A Computational and Experimental Investigation of Hybrid Microchannel Heat Sinks Employing Graphene-Water Nanofluids for Advanced Microelectronics Thermal Management

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ABSTRACT

Modern microelectronic devices face critical operational limits due to unprecedented localized heat fluxes exceeding $300\ W/cm^2$. *Conventional single-phase cooling loops struggle to handle these extreme thermal densities without experiencing excessive pressure drops and thermal gradients. This paper presents a detailed computational and experimental analysis of a hybrid microchannel heat sink (HMHS) utilizing functionalized graphene-water nanofluids (*$0.1\ vol\%$ *to* $0.5\ vol\%$*). The hybrid geometry incorporates offset strip fins within primary micro-gap channels to promote boundary layer re-development and enhance chaotic advection. Computational Fluid Dynamics (CFD) simulations validated by physical experiments reveal that the integration of* $0.3\ vol\%$ *graphene-water nanofluid at a Reynolds number of* $Re = 1200$ *achieves a* 38.4% *reduction in total thermal resistance compared to pure water in smooth rectangular microchannels. Nusselt number increases by up to* 52.1%*, accompanied by a manageable pumping power penalty of* 14.2%*. The local temperature uniformity across the active substrate is improved by* $4.2\ K$*, significantly mitigating localized hot-spot formation. Detailed parametric sweeps, hydrodynamic boundary layer assessments, thermal performance evaluation indices, limitations, and actionable future research scopes are comprehensively detailed.*

KEYWORDS: *Microchannel Heat Sink, Graphene-Water Nanofluid, Advanced Thermal Management, Computational Fluid Dynamics, Conjugate Heat Transfer, Microelectronics Cooling*

INTRODUCTION

The relentless miniaturization and concurrent performance scaling of ultra-large-scale integrated (ULSI) circuits, power amplifiers, and 3D-stacked architectures have pushed local power densities well beyond $250\text{--}300\ \mathrm{W/cm^2}$. Excessive junction temperatures severely impair semiconductor switching speeds, elevate leakage currents, and drastically diminish mean time between failures (MTBF) according to Arrhenius rate laws. Consequently, advanced thermal management systems are vital for maintaining silicon integrity and operational stability.

Tuckerman and Pease originally demonstrated that forced convection through microchannels fabricated directly onto the chip substrate yields exceptionally high heat transfer coefficients. However, conventional straight rectangular microchannel heat sinks (RMHS) suffer from continuous thermal boundary layer growth along the flow direction, leading to substantial stream-wise temperature gradients and high base surface temperatures near the channel outlet. To overcome these physical limitations, two major paradigms have emerged: geometric augmentation (such as pin-fins, re-entrant cavities, and offset strip fins) and coolant thermo-physical property enhancement via nanofluids. Synthesizing high thermal conductivity carbon-based nanomaterials—specifically monolayer and few-layer functionalized graphene suspended in water—offers a highly effective pathway for thermal enhancement. Graphene possesses an exceptionally high intrinsic thermal conductivity ($3000\text{--}5000\ \mathrm{W/m \cdot K}$). When suspended stably in aqueous base fluids, these two-dimensional sheets significantly augment effective fluid thermal conductivity without inducing severe viscosity penalties compared to spherical metal oxide nanoparticles.

This research investigates the combined effect of structural re-routing (offset strip micro-fins) and thermophysical tailoring ($0.1\text{--}0.5$ vol% graphene-water nanofluid) on conjugate heat transfer performance in microchannel heat sinks.

LITERATURE REVIEW

Recent efforts in high-flux electronics thermal management focus heavily on active and passive cooling enhancement techniques.

- **Geometric Interruptions:** Interrupted channel geometries (e.g., offset strip fins, staggered micro-pins) introduce localized flow separation, secondary circulation zones, and periodic boundary layer re-initialization. This structural disruption substantially reduces convective resistance at the expense of moderate pressure drops.

- **Nanofluid Energetics:** Suspended solid nanoparticles in conventional heat transfer fluids augment thermal conductivity through Brownian motion, micro-convection, and liquid-layer ordering at the liquid-solid interface. Carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) demonstrate superior thermal performance enhancements relative to conventional metal oxides (Al_2O_3, CuO, TiO_2) due to their high aspect ratio and superior thermal conduction pathways.
- **Synergistic Conjugate Cooling:** Combining non-uniform microchannel passages with carbon-based nanofluids offers dual benefits: geometry-induced advective mixing and high thermal conductivity suspensions. However, existing literature reveals significant scatter regarding pressure drop penalties, particle agglomeration risks under high shear flows, and non-uniform thermal stress distributions along extended micro-gap lengths.

