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Hybrid Nanofluid Spray Cooling Based Predictive Model Development for Advanced Thermal Management of Next Generation Electric Vehicles High-Power Electronics#

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ABSTRACT

Electric vehicle (EV) powertrains predominantly rely on compact, high-density SiC/GaN power modules in traction inverters, on-board chargers, and DC-DC converters, where aggressive drive-cycle transients push local heat flux to 500-1000 W/cm^2. These EV-specific duty constraints, tight packaging, weight/volume limits, and reliability under vibration, render conventional single-phase coolants inadequate. This study targets the EV high power electronics incorporating hybrid nanofluid spray cooling by developing a semi-analytical predictive framework for the heat-transfer coefficient (HTC) of hybrid nanofluids (HNFs) for high heat flux. The model embeds synergistic thermophysical effects such as effective conductivity, heat capacity, density/velocity ratios) and is validated against benchmark data for Al_2O_3-CNT, Al_2O_3-Ag, CNT-Ag, and GNP-Ag at mixing ratios 0.1-0.9 to 0.9-0.1 and fluxes 500 and 1000 W/cm^2. The model achieves adjusted R^2 = 94.5% (max R^2 = 95.4%) and correctly ranks HNF chemistries for EV conditions; notably, CNT-Al_2O_3 (0.9-0.1) delivers the highest HTC enhancement among tested systems. By mapping HNF composition to HTC under different spray velocities, the model enables rapid coolant down-selection for EV modules to support miniaturization, lower junction temperatures, and efficiency gains. The contribution bridges material-level formulation and system-level EV thermal design, providing a tractable tool for EV thermal engineers to screen next-generation coolants for electrified drivetrains.

Keywords: heat transfer coefficient, electronics cooling, semi-analytical model, hybrid nanofluid, electric vehicles, spray cooling

NONMENCLATURE

Abbreviations	
CHF	Critical heat flux
CFD	Computational fluid dynamics
CNTs	Carbon nanotubes
DBC	Direct bond copper
EVs	Electric vehicles
GNPs	Graphene nanoparticles
HNFs	Hybrid nanofluids
HPEs	High power electronics
HTC	Heat transfer coefficient (W/m^2. K)
HTF	Heat transfer fluid
IGBT	Insulated gate bipolar transistor
MR	Mixing ratio
Symbols	
d	Orifice diameter (m)
h	Heat transfer coeff. (W/m^2. K)
k	Thermal conductivity (W/m.K)
ρ	Nanoparticle density (kg/m^3)
σ	Surface tension (N/m)
μ	HNF Viscosity (Ns/m^2)
φ	HNF Volumetric fraction
θ	Spray angle

1. INTRODUCTION

Transport electrification has driven high-power electronics (HPEs) in electric vehicles (EVs) to operate at heat-flux levels where junction-temperature control ultimately dictates reliability and lifetime. Field data consistently identifies that thermal overstress is the primary failure mode (≈55%), followed by vibration (20%), humidity (19%), and dust (6%) [1]. Semiconductor-device failures alone account for ≈21% of electronic malfunctions [2]. With faster switching and higher power

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density, heat fluxes ≈500 W/cm^2 are already reported and are projected to approach 1000 W/cm^2 in next-generation modules [3,4]. Conventional single-phase coolants (water, dielectrics) deployed in jet impingement, microchannels, and spray-cooling architectures struggle to meet these loads, with reported heat removal often limited to ≈312 W/cm^2 under comparable conditions [5–7]. This motivates advanced heat-transfer fluids (HTFs) that combine high thermal conductivity with dispersion stability and application-grade rheology [8]. Nanofluids, engineered dispersions of nano-sized solids in a base fluid, can enhance thermal transport. For instance, TiO_2-H_2O at 0.1 wt% controlled device temperature under 500 W loading [9] and Cu-based sprays improved HTC by ≈10.6% over water [10] . Yet single-component nanofluids face trade-offs: Al_2O_3 offers stability but modest conductivity, while Ag/Cu deliver high conductivity but poorer dispersion stability. Hybrid nanofluids (HNFs) purposefully blend complementary nanoparticles to exploit synergistic transport Experimentally, Ag-GNP sprays boosted CHF by up to 126% in IGBT cooling and MWCNT-TiO_2 sprays yielded ~27.3% HTC gains versus water [13], supporting HNFs as candidates for EV-grade thermal management. However, widely used spray-cooling correlations, developed for water or dielectrics, how bounded accuracy (e.g., ±15%/±30% for cooling/thermal efficiency [11]; ≤6.7% CHF-correlation deviation for HFE-7100 [12]) and sensitivity to flow/orientation (vertical sprays attaining CHF ≈596 W/cm^2 at ~120°C [13]). Even for single-particle nanofluids, correlation fidelity can degrade as particle fraction rises due to agglomeration and interfacial resistance [14].

