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Non-Toxic, Non- Aqueous GNP+SiC/PG Hybrid Nanofluid for High-Temperature Oblique Microchannel Cooling: A CFD Based Parametric Study

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Abstract

Effective thermal management in miniaturized electronics necessitates advanced coolants. This computational study systematically evaluates the thermo-hydraulic characteristics of a Graphene Nanoplatelet-Silicon Carbide (GNP+SiC) hybrid nanofluid dispersed in propylene glycol (PG), a less-toxic base fluid with potential for high-temperature applications. The investigation focuses on fluid flow within a microchannel incorporating triangular oblique elements designed for enhanced convective heat transfer. A validated Computational Fluid Dynamics (CFD) model was employed to analyze the impacts of total nanoparticle concentration (0-1.5 vol%, 1:1 GNP:SiC ratio), GNP:SiC mixing proportions (at 1.0 vol% total), Silicon Carbide (SiC) nanoparticle diameter (spherical, 10-90 nm), and SiC particle morphology (aspect ratio variations) on friction factor, Nusselt number (Nu), and Thermal Performance Factor (TPF) across flow rates of 1–5 l/min. Key findings indicate that increased total nanoparticle loading augmented both heat transfer (Nu up to ~104%) and frictional losses (up to ~11%), yet yielded substantial TPF improvements (up to 97%). Higher GNP content amplified thermal enhancement (Nu up to ~99%) but also increased friction, whereas greater SiC proportions mitigated frictional penalties. Smaller spherical SiC particles and higher aspect ratio SiC particles both led to increased Nu (up to ~86% and ~92.55% enhancement, respectively), though the latter also incurred higher friction (up to ~8.26% increase). This research offers novel insights into tailoring GNP+SiC/PG hybrid nanofluid properties, providing critical data for optimizing thermal performance against hydrodynamic constraints in specialized cooling applications.

Keywords: Advanced Cooling, Oblique Microchannel, CFD, GNP+SiC/PG, Non-Aqueous Hybrid Nanofluid.

Introduction

The escalating thermal management demands in miniaturized and high-performance technological systems, encompassing microelectronics, compact heat exchangers, and advanced automotive applications, necessitate the development of superior cooling solutions (1, 2). Conventional heat transfer fluids like PG, despite its advantageous low-temperature properties and non-toxicity, exhibit inherently low thermal conductivities (3). This characteristic fundamentally limits their efficacy in dissipating high heat fluxes within space-constrained devices, thereby impacting overall system performance and reliability (4). Consequently, considerable research has focused on innovative heat transfer media, with nanofluids emerging as a particularly promising avenue (5). Nanofluids, engineered colloidal suspensions of nanometer-sized particles (typically <100 nm) in a base fluid, have demonstrated the capacity to significantly augment the effective thermal conductivity and convective heat transfer capabilities of the host fluid, even at modest particle concentrations (6).Initial research in this domain predominantly explored mono-nanofluids, utilizing single nanoparticle types, often metal oxides such as alumina (Al_2O_3) or copper oxide (CuO) (7). Even recent studies continue to refine our understanding of these systems, for example, by optimizing the stability and thermo-hydraulic performance of Al_2O_3/PG nanofluids in micro-scale confinements (8). However, single-nanoparticle systems frequently present a complex trade-off: achieving desired thermal enhancements often comes at the cost of increased fluid viscosity, potential for abrasion, and challenges in maintaining long-term colloidal stability, particularly at higher nanoparticle loading (9). To overcome these limitations and

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further exploit the benefits of nanoscale thermal transport, the concept of hybrid nanofluids has gained substantial traction (10). Hybrid nanofluids involve the dispersion of two or more distinct nanoparticle types within a base fluid, aiming to synergize their unique attributes. This approach seeks superior overall thermal performance, enhanced stability, and a more favorable balance between heat transfer augmentation and pumping power penalties compared to mono-nanofluids (11). Contemporary research has often focused on oxide-oxide hybrid systems. For instance, Al_2O_3-CuO/water hybrid nanofluids have been reported to offer improved thermal conductivity and convective heat transfer over their single-component counterparts (12). The experimental work by Vinoth and Sachuthananthan, characterizing Al_2O_3/water and Al_2O_3-CuO/water hybrid nanofluids in microchannels, provides crucial data for validating numerical models (13).

Despite advancements with oxide-based systems, a compelling scientific motivation exists to explore non-oxide nanomaterials with intrinsically superior thermophysical properties. Graphene nanoplatelets (GNPs) are particularly attractive due to their exceptionally high intrinsic thermal conductivity (potentially >3000 W/mK), large specific surface area, and low density (14). While GNP-based nanofluids show remarkable heat transfer enhancement, achieving stable dispersion, especially in non-aqueous base fluids like PG, remains a key research challenge (15). Silicon carbide (SiC), another promising non-oxide material, is noted for its high thermal conductivity (120-270 W/mK) and excellent thermal and chemical stability (16). The strategic hybridization of GNPs with SiC nanoparticles thus offers a novel approach. From the point of view of high thermal performance and stability, GNP+SiC hybrid nanofluids are hypothesized to be better than existing oxides nanoparticles commonly used. This proposition stems from the potential for GNPs to form efficient heat conduction pathways, while SiC nanoparticles could act as stabilizing agents, mitigating GNP agglomeration and contributing their own thermal conductivity (17). The choice of PG as the base fluid is pertinent for applications demanding low toxicity and good low-temperature performance. However, systematic investigations of GNP+SiC/PG hybrid nanofluids in advanced microchannel geometries are notably scarce.

The effective application of such nanofluids in microchannel heat sinks is critical for managing thermal loads in compact electronic and mechanical systems (18). While microchannels offer a high surface-area-to-volume ratio, the confined flow can lead to significant pressure drops, necessitating evaluation of the friction factor and the overall TPF (19). Microchannel geometry significantly influences performance. Recent research has explored passive enhancement techniques, such as incorporating features to induce secondary flows (20). In this research work, the GNP+SiC/PG hybrid nanofluid is investigated within a microchannel featuring triangular oblique channels. This specific geometry, designed to generate swirling flow and augment convective heat transfer, has not been extensively studied with advanced non-oxide hybrid nanofluids, presenting a distinct area for novel inquiry.

A thorough understanding of parametric influences on hybrid nanofluid performance is essential. Key parameters include total nanoparticle concentration, mixing ratio, and nanoparticle morphology (size and shape) (10). These factors significantly impact thermal conductivity, viscosity, and stability (9, 11). While some studies address these for certain hybrid systems, systematic investigations for GNP+SiC/PG, particularly concerning the distinct effects of component size and shape on thermo-hydraulic performance in specialized microchannels, are limited (12).