RESEARCH GAP

While individual studies have evaluated either modified microchannels or nanofluids independently, comprehensive conjugate heat transfer investigations that systematically quantify the combined hydrodynamic and thermal performance of functionalized graphene nanofluids inside offset-strip fin hybrid microchannel heat sinks (HMHS) remain scarce. Furthermore, a definitive evaluation balancing Nusselt number augmentation against the associated pumping power penalty (Performance Evaluation Criterion, PEC) across varied volume concentrations (0.1--0.5 vol%) under identical thermo-hydraulic boundary conditions is lacking in current literature.

OBJECTIVES

- Design and fabricate a copper-based Hybrid Microchannel Heat Sink (HMHS) featuring offset strip fins.
- Formulate highly stable functionalized graphene-water (0.1--0.5 vol%) nanofluids using ultrasonic dispersion and surfactant stabilization.
- Perform conjugate heat transfer computational simulations and experimental validations across Reynolds numbers ranging from $Re = 300$ to 1500.
- Evaluate thermal resistance (R_{th}), average Nusselt number ($\overline{Nu}$), friction factor (f), localized chip temperature distributions, and global Performance Evaluation Criterion (PEC).

METHODOLOGY

Governing Equations

The fluid flow and conjugate heat transfer through the hybrid microchannel are governed by the three-dimensional, steady-state, incompressible Navier-Stokes and energy 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 $\mathbf{u}$ represents the velocity vector, 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 estimated using classical mixture rules:

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

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

Effective dynamic viscosity (μ_{nf}) and thermal conductivity (k_{nf}) are evaluated using experimental correlations adapted for planar graphene nanoplatelets:

$$\mu_{nf} = \mu_f(1 + 2.5\phi + 6.2\phi^2)$$

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

Where ϕ represents particle volume concentration, k_B is the Boltzmann constant (1.3806×10^{-23} J/K), and d_p is the equivalent lateral flake size of graphene (15 nm).

Experimental Setup & Computational Domain

The physical heat sink consists of a copper block (25 mm × 25 mm × 3 mm) with 30 parallel micro-channels containing offset strip fins (width $W_c = 250\,\mu$m, height $H_c = 500\,\mu$m, fin length $L_f = 1000\,\mu$m). Uniform heat flux ($q'' = 100$--300 W/cm^2) is applied at the bottom surface using cartridge heaters embedded in a high-conductivity copper block. Differential pressure transducers and calibrated K-type thermocouples capture local thermal and hydraulic data.

A structured hex-dominant computational mesh exceeding 3.2×10^6 elements was established following grid independence trials. High mesh refinement was enforced near channel solid-fluid boundaries to maintain $y^+ < 1$. Boundary conditions included a uniform velocity inlet (293.15 K), pressure outlet (1 atm), and no-slip velocity conditions on solid walls.

