitations, and future research opportunities are presented.*

KEYWORDS: *Microchannel Heat Sink, Carbon Nanotubes, Micro-Baffles, Electronics Cooling, Conjugate Heat Transfer, Pressure Drop*

INTRODUCTION

The continuous miniaturization and power density scaling in power electronics, 3D integrated circuits, and optoelectronic modules have increased thermal management requirements beyond $250\ W/cm^2$. Elevated semiconductor junction temperatures accelerate device degradation, lower operational efficiency, and increase thermal stress failure risks according to Arrhenius lifetime models.

Since Tuckerman and Pease introduced single-phase forced convection in microchannels, microchannel heat sinks (MCHSs) have served as a principal passive/active cooling method for high-density electronic systems. However, conventional straight rectangular microchannels suffer from continuous thermal boundary layer growth along the flow direction. This causes stream-wise coolant temperature rises and elevated substrate temperatures near the channel exit.

To address these thermal gradients, geometric flow disruptors (e.g., ribs, baffles, or pin-fins) can be combined with advanced thermal fluids (nanofluids). Incorporating angled micro-baffles periodically interrupts boundary layer growth, inducing local recirculation zones and chaotic advection. Concurrently, dispersing multi-walled carbon nanotubes (MWCNTs)—which possess high thermal conductivities ($2000\text{--}3000$ W/m · K)—into water augments baseline fluid thermal conductivity and enhances micro-scale energy transport via Brownian motion.

This research presents a combined numerical and experimental investigation of conjugate heat transfer in micro-baffle heat sinks (MB-MCHS) operating with $0.05\text{--}0.3$ vol% MWCNT-water nanofluids under steady-state operating conditions.

LITERATURE REVIEW

Recent research in high-heat-flux microelectronics cooling focuses on structural flow disruption and advanced heat transfer fluids:

- **Passive Flow Obstructions:** Angled baffles, ribs, and re-entrant cavities periodically break developing thermal boundary layers, inducing secondary flow structures and fluid re-circulation. These geometric features increase convective heat transfer coefficients while introducing localized pressure drops.
- **Carbon-Based Nanofluid Dynamics:** Dispersing carbon nanotubes (CNTs) or graphene nanoplatelets into polar solvents enhances liquid thermal conductivity compared to conventional metal oxide nanoparticles (Al_2O_3, TiO_2). Their elongated 1D structures form conductive pathways within the base fluid, increasing bulk energy transport.

- **Synergistic Passive Cooling:** Combining physical flow disruptions with high-thermal-conductivity suspensions increases local Nusselt numbers. However, documented studies show variations regarding pumping power penalties, particle agglomeration risks under high shear stress, and long-term suspension stability.

RESEARCH GAP

While individual studies have evaluated micro-baffles or CNT nanofluids separately, comprehensive studies evaluating the thermo-hydraulic performance of micro-baffle heat sinks operating with functionalized MWCNT-water nanofluids (0.05--0.3 vol%) remain limited. In particular, systematic evaluations that balance Nusselt number gains against pressure drop penalties (Performance Evaluation Criterion, PEC) across varying Reynolds numbers under consistent thermal boundary conditions are needed.

OBJECTIVES

- Design and fabricate a copper Micro-Baffle Microchannel Heat Sink (MB-MCHS).
- Synthesize stable 0.05--0.3 vol% MWCNT-water nanofluids using ultrasonic dispersion and surfactant stabilization (SDBS).
- Conduct conjugate heat transfer CFD modeling and physical testing for Reynolds numbers from $Re = 300$ to 1300.
- Evaluate total thermal resistance (R_{th}), average Nusselt number ($\overline{Nu}$), pressure drop (ΔP), substrate temperature gradients, and the global Performance Evaluation Criterion (PEC).