This literature review reveals specific research gaps, primarily which advanced non-oxide hybrid systems like GNP+SiC in PG are underexplored compared to oxide-based nanofluids. Furthermore, systematic data regarding how GNP and SiC nanoparticle mixing ratios, overall concentration, and their individual sizes and shapes influence the thermo-hydraulics of the mixture are lacking. Moreover, the performance of such advanced hybrid nanofluids in complex microchannel geometries, specifically those featuring triangular oblique channels, is not well-documented. Consequently, a significant need exists for research capable of providing guidelines for tailoring nanofluid properties to meet specific performance targets.

The present numerical investigation aims to address these gaps by analyzing the thermo-hydraulic performance of GNP+SiC/PG hybrid nanofluids in a microchannel with triangular oblique elements. The novelty of this research is threefold. Firstly, it systematically examines the GNP+SiC/PG hybrid nanofluid, aiming to establish its performance credentials. Secondly, it evaluates this nanofluid within a microchannel featuring triangular oblique channels. Thirdly, and most critically, the results of this research work are anticipated to be helpful for customizing properties based on particle structure and size for desired performance required in terms of stability, thermal performance, and pumping power requirement. This is achieved through a rigorous parametric study varying flow rates (1-5 l/min), overall nanoparticle concentration, GNP+SiC mixing ratio, and the size/shape attributes of SiC nanoparticles, elucidating their effects on friction factor, Nu, and TPF.

A CFD methodology, via COMSOL Multiphysics®, is employed. The model is first validated against experimental data from Vinoth and Sachuthananthan (13). Subsequently, the GNP+SiC/PG system is simulated in the specialized microchannel. Preliminary results suggest superior thermal performance for the GNP+SiC/PG hybrid nanofluid compared to typical oxide-based systems. Nanoparticle concentration, mixing ratios, and morphology significantly influence heat transfer and friction. These findings indicate a strong potential for optimizing the TPF by careful parameter selection, offering pathways to tailored thermal solutions for microprocessors, compact heat exchangers, and battery thermal management.

The primary objective is to analyze the high-temperature thermo-hydraulic performance of the hybrid nanofluid compared to the base fluid, while optimizing the mixing ratios within the oblique microchannel geometry.

Methodology

This investigation numerically explores the thermo-hydraulic characteristics of a GNP+SiC hybrid nanofluid dispersed in PG, flowing within a microchannel featuring triangular oblique elements. The methodology encompasses geometric modeling, the governing mathematical framework, the numerical solution strategy including determination of effective nanofluid properties, boundary condition definitions, and rigorous validation, followed by a planned parametric analysis.

Computational Domain and Governing Physics

The microchannel geometry, designed to enhance convective heat transfer through induced fluid mixing, is based on the dimensional principles of the experimental setup by Vinoth and Sachuthananthan, facilitating subsequent model validation (13). A 1:5 scaled-down model was adopted for computational efficiency, with detailed specifications of the channel and its integrated triangular oblique elements provided in Table 1.

Table 1: Triangular microchannel geometry specification

Parameters	Triangular Microchannel Measurement
Fin width (mm)	0.900
Fin depth (mm)	0.900
Fin length (mm)	0.950
Fin pitch (mm)	0.800
Oblique angle (deg)	26

The three-dimensional computational domain, illustrated in Figure 1 (A), includes both the fluid pathway and the surrounding solid substrate (Copper), enabling the analysis of conjugate heat transfer. Geometry specification parameters are shown in Figure 1(C).

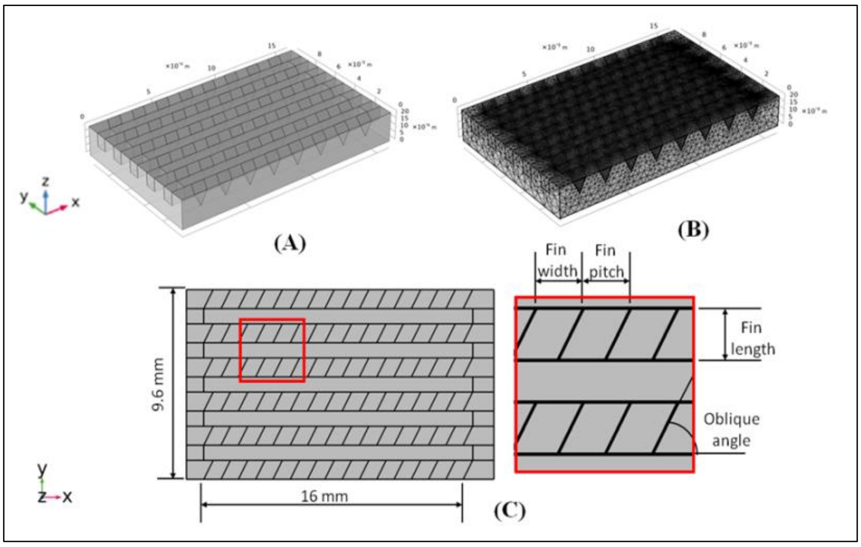

Figure 1: (A) 3D Representation of the Microchannel with Triangular Oblique Sections, (B) Meshing detail showing fluid and solid domains with Refined Elements near Walls and Oblique Features, (C) Microchannel Geometry Specification

The fluid flow and heat transfer are governed by the steady-state, laminar, incompressible Navier-Stokes and energy equations. The GNP+SiC/PG hybrid nanofluid is treated as a homogeneous, Newtonian, single-phase fluid with effective thermophysical properties.

The governing equations are shown in equations [1-4].

Continuity Equation:

$$\nabla . u = 0 \quad [1]$$

Momentum Equation (Navier-Stokes):

$$\rho_{nf}(u.\nabla)u = -\nabla p + \mu_{nf}\nabla^2 u \quad [2]$$

Energy Equation (Fluid Domain):

$$\rho_{nf}c_{nf}(u.\nabla)T_f = k_{nf}\nabla^2 T_f \quad [3]$$

Energy Equation (Solid Domain):

$$k_s\nabla^2 T_s = 0 \quad [4]$$

Where **u** is the velocity vector, p is the pressure, T is the temperature, ρ is the density, μ is the dynamic viscosity, c_p is the specific heat capacity at constant pressure, and k is the thermal conductivity. The subscripts 'nf', 'f', and 's' denote nanofluid, fluid, and solid, respectively. The single-phase assumption is justified for the dispersed GNP+SiC hybrid nanofluid as the particle volume concentration is dilute (ϕ<1.5%) and the particle size is ultrafine (<100 nm), ensuring negligible slip velocity between the particles and the base fluid, consistent with methodologies established in literature (12, 19).