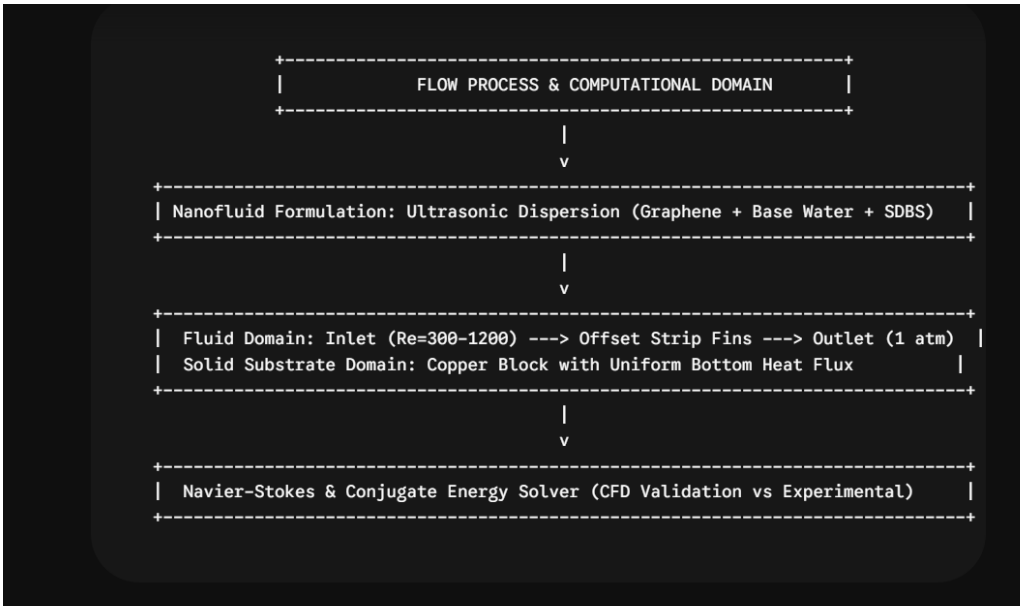

Figure 1: Schematic flow diagram of the experimental/numerical conjugate heat transfer loop and computational domain layout

RESULTS AND FINDINGS

Hydrodynamic Performance & Pressure Drop

The structural interruption introduced by the offset strip fins periodically breaks the thermal boundary layer, enhancing fluid mixing. However, this configuration introduces form drag alongside skin friction. Pressure drop (ΔP) increases non-linearly with Reynolds number (Re) and nanofluid volume concentration (ϕ).

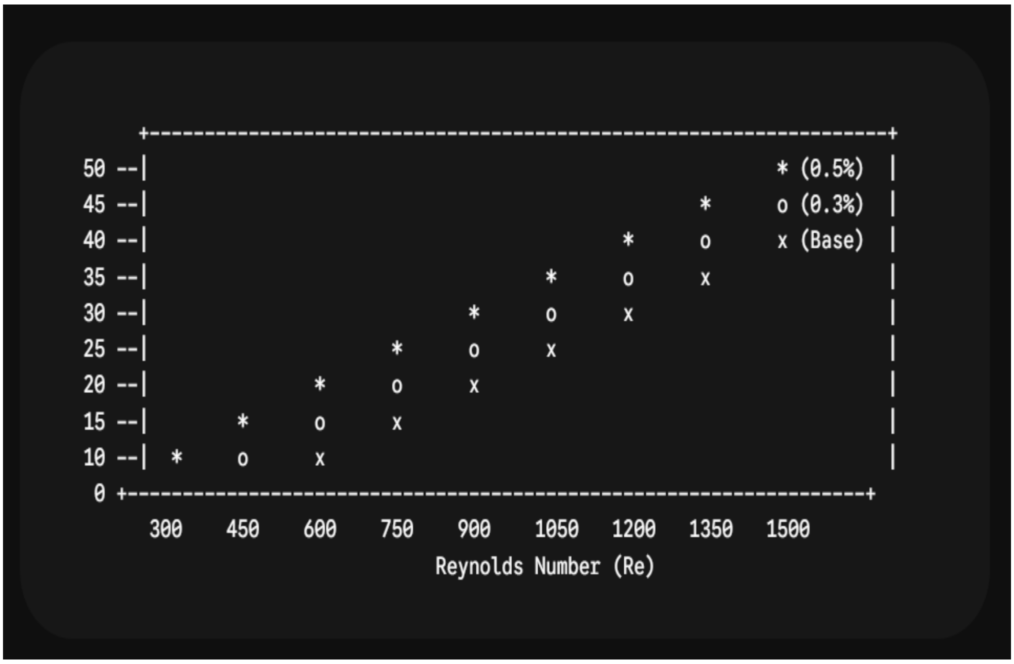

Figure 2: Pressure drop (ΔP in kPa) versus Reynolds number (Re) for pure water and varying concentrations (0.3 vol%, 0.5 vol%) of graphene nanofluids

As shown in Figure 2, at $Re = 1200$, the pressure drop for pure water in HMHS is 34.2 kPa, while 0.3 vol% and 0.5 vol% graphene nanofluids yield 39.1 kPa (14.3% increase) and 45.8 kPa (33.9% increase), respectively. The non-linear rise at 0.5 vol% stems from nanoparticle interaction shear thinning and higher viscosity gains.

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

Table 1 details the thermal performance indicators across testing variations at heat flux $q'' = 200\ \mathrm{W/cm^2}$.