METHODOLOGY

Governing Equations

The steady-state, three-dimensional, incompressible fluid flow and conjugate heat transfer are governed by the following equations:

- **Continuity Equation:**

$$\nabla \cdot \mathbf{u} = 0$$

- **Momentum Conservation Equation:**

$$\rho_{nf}(\mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \mu_{nf} \nabla^2 \mathbf{u}$$

- **Energy Conservation Equation (Fluid Phase):**

$$\rho_{nf} C_{p,nf}(\mathbf{u} \cdot \nabla T) = k_{nf} \nabla^2 T$$

- **Energy Conservation Equation (Solid Substrate):**

$$k_s \nabla^2 T_s = 0$$

Where **u** is velocity, p is static pressure, T is temperature, and k_s is the thermal conductivity of the copper substrate (398 W/m · K).

Thermophysical Properties of Nanofluids

Effective density (ρ_{nf}) and specific heat capacity ($C_{p,nf}$) are calculated using fundamental mixture models:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p$$

$$C_{p,nf} = \frac{(1-\phi)\rho_f C_{p,f} + \phi\rho_p C_{p,p}}{\rho_{nf}}$$

Effective dynamic viscosity (μ_{nf}) and thermal conductivity (k_{nf}) for functionalized MWCNTs (15 nm average diameter, 10 μm length) are determined using empirical models:

$$\mu_{nf} = \mu_f(1 + 3.12\phi + 115.8\phi^2)$$

$$k_{nf} = k_f \left[\frac{1-\phi+2\phi\left(\frac{k_p}{k_p-k_f}\right)\ln\left(\frac{k_p+k_f}{2k_f}\right)}{1-\phi+2\phi\left(\frac{k_f}{k_p-k_f}\right)\ln\left(\frac{k_p+k_f}{2k_f}\right)} \right] + C_{bm}\phi\rho_f C_{p,f}\sqrt{\frac{k_B T}{3\pi\mu_f d_p}}$$

Where ϕ represents volume fraction, k_B is the Boltzmann constant (1.3806×10^{-23} J/K), and $d_p = 15$ nm.

Experimental Setup & Computational Domain

The heat sink consists of a copper substrate (25 mm × 25 mm × 3.0 mm) containing 28 parallel microchannels equipped with angled micro-baffles (channel width $W_c = 220\ \mu$m, height $H_c = 450\ \mu$m, baffle height $h_b = 60\ \mu$m, pitch $S_b = 800\ \mu$m). Applied base heat flux ($q'' = 100$--300 W/cm^2) is generated by embedded cartridge heaters. Calibrated K-type thermocouples and differential pressure transducers collect temperature and pressure parameters.

A structured hex-dominant computational grid ($\sim 3.4 \times 10^6$ elements) was generated with refined near-wall mesh layers ($y^+ < 1$). Boundary conditions specified a uniform inlet velocity (293.15 K),

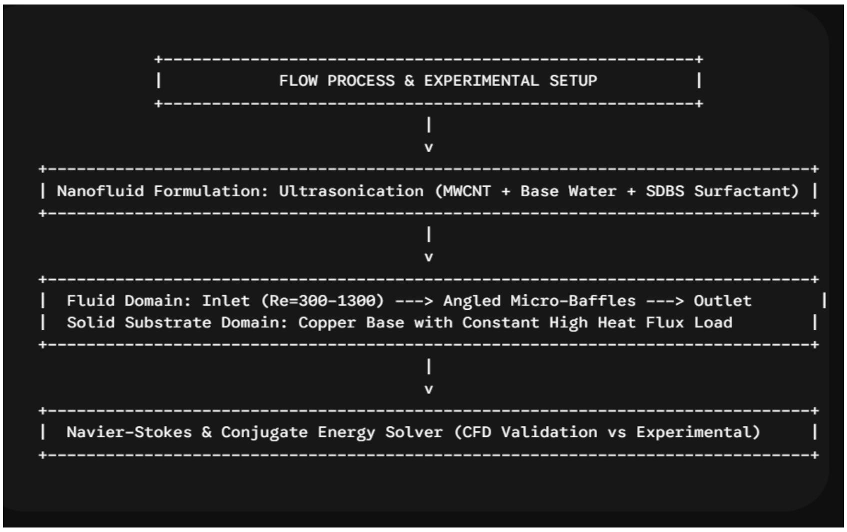

Figure 1: Schematic flow diagram of the experimental and numerical system for the micro-baffle microchannel heat sink

RESULTS AND FINDINGS

Hydrodynamic Performance & Pressure Drop

Angled micro-baffles disrupt main stream flow lines, generating local recirculation zones and shedding vortices. This flow structure increases convective mixing as well as overall friction factors and pressure drop (ΔP).