Hybrid Nanofluid Properties and Boundary Conditions

Effective thermophysical properties for the GNP+SiC/PG hybrid nanofluid, as well as for the Al_2O_3/water and Al_2O_3+CuO/water nanofluids used in validation, were determined using established models. Density (ρ_{nf}) and specific heat capacity ($c_{p,nf}$) were calculated via the mixture rule based on total ($\varphi_{total} = \varphi_{np1} + \varphi_{np2}$) and individual nanoparticle volume fractions. The effective density (ρ_{nf}) and specific heat capacity ($c_{p,nf}$) are calculated using the mixture rule shown in equation [5] and [6].

$$\rho_{nf} = (1-\varphi_{total})\rho_{bf} + \varphi_{np1}\rho_{np1} + \varphi_{np2}\rho_{np2} \quad [5]$$

$$(\rho c_p)_{nf} = (1-\varphi_{total})(\rho c_p)_{bf} + \varphi_{np1}(\rho c_p)_{np1} + \varphi_{np2}(\rho c_p)_{np2} \quad [6]$$

Effective dynamic viscosity ((μ_{nf}) incorporated particle shape effects, potentially using a modified Krieger-Dougherty type model for the GNP (platelets) and SiC (spheres) mixture, or a simpler Brinkman model for spherical approximations as shown in equation [7a] (21, 22):

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\varphi_{total})^{2.5}} \quad [7a]$$

$$\mu_{nf} = \mu_{bf}(1-\frac{\varphi_{np1}}{\varphi_{max}})^{-n_{np1}}(1-\frac{\varphi_{np2}}{\varphi_{max}})^{-n_{np2}} \quad [7b]$$

Considering the effect of the nanoparticle shape effective viscosity is calculated based on the Krieger-Dougherty modified equation model for hybrid nanofluid shown in correlation [7b] (21). Where, n_{np1} and n_{np2} are shape factors defined as $n = \frac{3}{\psi}$, for each nanoparticle shape and ψ is sphericity of the nanoparticle shape defined as ratio of surface area of sphere of same volume with actual surface area of the particles. For spherical nanoparticles $\psi = 1$ and$n = 3$. φ_{max} in the correlation indicates the maximum packing fraction of the nanoparticles. Typical values of the n and φ_{max} for GNP and SiC nanoparticles are shown in **Table 2** (23, 24). For GNP, a platelet structure with a lateral dimension to thickness aspect ratio ($AR_{L/T}$) is assumed. For SiC, spherical, ellipsoidal, and rod-like (cylindrical) shapes with varying length-to-diameter aspect ratios ($AR_{L/D}$) are considered. Sphericity, a measure of how closely a particle resembles a sphere, is calculated based on geometric considerations; for instance, for a prolate spheroid (ellipsoid) with $AR_{L/D} = 2$, $\psi \approx 0.90$, yielding $n \approx 3.3$. For cylindrical rods, ψ decreases with increasing $AR_{L/D}$. The maximum packing fraction, φ_{max}, generally decreases for non-spherical particles due to steric hindrance and orientation effects (25). These parameters are crucial inputs for the effective property models (Equations [7b] and [8]) used to predict the hybrid nanofluid's behavior.

Table 2: Typical Values of Shape Parameters of Nanoparticles

Material	Shape	Aspect Ratio (AR)	Sphericity (ψ)	Shape Factor (n)	Maximum Packing Factor (φ_{max})
GNP	Platelets	1:10	0.50	6.00	0.150
SiC	Spherical	1:1	1.00	3.00	0.630
SiC	Ellipsoidal	2:1	0.90	3.30	0.550
SiC	Rod-like	5:1	0.76	3.90	0.400
SiC	Long rods	10:1	0.60	5.00	0.300
SiC	High-aspect nanorods	20:1	0.48	6.25	0.225
SiC	Nanowires	50:1	0.35	8.60	0.175
SiC	Nanotubes	100:1	0.28	10.70	0.125
SiC	Platelets (thin)	1:5	0.80	4.00	0.250
SiC	Thin platelets	1:10	0.50	6.00	0.150

Effective thermal conductivity (k_{nf}) was estimated using the Hamilton-Crosser model for shape-dependent studies, with an effective particle conductivity ($k_{p,eff}$) and shape factor (n_{eff}) for the hybrid mixture. For size-dependent analyses (assuming spherical particles), the Koo-Kleinstreuer-Li (KKL) model, incorporating Brownian motion, was utilized (26, 27).

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{p,eff}+(n_{eff}-1)k_{bf}-(n_{eff}-1)\varphi_{total}(k_{bf}-k_{p,eff})}{k_{p,eff}+(n_{eff}-1)k_{bf}+\varphi_{total}(k_{bf}-k_{p,eff})} \quad [8]$$

Where $k_{p,eff} = \frac{\varphi_{np1}k_{np1}+\varphi_{np2}k_{np2}}{\varphi_{total}}$ represents an effective particle conductivity for the hybrid mixture, and effective shape factor $n_{eff} = \frac{\varphi_{np1}n_{np1}+\varphi_{np2}n_{np2}}{\varphi_{total}}$. For size-dependent studies, we have used KKL model, which incorporates the effect of Brownian motion, particularly for thermal conductivity shown in the equation [9] (27). Particles of spherical shaped only has been considered for the study of size effect.

$$k_{nf} = k_{static} + k_{Brownian} \quad [9a]$$

$$k_{Brownian} = 5 \times 10^4 \beta(\rho_{np1}c_{p,np1}\sqrt{\frac{k_BT}{\mu_{bf}d_{np1}}} + \rho_{np2}c_{p,np2}\sqrt{\frac{k_BT}{\mu_{bf}d_{np2}}}) \quad [9b]$$

Where k_{static} is calculated based on Maxwell model from equation [8] with n=3. In the equation [9b], β is an empirical constant, k_B is Boltzmann constant, T is temperature (K), d_{np} is diameter of nanoparticle. Thermophysical properties for PG, GNP, SiC, Al_2O_3, and CuO were sourced from reliable literature and databases listed in **Table 3** (28, 29).

Table 3: Bulk Properties of Base Fluid and Nanoparticles

Material	Density(ρ) (kg/m³)	Viscosity (μ) (Ns/m²)	Thermal conductivity (k) (W/m K)	Specific heat (c_p) (J/kg K)
Water	995.1	0.000855	0.62	4178
PG	1035	0.04	0.2	2450
Al_2O_3	3600	-	36	769
CuO	6500	-	18	540
GNP	2200	-	2000	710
SiC	3100	-	150	700

Boundary conditions included a uniform inlet velocity (1-5 L/min, scaled) and temperature (T_{in} = 298.15 K), a zero-gauge pressure outlet, a constant heat flux (q'' = 50 kW/m^2) on the bottom solid wall, adiabatic conditions on other external solid walls, and no-slip with thermal coupling at fluid-solid interfaces.

