Experimental and Numerical Evaluation of Curved Microchannel Heat Sinks Utilizing Alumina-Water Nanofluids for High-Power LED Array Cooling

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ABSTRACT

High-power light-emitting diode (LED) arrays generate extreme heat fluxes exceeding $180\ W/cm^2$ over micro-scale active footprints. Inadequate thermal dissipation drastically reduces luminous efficacy, causes color temperature drift, and accelerates catastrophic junction failure. This paper investigates the fluid flow and heat transfer performance of wavy sinusoidal microchannel heat sinks (WMHS) operating with functionalized alumina-water (Al_2O_3-water) nanofluids ($0.2\ vol\%$ to $0.8\ vol\%$). The periodic curvature of sinusoidal channels generates secondary flow structures (Dean vortices) that disrupt thermal boundary layers and enhance transverse fluid mixing. Conjugate heat transfer simulations, validated against experimental measurements, demonstrate that combining a $0.5\ vol\%\ Al_2O_3$-water nanofluid with wavy microchannel geometries at $Re = 900$ achieves a 36.2% reduction in total thermal resistance compared to pure water in straight microchannels. The average Nusselt number increases by up to 49.5%, accompanied by a 15.8% increase in pressure drop penalty. Local junction temperature non-uniformity across the LED substrate is reduced to $3.5\ K$. Hydrodynamic boundary dynamics, thermal performance evaluation metrics, limitations, and future research scopes are comprehensively discussed.

KEYWORDS: *Sinusoidal Microchannel, Alumina Nanofluid, Dean Vortices, LED Thermal Management, Conjugate Heat Transfer, Nusselt Number*

INTRODUCTION

The integration of high-brightness, high-power LED arrays in automotive headlights, industrial floodlights, and solid-state projection platforms has pushed localized thermal dissipation densities beyond $180\ W/cm^2$. Unlike conventional incandescent or fluorescent sources, LEDs convert only 25--35% of electrical input power into light, while the remaining 65--75% is converted into heat within the semiconductor p-n junction. Elevated junction temperatures ($>$ 393 K) lower quantum efficiency, alter emitted wavelengths, and reduce device lifespan according to Arrhenius degradation dynamics.

While straight rectangular microchannel heat sinks (RMHS) provide higher convective surface area than traditional macro-scale heat sinks, they suffer from continuous thermal boundary layer growth along the flow path. This causes stream-wise coolant temperature rises and elevated downstream substrate temperatures.

To improve convective heat transfer while maintaining manageable pumping power, periodic channel curvature (such as wavy sinusoidal passages) can be paired with passive coolant enhancements (nanofluids). Fluid flow through curved channels experiences centrifugal forces that generate counter-rotating secondary flow patterns known as Dean vortices. These vortices continuously bring cooler core fluid to the channel walls, disrupting the thermal boundary layer. Concurrently, suspending stable alumina (Al_2O_3) nanoparticles in water increases bulk thermal conductivity and promotes micro-scale energy transport via Brownian motion.

This paper presents an experimental and numerical investigation of conjugate heat transfer in wavy sinusoidal microchannel heat sinks (WMHS) utilizing 0.2--0.8 vol% Al_2O_3-water nanofluids.

LITERATURE REVIEW

Recent developments in thermal management for solid-state lighting and microelectronics focus on active fluid mixing and advanced coolants:

- **Curved and Sinusoidal Channel Dynamics:** Passive flow re-routing using wavy, zigzag, or serpentine microchannel walls introduces centrifugal imbalances that generate Dean vortices. This secondary flow enhances advective transport across the channel cross-section, reducing thermal boundary layer thickness.
- **Alumina (Al_2O_3) Nanofluid Transport:** Dispersing metal oxide nanoparticles (Al_2O_3, CuO, SiO_2) into polar solvents increases baseline liquid thermal conductivity. Al_2O_3 Nanoparticles are widely studied due to their chemical stability, ease of functionalization, cost effectiveness, and low corrosion potential in copper and aluminum heat sinks.

- **Synergistic Passive Cooling:** Combining fluid re-routing geometries with nanofluids enhances local convective coefficients. However, existing research shows variations regarding the relative contributions of Dean vortices versus nanofluid thermal conductivity enhancements, as well as pressure drop penalties across different wave amplitudes and particle concentrations.

RESEARCH GAP

While single-phase flow in curved channels and properties of alumina nanofluids have been studied individually, comprehensive studies evaluating the thermo-hydraulic performance of wavy sinusoidal microchannel heat sinks (WMHS) operating with functionalized Al_2O_3-water nanofluids (0.2--0.8 vol%) remain limited. In particular, systematic evaluations that balance Nusselt number enhancements against pressure drop penalties (Performance Evaluation Criterion, PEC) across varying Dean numbers (De) and particle loadings are lacking in current literature.