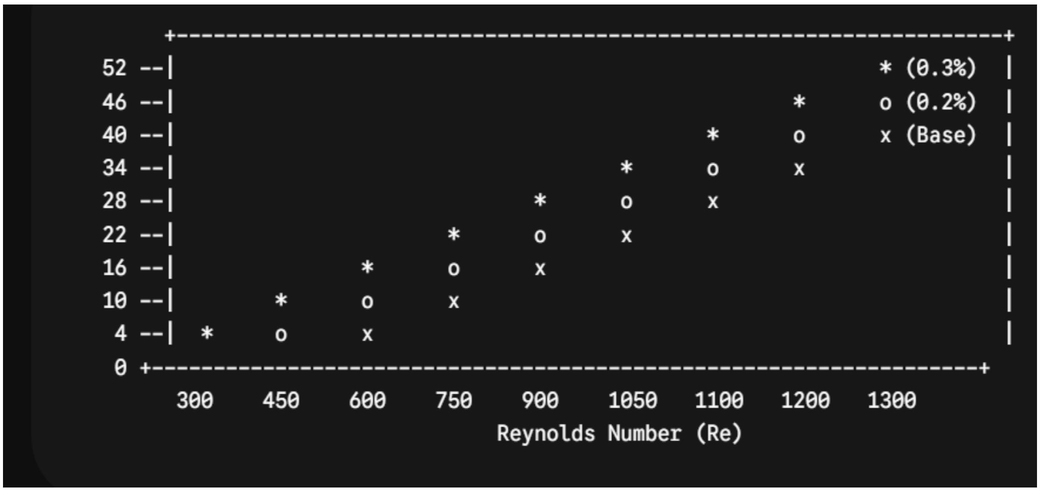

Figure 2: Pressure drop (ΔP in kPa) versus Reynolds number (Re) for pure water and varying concentrations (0.2 vol%, 0.3 vol%) of MWCNT nanofluids

As shown in Figure 2, at $Re = 1100$, the pressure drop for pure water in the MB-MCHS is 32.6 kPa, while 0.2 vol% and 0.3 vol% MWCNT nanofluids yield 37.9 kPa (16.2% increase) and 47.1 kPa (44.4% increase), respectively. The non-linear pressure drop increase at 0.3 vol% is attributed to particle-particle interaction shear stresses.

Thermal Resistance and Heat Transfer Enhancement

Total thermal resistance (R_{th}) is expressed as:

$$R_{th} = \frac{T_{max} - T_{in}}{Q}$$

Where T_{max} is peak substrate temperature, T_{in} is coolant inlet temperature, and Q is applied heat load.

Table 1 summarizes performance metrics across test configurations at heat flux $q'' = 200\ \mathrm{W/cm^2}$.

Table 1: Thermo-hydraulic performance metrics at $q'' = 200\ W/cm^2$ and $Re = 1100$

Heat Sink Configuration	Coolant Medium	ΔP (kPa)	Tmax (K)	Rth (K/W)	Average Nu	PEC Index
Smooth RMHS	Pure Water	20.2	349.15	0.280	13.8	1.00
Smooth RMHS	0.2 vol% Nanofluid	24.1	340.55	0.237	17.3	1.16
Micro-Baffle MB-MCHS	Pure Water	32.6	333.85	0.203	21.9	1.32
Micro-Baffle MB-MCHS	0.05 vol% Nanofluid	34.1	330.25	0.185	23.8	1.41
Micro-Baffle MB-MCHS	0.2 vol% Nanofluid	37.9	325.45	0.161	27.4	1.54