Numerical Scheme, Grid Independence, and Validation

The governing equations were solved using the Finite Element Method (FEM) in COMSOL Multiphysics®5.5. Laminar flow and conjugate heat transfer physics were coupled. An unstructured tetrahedral mesh, refined near walls and oblique elements (Figure 1(B)], employed second-order Lagrange elements for velocity and temperature, and linear elements for pressure. A segregated solver with appropriate stabilization techniques achieved convergence when scaled residuals dropped below 10^{-6} and global parameters stabilized.

A grid independence study, varying element counts and monitoring average Nu and pressure drop (ΔP) for a representative Al_2O_3+CuO/H_2O case, ensured results were mesh-independent (variation < 1%). The selected mesh 508170 elements balanced accuracy and computational cost (Table 4).

Table 4: Grid Independence Test Result

Total number of elements	Pressure drop (kPa)	% Change in pressure drop	Nu	% Change in Nu
66271	3.425	-	6.87	-
121303	3.694	7.85	7.28	5.97
230356	3.781	2.36	7.361	1.11
508170	3.828	1.24	7.425	0.87
976886	3.839	**0.29**	7.434	**0.12**

Model validation was performed against experimental data from Vinoth and Sachuthananthan for Al_2O_3/water and Al_2O_3+CuO/water nanofluids, replicating their scaled geometry and conditions (13). Simulated pressure drop (Figure 2(A)) and Nu (Figure 2(B)) showed strong agreement with experimental values, instilling confidence in the model for the GNP+SiC/PG study.

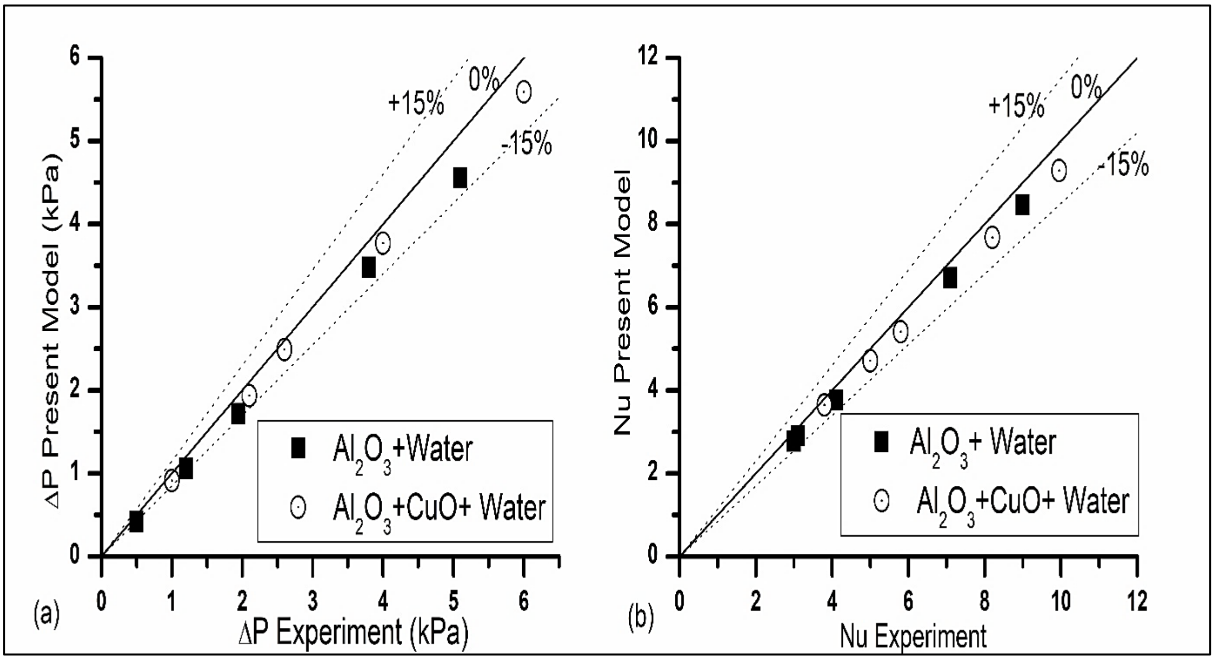

Figure 2: Comparison of Simulated vs. Experimental (13) (**A**) ΔP (**B**) Nu

Parametric Investigation

Following validation, the thermo-hydraulic performance of GNP+SiC/PG hybrid nanofluid was systematically investigated. The study analyzed the effects of:

- **Total Nanoparticle Concentration (φ_{total}):** Varied from 0% (pure PG) to 1.5%, at a fixed GNP: SiC mixing ratio (1:1), across flow rates (1-5 l/min).
- **Nanoparticle Mixing Ratio (GNP: SiC):** Varied (100:0 to 0:100) at a fixed total concentration (1.0%), across all flow rates.
- **Nanoparticle Size (d_{np}):** Spherical SiC particle diameter was varied from 10 nm to 90 nm, at selected total concentrations /mixing ratios at a representative flow rate of 3 l/min, keeping GNP characteristics constant.
- **Nanoparticle Structure (Shape):** The aspect ratio of SiC nanoparticles was varied (representing different shapes like ellipsoid, nanorods, platelets, as detailed in **Table 2**), at total concentration of 1% and mixing ratio 1:1 and a representative flow rate of 3 l/min, keeping GNP characteristics constant (as platelets).

Performance was evaluated in terms of friction factor (f), average Nu, and TPF. TPF is defined in equation [10].

$$TPF = \frac{Nu_{nf}/Nu_{bf}}{(f_{nf}/f_{bf})^{1/3}} \qquad [10]$$

Results and Discussion

This section presents and critically analyzes the numerical findings from the investigation into the thermo-hydraulic performance of GNP+SiC/PG hybrid nanofluids within a microchannel featuring triangular oblique elements. The discussion integrates these results with established physical principles and relevant literature to elucidate the observed trends and their implications. The model, having been rigorously validated against experimental data from Vinoth and Sachuthananthan, provides a reliable framework for the subsequent parametric explorations (13). The Thermal Performance Factor (TPF) serves as the normalized engineering metric to evaluate the compromise between thermal enhancement and hydraulic penalty.