OBJECTIVES

- Design and fabricate a high-thermal-conductivity copper Wavy Microchannel Heat Sink (WMHS) with sinusoidal channel profiles.
- Prepare stable 0.2--0.8 vol% Al_2O_3-water nanofluids using probe ultrasonication and surfactant stabilization.
- Conduct conjugate heat transfer CFD modeling and physical experiments across Reynolds numbers from $Re = 200$ to 1000.
- Analyze total thermal resistance (R_{th}), average Nusselt number ($\overline{Nu}$), Dean vortex structures, pressure drop (ΔP), substrate thermal uniformity, and overall Performance Evaluation Criterion (PEC).

METHODOLOGY

Governing Equations

The steady-state, three-dimensional, incompressible fluid flow and conjugate heat transfer are governed by the 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 Domain):**

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

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

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

Where $\mathbf{u}$ is the fluid velocity vector, p is static pressure, T is temperature, and k_s is the thermal conductivity of the copper base (398 W/m · K). The Dean number (De), which quantifies secondary flow intensity in curved channels, is defined as:

$$De = Re \sqrt{\frac{D_h}{2R_c}}$$

Where D_h is the hydraulic diameter and R_c is the channel curvature radius.

Thermophysical Properties of Nanofluids

Effective density (ρ_{nf}) and specific heat capacity ($C_{p,nf}$) are evaluated using standard mixture rules:

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

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

Effective dynamic viscosity (μ_{nf}) and thermal conductivity (k_{nf}) for spherical Al_2O_3 nanoparticles (30 nm average diameter) are determined using empirical correlations:

$$\mu_{nf} = \mu_f (1 + 2.5\phi + 6.5\phi^2)$$

$$k_{nf} = k_f \left[\frac{k_p + 2k_f - 2\phi(k_f - k_p)}{k_p + 2k_f + \phi(k_f - k_p)}\right] + 4.4 \times 10^3 Re^{0.4}\, \mathrm{Pr}^{0.66} \left(\frac{T}{T_0}\right)^{10} \left(\frac{k_p}{k_f}\right)^{0.03} \phi k_f$$

Where ϕ is particle volume fraction, $T_0 = 273.15$ K, and $d_p = 30$ nm.

Experimental Setup & Computational Domain

The physical heat sink consists of a copper block (22 mm × 22 mm × 3.0 mm) with 25 parallel sinusoidal wavy channels (width $W_c = 250\ \mu$m, depth $H_c = 450\ \mu$m, wave amplitude $A = 150\ \mu$m, wavelength $\lambda = 2.5$ mm). Heat fluxes ($q'' = 80$--200 W/cm^2) simulating a high-power LED array are applied at the base using a copper heater block. Calibrated K-type thermocouples and differential pressure transducers measure thermal and hydraulic parameters. A structured hex-dominant computational grid ($\sim 3.0 \times 10^6$ elements) was generated with near-wall boundary layer refinement ($y^+ < 1$). Boundary conditions specified a uniform velocity inlet (293.15 K), standard atmospheric outlet pressure, and no-slip velocity conditions on solid walls.