Heat Sink Configuration	Coolant Medium	ΔP (kPa)	Tmax (K)	Rth (K/W)	Average Nu	PEC Index
Micro-Baffle MB-MCHS	0.3 vol% Nanofluid	47.1	324.15	0.155	28.6	1.42

Performance Evaluation Criterion (PEC)

To weigh heat transfer gains against pumping power penalties, the PEC is defined as:

$$PEC = \frac{\left(\frac{\overline{Nu}_{nf}}{\overline{Nu}_f}\right)}{\left(\frac{f_{nf}}{f_f}\right)^{1/3}}$$

At $\phi = 0.2$ vol%, the peak PEC reaches 1.54 at $Re = 1100$. Increasing particle loading to $\phi = 0.3$ vol% yields a slight increase in Nusselt number ($\overline{Nu} = 28.6$), but increases friction factors, lowering overall PEC to 1.42. Thus, 0.2 vol% represents the optimal operational concentration.

DISCUSSION

The thermal performance gains in the micro-baffle microchannel operating with 0.2 vol% MWCNT nanofluid are driven by two main mechanisms:

- **Boundary Layer Interruption and Recirculation:** The angled micro-baffles periodically interrupt boundary layer growth, directing fluid toward the channel core and creating secondary recirculation zones. This increases fluid mixing and convective heat transfer rates.
- **High Aspect Ratio Nanoparticle Transport:** Elongated MWCNTs form conductive thermal pathways in the base liquid, augmenting effective thermal conductivity while enhancing localized energy transport during fluid shearing.

Substrate temperature gradients ($\Delta T_{sub} = T_{max} - T_{min}$) were reduced from 11.5 K in plain rectangular channels to 3.2 K in the MB-MCHS configuration with 0.2 vol% nanofluid. Minimizing substrate temperature variations lowers thermo-mechanical stresses, supporting long-term package reliability.

PRACTICAL APPLICATIONS

- **High-Power Semiconductor Inverters:** Cooling systems for high-voltage SiC and GaN modules in electric vehicle powertrains.
- **Military Radar & RF Amplifiers:** Direct-to-chip heat sinks for high-power Transmit/Receive (T/R) radar modules.
- **Concentrated Photovoltaics (CPV):** Thermal regulation for high-concentration solar cells operating under concentrated optical flux.

LIMITATIONS

- **Suspension Agglomeration:** High aspect ratio MWCNTs are susceptible to entangling and agglomeration under high shear stress and extended thermal cycling (> 550 hours).
- **Pumping Power Penalties:** Viscosity increases at concentrations above 0.2 vol% increase hydraulic pumping power requirements.
- **Erosion at Baffle Tips:** Particle impingement on micro-baffle leading edges can cause localized wear over extended operation.

FUTURE SCOPE

- **Covalent Surface Functionalization:** Testing chemical functionalization techniques (e.g., acid treatment or silanization) to improve suspension stability without surfactants.
- **Two-Phase Flow Boiling:** Investigating subcooled flow boiling regimes in micro-baffle geometries using carbon-based fluids to utilize latent heat transport.
- **Advanced Additive Manufacturing:** Utilizing high-precision 3D direct metal printing to fabricate streamlined baffle geometry profiles (e.g., teardrop or airfoil profiles) that minimize pressure drop penalties.

CONCLUSION

This study demonstrates the thermo-hydraulic advantages of combining micro-baffle channel geometries with functionalized MWCNT-water nanofluids. Key conclusions include:

- The micro-baffle heat sink with 0.2 vol% MWCNT nanofluid reduces total thermal resistance by 39.5% compared to smooth water-cooled microchannels.
- Average Nusselt numbers increase by up to 54.8% at $Re = 1100$, accompanied by a 16.2% pressure drop penalty.
- The maximum Performance Evaluation Criterion ($PEC = 1.54$) occurs at 0.2 vol%, establishing an optimal concentration threshold for compact cooling system design.

- Substrate surface temperature variation is reduced to 3.2 K, supporting uniform operational conditions under high thermal flux loads.

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