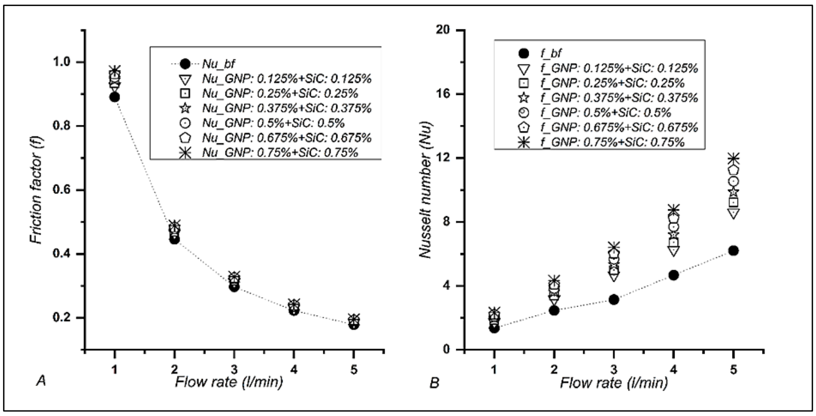

Figure 3: Effect of total Concentration of Nanoparticles on (A) f, (B) Nu

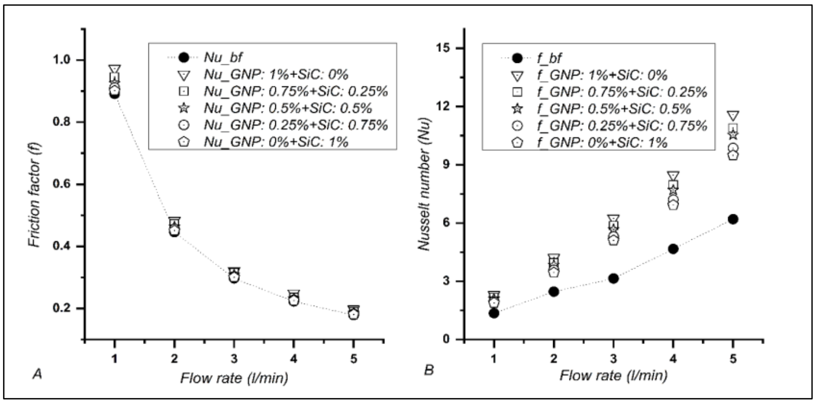

Figure 4: Effect of Mixing Ratio of GNP and SiC on (A) f, (B) Nu

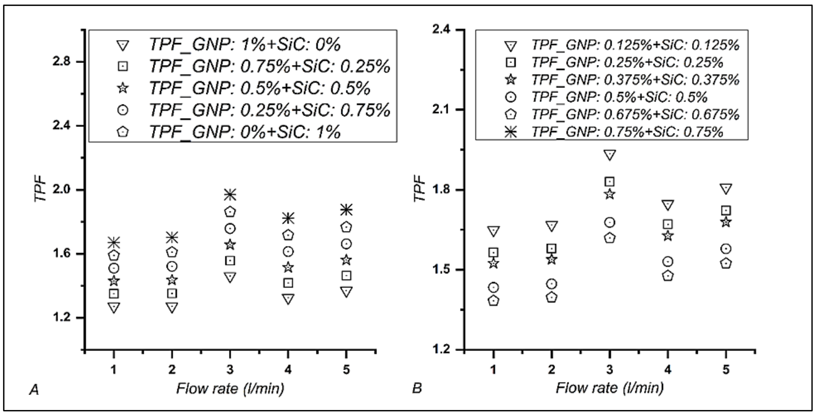

Figure 5: Variation of TPF at (A) Constant Mixing Ratio but Varying Total Concentration, (B) Fixed Total Concentration but Varying Mixing Ratio

Effect of Total Nanoparticle Concentration

The influence of the total volumetric concentration (φ_{total}) of GNP+SiC nanoparticles on the friction factor (f), average Nu, and TPF was investigated, maintaining a constant 1:1 mixing ratio of GNP to SiC. Figure 3 illustrates the variation of these parameters with φ_{total} across the studied range of flow rates (1-5 l/min). As depicted in Figure 3(A) and (B), both the friction factor and the Nu exhibit a discernible increasing trend with an augmentation in the total nanoparticle concentration. The rise in friction factor of around 5.36-10.71 % can be primarily attributed to the increased effective viscosity of the hybrid nanofluid at higher particle loadings (9, 30). The presence of more nanoparticles enhances internal shear resistance within the fluid, leading to greater pressure drop for a given flow rate. Concurrently, the observed increase of around 48.65-103.74 % in Nu with φ_{total} is a direct consequence of the enhanced effective thermal conductivity of the hybrid nanofluid (11). A higher concentration of highly conductive GNP and SiC particles provides more pathways for heat conduction and potentially intensifies particle-fluid interactions that disrupt the thermal boundary layer, thereby improving heat transfer.

Encouragingly, the TPF, which provides a balanced assessment of thermal enhancement against hydrodynamic penalty, also demonstrates an increasing (46.11-96.95 %) trend with total nanoparticle concentration in the full spectrum of tested range (Figure 5(A)). This suggests that, for the 1:1 GNP:SiC ratio, the benefits of enhanced heat transfer (Nu increase) initially outweigh the detrimental effects of increased friction (f increase). This observation is consistent with findings for other hybrid nanofluid systems where an optimal concentration often exists beyond which the viscosity penalty becomes too dominant (12, 31). The synergistic effect of combining high-conductivity GNP with the stabilizing and also conductive SiC appears to contribute positively to the TPF at these concentrations.

Effect of Nanoparticle Mixing Ratio

To discern the individual contributions and synergistic interplay of GNP and SiC, the mixing ratio of these nanoparticles was varied while maintaining a fixed total nanoparticle concentration of 1.0 vol%. Figure 4(A) presents the friction factor variation with the GNP:SiC mixing ratio. A clear trend is observed where the friction penalty decreases from 8.18% to 1.15% as the relative proportion of SiC nanoparticles increases. This behavior is primarily attributable to the morphological differences between GNP (platelets) and SiC (assumed spherical). Platelet-like GNP particles typically induce a higher viscosity increase compared to more isometric particles like spherical SiC at the same volume fraction, due to greater flow resistance and inter-particle interactions (14, 21). Thus, replacing GNP with SiC reduces the overall effective viscosity of the hybrid nanofluid.

Conversely, the thermal enhancement, represented by the Nu (Figure 4(B)), shows an increasing trend from 62.51-98.65 % with a higher relative proportion of GNP with respect to SiC, and this enhancement is more pronounced at higher flow rates. This is expected, given GNP's significantly superior intrinsic thermal conductivity compared to SiC. A greater presence of GNP facilitates more effective heat conduction pathways within the fluid. The enhanced effect at higher flow rates suggests that the improved advection complements the conductive benefits of GNP, leading to more efficient thermal energy transport.