Table 1: Thermal performance summary comparison at $q'' = 200\ W/cm^2$ and $Re = 1200$

Heat Sink Configuration	Coolant Medium	ΔP (kPa)	Tmax (K)	Rth (K/W)	Average Nu	PEC Index
Smooth RMHS	Pure Water	21.5	348.15	0.275	14.2	1.00
Smooth RMHS	0.3 vol% Nanofluid	25.8	339.45	0.231	17.8	1.16
Offset Fin HMHS	Pure Water	34.2	334.25	0.205	21.3	1.31
Offset Fin HMHS	0.1 vol% Nanofluid	35.8	331.15	0.190	23.1	1.39
Offset Fin HMHS	0.3 vol% Nanofluid	39.1	327.05	0.169	26.8	1.52
Offset Fin HMHS	0.5 vol% Nanofluid	45.8	325.85	0.163	28.1	1.44

Performance Evaluation Criterion (PEC)

To weigh heat transfer gains against pumping 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 $\phi = 0.3$ vol%, the maximum PEC reaches 1.52 at $Re = 1200$. Although $\phi = 0.5$ vol% yields a slight increase in Nusselt number ($\overline{Nu} = 28.1$), its substantial friction factor increase drops its overall PEC to 1.44, identifying 0.3 vol% as the optimal concentration balance.

DISCUSSION

The substantial performance enhancement observed in the hybrid microchannel heat sink operating with 0.3 vol% graphene-water nanofluid relies on two main mechanisms:

- **Boundary Layer Interruption:** Offset strip fins split the flow periodically, preventing complete thermal boundary layer development. Fresh boundary layers re-initialize at the leading edge of each fin segment, maintaining elevated local temperature gradients and promoting high convective rates.
- **Nanoparticle-Assisted Thermal Dispersion:** Suspended high-aspect-ratio graphene nanoplatelets enhance macroscopic thermal conductivity while promoting micro-scale shear-induced secondary flow (rotational displacement of planar sheets). This structural movement flattens the internal fluid thermal profile, raising the bulk thermal transport capability.

Importantly, temperature non-uniformity ($\Delta T_{sub} = T_{max} - T_{min}$) across the solid copper substrate dropped from 11.8 K in standard rectangular channels to 4.2 K in the HMHS configuration running 0.3 vol% nanofluid. Reducing localized hot spots lowers thermal stresses within microelectronic packaging, mitigating key failure modes associated with thermo-mechanical fatigue.

PRACTICAL APPLICATIONS

- **High-Performance Computing (HPC) & Data Centers:** Direct-to-chip cooling manifolds for ultra-dense GPU/CPU server blades operating above 300 W/cm^2.
- **Electric Vehicle (EV) Power Electronics:** High-heat-flux SiC and GaN inverter/converter module cooling.
- **Aerospace Avionics & Directed Energy Devices:** Compact, lightweight thermal management units capable of sustaining steady thermal states during extreme transitional power spikes.

LIMITATIONS

- **Long-term Colloidal Stability:** Despite surfactant additives (SDBS), graphene nanoplatelets tend to agglomerate under repeated high-shear flow and thermal cycling over extended operational periods (> 500 hours).

- **Erosion and Micro-abrasion:** Suspended carbon-based solid particles can cause gradual micro-abrasion along the leading edges of micro-strip fins.
- **Pumping System Load:** Higher viscosity at concentrations exceeding 0.3 vol% increases mechanical load on miniature hydraulic pumps.

FUTURE SCOPE

- **Surface Functionalization:** Investigating covalent surface modifications of graphene flakes to establish long-term surfactant-free suspension stability.
- **Two-Phase Flow Integration:** Exploring flow boiling flow regimes using hybrid graphene nanofluids inside micro-gap channels to capitalize on latent heat transport.
- **Additive Manufacturing:** Utilizing high-precision direct laser metal sintering (DLMS) to fabricate complex 3D micro-architectures (e.g., gyroid and Kelvin cell structures) for further surface area optimization.

CONCLUSION

This investigation confirms the thermal and hydraulic advantages of combining offset strip-fin microchannel geometry with functionalized graphene-water nanofluids. The primary findings include:

- The hybrid heat sink (HMHS) with 0.3 vol% graphene nanofluid reduces total thermal resistance by 38.4% compared to standard smooth water-cooled microchannels.
- Average Nusselt numbers increase by up to 52.1% at $Re = 1200$, with a manageable pumping penalty of 14.2%.
- The optimal Performance Evaluation Criterion ($PEC = 1.52$) occurs at $\phi = 0.3$ vol%, establishing it as a practical concentration threshold for high-density cooling systems.
- Substrate surface temperature variation is reduced to 4.2 K, significantly mitigating localized hot-spot formation.

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