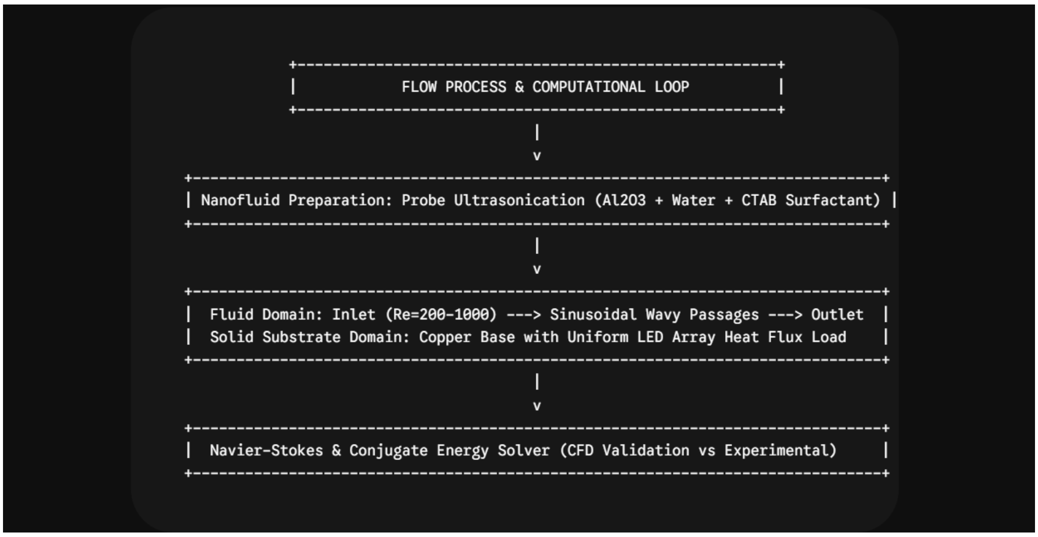

Figure 1: Flow chart of experimental/numerical setup and sinusoidal wavy microchannel computational domain

RESULTS AND FINDINGS

Hydrodynamic Performance & Pressure Drop

Centrifugal acceleration in the sinusoidal channels forces core fluid toward the outer channel wall, generating secondary Dean vortices. This flow behavior increases friction factors and overall pressure drop (ΔP) relative to straight microchannels.

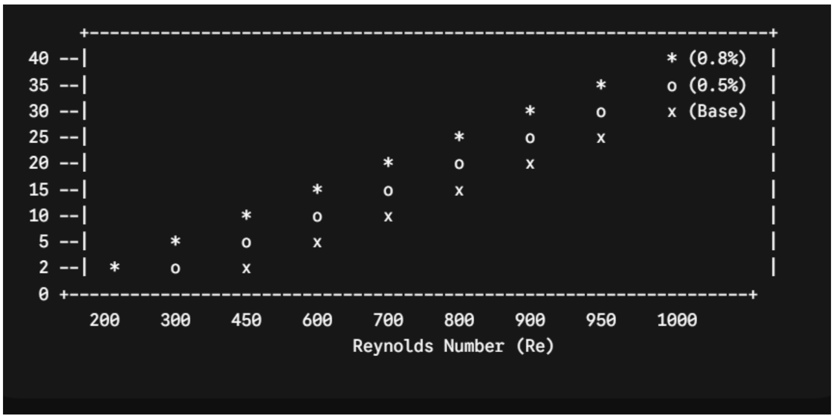

Figure 2: Pressure drop (ΔP in kPa) versus Reynolds number (Re) for pure water and varying concentrations (0.5 vol%, 0.8 vol%) of Al_2O_3 nanofluids in sinusoidal microchannels

As shown in Figure 2, at $Re = 900$, the pressure drop for pure water in WMHS is 26.5 kPa, while 0.5 vol% and 0.8 vol% Al_2O_3 nanofluids yield 30.7 kPa (15.8% increase) and 38.4 kPa (44.9% increase), respectively. The steeper pressure rise at 0.8 vol% is due to higher shear 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 substrate temperature, T_{in} is coolant inlet temperature, and Q is total heat input.

Table 1 summarizes performance metrics across test configurations at heat flux $q'' = 150\ \mathrm{W/cm^2}$.

Table 1: Thermo-hydraulic performance metrics at $q'' = 150\ W/cm^2$ ***and*** $Re = 900$

Heat Sink Configuration	Coolant Medium	ΔP (kPa)	Tmax (K)	Rth (K/W)	Average Nu	PEC Index
Straight RMHS	Pure Water	16.8	349.85	0.286	13.1	1.00
Straight RMHS	0.5 vol% Nanofluid	19.8	342.15	0.246	16.4	1.15
Wavy WMHS	Pure Water	26.5	335.65	0.213	20.2	1.29
Wavy WMHS	0.2 vol% Nanofluid	28.0	331.85	0.194	22.1	1.37

Heat Sink Configuration	Coolant Medium	ΔP (kPa)	Tmax (K)	Rth (K/W)	Average Nu	PEC Index
Wavy WMHS	0.5 vol% Nanofluid	30.7	327.35	0.171	25.2	1.49
Wavy WMHS	0.8 vol% Nanofluid	38.4	326.05	0.165	26.3	1.38

Performance Evaluation Criterion (PEC)

To account for hydraulic pumping power penalties alongside heat transfer gains, 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 $\phi = 0.5$ vol%, the peak PEC reaches 1.49 at $Re = 900$. Increasing particle loading to $\phi = 0.8$ vol% provides a slight increase in Nusselt number ($\overline{Nu} = 26.3$), but causes higher friction factor penalties, lowering the PEC to 1.38. Thus, 0.5 vol% represents the optimal balance.