The TPF, plotted in Figure 5(B) against varying mixing ratios for different flow rates, reveals a complex interplay. While higher GNP content boosts Nu, it also increases 'f'. An optimal flow rate, considering the TPF, was identified around 3 l/min. At this flow rate, pure GNP, yield the most effective overall performance, but stability and cost consideration will make the final decision to optimize the ratio. But with the change of mixing ration in the test range TPF increases from 61-93 % with relative concentration of GNP: SiC. This clearly suggests the potential for further optimization. This highlights the importance of optimizing mixing ratios for specific operational conditions rather than solely maximizing thermal conductivity or minimizing viscosity (11, 19).

Effect of SiC Nanoparticle Size

The influence of SiC nanoparticle size (assuming spherical morphology, d_{np} varied from 10 nm to 90 nm) on thermo-hydraulic performance was investigated, keeping GNP characteristics, total concentration, and mixing ratio constant. Figure 6 illustrates that both the friction factor and the Nu decrease with increasing SiC particle size of around (12% to 7.5 %) and (86 % to 76 %) respectively. The reduction in friction factor shown in Figure 6(A) with larger particles can be linked to a decrease in the total surface area of nanoparticles per unit volume for a given volume fraction. Smaller particles present a larger cumulative surface area, leading to more significant particle-fluid interactions and consequently higher effective viscosity (9, 22).

The observed decrease in Nu (Figure 6(B)) with increasing SiC particle size can be explained by several factors pertinent to nanofluids. Smaller nanoparticles generally exhibit more intense Brownian motion, which contributes to micro-convection and energy transport, thereby enhancing thermal conductivity as described by models like KKL (24). Furthermore, smaller particles provide a greater interfacial area between the particle and base fluid, which can be crucial for heat transfer, assuming good thermal contact. As particle size increases, these nanoscale effects diminish. It is crucial to note that while the simulation shows this trend, practical considerations of nanofluid stability also favour smaller, well-dispersed nanoparticles, as larger particles are more prone to agglomeration and sedimentation, which would detrimentally affect long-term performance and potentially clog microchannels (15). Thus, an optimal particle size in practice would balance these simulated thermo-hydraulic trends with long-term stability requirements, which are not directly captured by the current single-phase simulation model but are a critical experimental consideration.

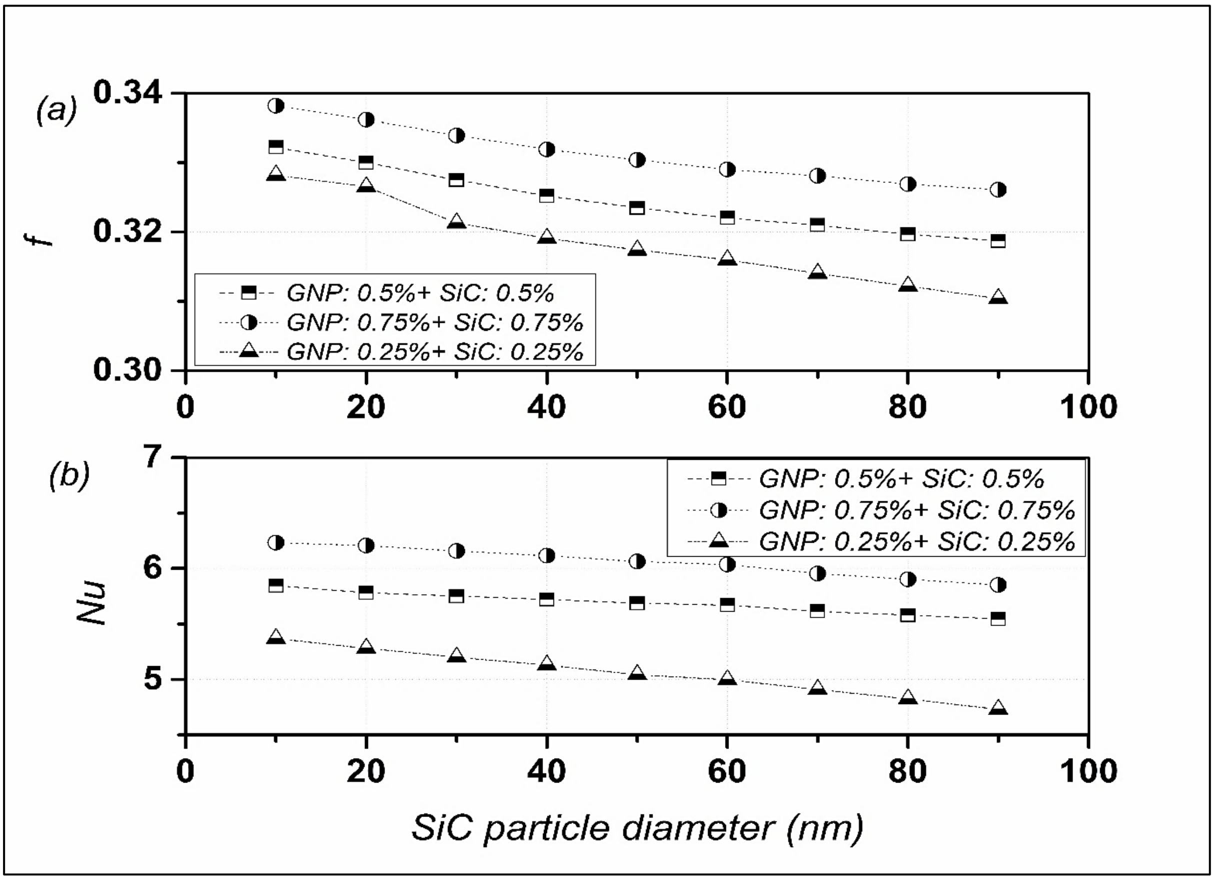

Figure 6: (A) Friction Factor vs. SiC Particle Size, (B) Nu vs. SiC Particle Size – at fixed φ_{total}, Mixing Ratio, and Flow Rate

Effect of SiC Nanoparticle Shape (Aspect Ratio)

Finally, the impact of SiC nanoparticle shape, characterized by varying its aspect ratio (representing morphologies from spheres to nanorods/whiskers (Table 2), with GNP maintained as platelets), was examined. The results, presented as bar diagrams in Figure 7(A) and (B), demonstrate that as the aspect ratio of SiC particles increases (i.e., particles become more elongated), both the friction factor and the Nu tend to increase. The rise in friction factor with higher aspect ratio particles (from 5.12% for spherical to 8.26 % for nanotubes) is consistent with rheological studies of suspensions containing non-spherical particles (21). Elongated particles offer greater resistance to flow and are more likely to form entanglements or structured networks, thereby increasing the effective viscosity of the nanofluid.

The simultaneous increase in Nu with higher SiC aspect ratios (80.54 % for spherical to 92.55 % for nanotubes) suggests that elongated particles can enhance heat transfer. This could be due to improved thermal percolation pathways formed by the anisotropic particles, a larger surface area for interaction with the fluid for a given volume compared to perfect spheres of the same volume and potentially enhanced disruption of the thermal boundary layer (25). The selection of an optimal SiC particle shape thus involves a trade-off. While higher aspect ratios can boost heat transfer, they also incur a higher pumping power penalty. The choice would depend heavily on the specific application: for systems where, pumping power is a major constraint, near-spherical SiC might be preferred. Conversely, for applications demanding maximum heat dissipation where higher pressure drops can be tolerated, higher aspect ratio SiC particles, in synergy with GNP platelets, might offer superior thermal performance. Stability and manufacturing cost of such anisotropic nanoparticles are also critical practical factors that would influence this selection process (10).

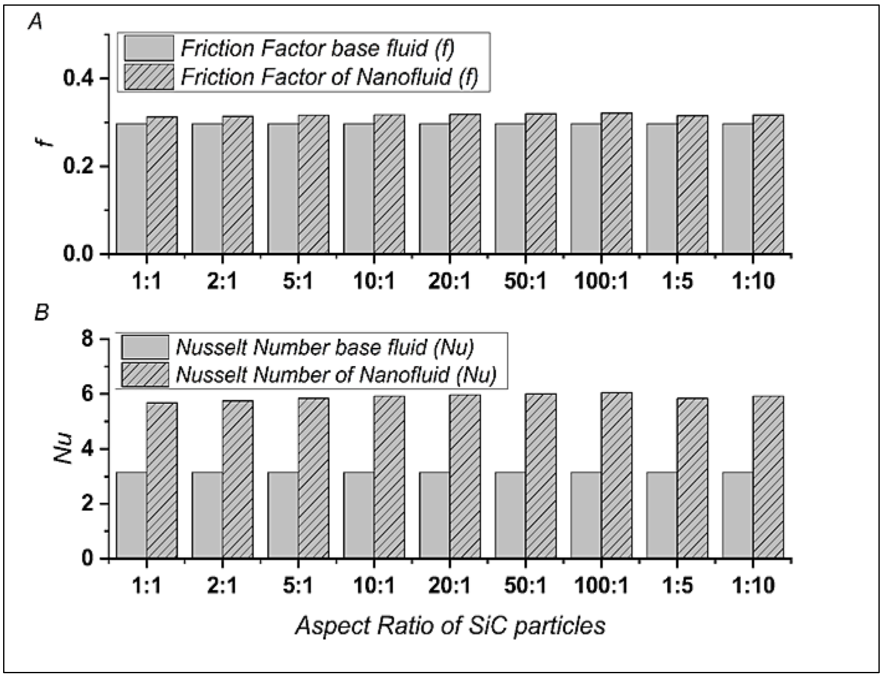

Figure 7: Bar diagrams for (A) friction factor and (B) Nu with SiC aspect ratio – at fixed φ_{total}, mixing ratio, and flow rate

Flow Structure and Boundary Layer Analysis

To elucidate the physical mechanism behind the enhanced thermal performance, a flow-structure analysis was conducted. **Figure 8** illustrates the velocity vector distribution, clearly demonstrating the generation of secondary flows induced by the oblique cuts. These geometric features force transverse fluid motion between adjacent channels, creating vigorous lateral mixing that disrupts the stable laminar streamlines typical of straight microchannels. This phenomenon is further quantified in Figure 9, where the temperature (A) and velocity (B) contours reveal that the thermal boundary layer is continuously interrupted and re-initialized at each oblique intersection. Unlike straight channels where the boundary layer thickens and heat transfer degrades downstream, Figure 9(B) indicates that the flow undergoes periodic acceleration and never reaches a fully matured, hydro dynamically developed state. Instead, the fluid remains in a quasi-developing regime characterized by thinner boundary layers and high thermal gradients. This continuous disruption, combined with the effective mixing of cooler core fluid with heated wall fluid shown in Figure 9(A), ensures that the convective heat transfer coefficient remains elevated throughout the channel length, synergistically amplifying the thermal benefits of the hybrid Nano fluid.