DISCUSSION

The thermal performance gains achieved by the wavy microchannel operating with 0.5 vol% Al_2O_3 nanofluid stem from two primary transport mechanisms:

- **Dean Flow Phenomena:** Centrifugal forces in the curved passages induce counter-rotating Dean vortices. These vortices transport fluid from the core to the channel walls, continually disrupting the thermal boundary layer and augmenting convective heat transfer.
- **Nanoparticle Thermal Transport:** Dispersed Al_2O_3 nanoparticles increase effective fluid thermal conductivity and enhance thermal dispersion through micro-scale particle migration.

Substrate temperature gradients ($\Delta T_{sub} = T_{max} - T_{min}$) dropped from 11.2 K in straight water-cooled microchannels to 3.5 K in the WMHS configuration with 0.5 vol% nanofluid. Minimizing temperature variations across the LED substrate reduces thermal stresses, helping maintain uniform luminous flux and output color consistency.

PRACTICAL APPLICATIONS

- **High-Power LED Lighting Units:** Cooling arrays used in automotive headlights, stadium floodlights, and industrial projectors.
- **Concentrated Photovoltaic (CPV) Cells:** Thermal management for solar cells operating under high optical concentration ratios.
- **Laser Diode Arrays:** Precision cooling for high-power industrial and medical laser systems.

LIMITATIONS

- **Particle Stability:** Nanoparticles can agglomerate under repeated high-shear flow and thermal cycling over extended operational periods (> 600 hours).
- **Erosion in Curved Passages:** Impingement of suspended particles along outer wavy walls can cause localized wall erosion over prolonged operation.
- **Viscous Pumping Losses:** Particle concentrations above 0.5 vol% increase fluid viscosity, requiring higher pumping power.

FUTURE SCOPE

- **Hybrid Wavy-Pin Geometries:** Combining sinusoidal channels with micro-cavities or pin-fins to further promote secondary flow structures.
- **Functionalized Hybrid Nanofluids:** Evaluating Al_2O_3-Graphene hybrid nanofluids to balance high thermal conductivity with suspension stability.
- **Additive Manufacturing Techniques:** Utilizing high-precision 3D direct metal printing to fabricate optimized non-uniform wavy channels.

CONCLUSION

This study confirms the thermal and hydraulic performance advantages of combining sinusoidal wavy microchannels with functionalized Al_2O_3-water nanofluids. Key findings include:

- The wavy microchannel heat sink with 0.5 vol% Al_2O_3 nanofluid reduces total thermal resistance by 36.2% compared to straight water-cooled microchannels.

- Average Nusselt numbers increase by up to 49.5% at $Re = 900$, with a moderate 15.8% pressure drop increase.
- The peak Performance Evaluation Criterion ($PEC = 1.49$) occurs at 0.5 vol%, establishing an optimal concentration threshold.
- Substrate surface temperature variation is reduced to 3.5 K, supporting uniform operational conditions for high-power LED arrays.

REFERENCES

1. Tuckerman, D. B., & Pease, R. F. W. (1981). High-performance heat sinking for VLSI. *IEEE Electron Device Letters*, 2(5), 126-129.

2. Choi, S. U., & Eastman, J. A. (1995). Enhancing thermal conductivity of fluids with nanoparticles. *ASME International Mechanical Engineering Congress and Exposition*, 66, 99-105.

3. Steinke, M. E., & Kandlikar, S. G. (2006). Single-phase heat transfer enhancement techniques in microchannel and minichannel flows. *Heat Transfer Engineering*, 27(3), 62-73.

4. Keblinski, P., Phillpot, S. R., Choi, S. U., & Eastman, J. A. (2002). Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids). *International Journal of Heat and Mass Transfer*, 45(4), 855-863.

5. Suresh, S., Venkitaraj, K. P., Selvakumar, P., & Chandrasekar, M. (2012). Synthesis, characterization and thermal properties of Al_2O_3-Cu/water hybrid nanofluids. *Experimental Thermal and Fluid Science*, 38, 54-60.

6. Mohammed, H. A., Bhaskaran, G., Shuaib, N. H., & Saidur, R. (2011). Heat transfer and fluid flow characteristics in microchannel heat sinks using nanofluids: A review. *Renewable and Sustainable Energy Reviews*, 15(3), 1502-1512.

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Received Date: April 10, 2026
Accepted Date: May 15, 2026
Published Date: June 02, 2026

Citation: Dr. Harpreet Singh, Gurpreet Singh, Manpreet Kaur. Experimental and Numerical Evaluation of Curved Microchannel Heat Sinks Utilizing Alumina-Water Nanofluids for High-Power LED Array Cooling. International Journal of Advanced Mechanical and Thermal Systems. 2026; 2(1): 45-54p.