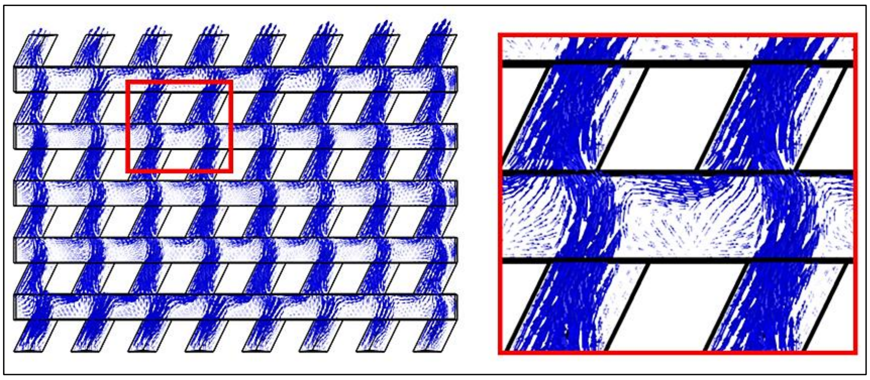

Figure 8: Velocity Vector Distribution showing Secondary Flow Generation

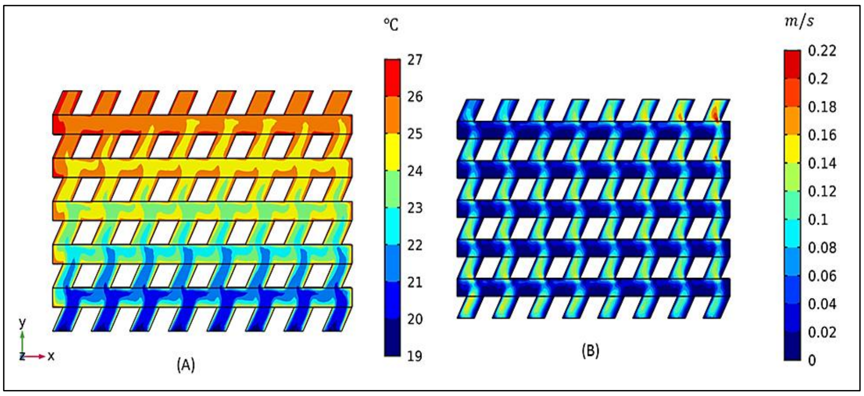

Figure 9: Contours of (A) Temperature Distribution, and (B) Velocity Magnitude

Overall Performance and Justification

The collective findings from this numerical investigation underscore the complex, multi-parameter-dependent nature of GNP+SiC/PG hybrid nanofluid performance. The results demonstrate that significant thermal enhancements are achievable. More importantly, it was highlighted that the potential for tailoring the nanofluid's characteristics by manipulating total concentration, the GNP:SiC mixing ratio, and the size and shape of the SiC component. For instance, applications requiring maximum heat transfer might favour higher GNP content and potentially higher aspect ratio SiC particles, accepting a higher friction penalty. In contrast, applications where pumping power is critical might benefit from lower total concentrations, a higher proportion of more spherical SiC, or smaller SiC particles, while still achieving a notable thermal improvement over the base fluid. This ability to customize, as demonstrated by the varying impacts on 'f', Nu, and consequently TPF, directly addresses one of the primary objectives of this research: to provide insights for designing nanofluids based on particle structure and size for desired performance targets, considering the interplay between thermal enhancement, stability, and pumping power. The heat transfer enhancement observed in the present study, characterized by a significant rise in the average Nusselt number with increased nanoparticle loading, corroborates findings from recent investigations into hybrid nanofluids. For instance, a few researchers (12) investigated the thermal performance of a hybrid $CuO+Al_2O_3$ aqueous nanofluid within porous metal foam channels and reported that the hybrid formulation yielded superior thermal enhancement (6–11%) compared to mono-component alumina nanofluids, despite ultralow particle loading. Their study highlighted that the synergistic interaction between hybrid components contributes to a higher local Nusselt number, particularly by leveraging the superior thermal properties of the copper component against the stability of the alumina support. Similarly, our results indicate that the GNP+SiC hybrid system effectively utilizes the high intrinsic thermal conductivity of GNP and the structural contribution of SiC to maximize heat extraction. Furthermore, consistent with the hydraulic observations reported by some researchers (12), where absolute pressure increased with hybrid fluid use, our study confirms that while the hybrid mixture incurs a friction penalty due to increased effective viscosity, this drawback is sufficiently offset by the substantial thermal gains, resulting in a favorable overall Thermal Performance Factor. The study confirms that the GNP+SiC/PG system, particularly within the investigated oblique channel microgeometry, offers a versatile platform for advanced thermal management, justifying its exploration despite potential challenges associated with advanced nanomaterials.

Limitations & Future Scope

While the current study focuses on the thermo-hydraulic performance of the GNP+SiC/PG hybrid nanofluid, practical implementation necessitates the consideration of real-world operational factors not captured by the single-phase numerical model. The single-phase approach employed here is well-justified for dilute suspensions; however, it inherently excludes complex particle-fluid interactions such as slip mechanisms, agglomeration over time, and localized particle-wall impacts. Consequently, the potential for microchannel erosion, a significant concern given the high hardness of Silicon Carbide (SiC) nanoparticle was not quantified in this study. Furthermore, although the PG-based nanofluid shows promise as a non-toxic alternative, its industrial viability depends on long-term suspension stability, compatibility with filtration systems, and manufacturability. Future research directions should therefore focus on the experimental validation of erosion and corrosion rates over extended flow cycles, investigation of sedimentation behaviour to ensure long-term stability and the development of multiphase numerical models to accurately predict performance at higher concentration regimes where particle interactions become dominant.

Conclusion

The thermo-hydraulic properties of grapheme nanoplatelet-silicon carbide (GNP+SiC) hybrid nanofluid in PG were thoroughly characterized by this numerical study when applied in a microchannel with triangular oblique components. The study filled in existing knowledge gaps about this sophisticated non-oxide hybrid system using a validated Computational Fluid Dynamics framework. It specifically focused on the effects of nanoparticle concentration, compositional mixing ratios, and the unique morphological characteristics (size and shape) of the SiC component within this specialized heat-enhancing geometry.

The principal outcomes derived from this research indicate that increasing the total GNP+SiC loading (at a 1:1 ratio) augmented both fluid friction (approx. 8% increase) and heat transfer (Nusselt number enhancement of approx. 75%), culminating in a significant improvement in the Thermal Performance Factor (TPF) by 69%. Furthermore, at a fixed 1.0 vol% total concentration, higher GNP proportions within the GNP:SiC mixture led to greater thermal enhancement (up to 98.65% Nu increase) but also higher friction (up to 8.18% increase), whereas increased SiC content minimized frictional losses; consequently, TPF improvements ranged from 61% to 93% across different mixing ratios. Regarding spherical SiC, decreasing the particle diameter (from 90 nm to 10 nm) enhanced heat transfer (Nu increase from ~76% to ~86%) and reduced the friction factor increase (from ~12% down to ~7.5%), a trend attributed to more potent nanoscale heat transfer mechanisms and larger effective surface areas. Finally, transitioning SiC particle morphology from spherical to higher aspect ratios (e.g., nanotubes) substantially increased both the Nusselt number (from ~80.51% to ~92.55% enhancement) and the friction factor (from ~5.12% to ~8.26% penalty), indicating a clear performance trade-off.

These results offer new quantitative understandings of the behavior of GNP+SiC/PG hybrid nanofluids, a system that has received less attention than traditional oxide-based substitutes, especially in complex microchannel geometries and a propylene glycol base. Important gaps in the literature are filled by the methodical examination of the impacts of mixing ratios and the particular influence of SiC particle size and shape.

Modulating these nanoparticle properties has been shown to have a considerable impact on thermo-hydraulic performance, which validates the originality of this work and directly supports the goal of enabling personalized nanofluid design. For applications prioritizing thermal dissipation, a higher aspect ratio SiC (nanotubes) with 1.0 vol% loading is recommended. Conversely, for systems with limited pumping power, spherical SiC particles are preferable to minimize pressure drop penalties. By confirming the feasibility of GNP+SiC/PG hybrid nanofluids as a flexible medium for sophisticated thermal control, the study offers a quantitative basis for upcoming experimental verification and real-world use in high-efficiency cooling applications.

Abbreviations

Al_2O_3: Alumina, $AR_{L/D}$: length-to-diameter aspect ratios, $AR_{L/T}$: lateral dimension to thickness aspect ratio, CFD: Computational Fluid Dynamics, CuO: copper oxide, FEM: Finite Element Method, GNP: Graphene Nanoplatelet, GNP+SiC: Graphene Nanoplatelet-Silicon Carbide, KKL: Koo-Kleinstreuer-Li, Nu: Nusselt number, PG: Propylene Glycol, SiC: Silicon Carbide, TPF: Thermal Performance Factor.

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Author Contributions

Anirban Bose: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Writing original draft, Arunabha Chanda: Supervision, Conceptualization, Writing – Review & Editing, Project Administration. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare that the research concept, data, and manuscript writing are original and not AI-generated. The use of AI tools was strictly limited to Grammarly for English language and grammar refinement. The authors take full responsibility for the content.

Ethics Approval

This study is based on computational modeling and simulation. It does not involve any research with human participants or animals; therefore, ethics approval was not required.

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