Critically, to the best of authors' knowledge, no semi-analytical correlation currently captures the coupled particle-particle and particle-fluid interactions unique to HNFs under EV-relevant ultra-high-heat-flux spray cooling [15]. To address this gap, we develop a convective, semi-analytical HTC model for HNFs comprising metallic oxide (Al_2O_3), non-metallic (graphene nanoplatelets, GNP; carbon nanotubes, CNT), and metallic (Ag) species at a fixed 1% total volume fraction and mixing ratios from 0.1-0.9 to 0.9-0.1. Eight binary formulations are screened under 500 and 1000 W/cm^2 with inlet velocities 5-30 m/s, representative of EV duty. The major work addressed in this work is
(i) a physics-grounded, design-tractable predictor for HNF spray cooling and (ii) identification of high-leverage pairings (e.g., CNT-Al_2O_3) that reconcile performance and dispersion practicality for compact, high-density EV power modules.

2. METHODOLOGY

2.1 Geometry & Mesh

A single-nozzle spray impingement on a square electronic chip (10 mm×10 mm) mounted on a DBC substrate (Cu/AlN/Cu) was modeled in ANSYS Fluent 2021. The liquid orifice (ϕ = 508 μm) was positioned 20 mm above the chip, while spray half-cone angle of θ = 32° is used. The fluid and solid domains were discretized using a CFD mesh refined near the jet core and wall to resolve steep thermal and velocity gradients. Furthermore, mesh quality and solution independence were checked (final mesh used for all simulations)

2.2 Multiphase & Governing Equations

Following common practice for nanofluid sprays [16,17], an Eulerian-Eulerian mixture model was adopted, treating the base fluid as primary and nanoparticles as secondary phases. Steady, incompressible flow with absolute velocity formulation and a pressure-based solver is employed for numerical analysis. The mixture continuity, momentum, and energy equations were solved for each phase, with interphase slip handled via the mixture model. The working equations and closures used for effective properties follow Eqs. (1)-(5) [18–21].

2.3 Fluids & Thermophysical Properties

Total particle volume fraction was fixed at 1% in line with prior thermal-management studies [22–24]. Binary hybrid nanofluids (HNFs) combined metallic oxide, metallic, and carbonaceous nanoparticles at prescribed mixing ratios to probe synergy:
0.1 CNT-0.9 Al_2O_3; 0.1 Ag-0.9 Al_2O_3; 0.1 Ag-0.9 CNT;
0.9 CNT-0.1 Al_2O_3; 0.9 Ag-0.1 Al_2O_3; 0.9 Ag-0.1 CNT.

Effective thermal conductivity and viscosity of each HNF were computed using volumetric-fraction formulations (mixture rules) consistent with [20–23]; nanoparticle physical properties are listed in Table 2 sufficient detail to allow the work to be reproduced. Methods already published should be indicated by a reference: only relevant modifications should be described.

2.4 Boundary Conditions & Operating Points

A uniform heat flux of 500 W/cm^2 and 1000 W/cm^2 was imposed at the chip base to emulate current and next-gen EV HPE loads. Inlet jet bulk velocities were set to 5 and 10 m/s for 500 W/cm^2, and 20 m/s and 30 m/s for 1000 W/cm^2 respectively. No-slip and impermeable wall conditions were applied; symmetry/pressure-outlet boundaries completed the domain. Spatial discretization employed first-order schemes for pressure and turbulent kinetic energy as in the baseline setup while PRESTO! (PREssure STaggering Option) approach was used for pressure interpolation.

Pressure-velocity coupling is carried out using SIMPLE algorithm. Residual criteria of 10^{-9} is used for all equations. . Post-processing extracted wall heat-transfer metrics (HTC, surface temperature fields) and phase distributions for each HNF at each operating point.

2.5 *Modeling Rationale*

The Eulerian-Eulerian mixture approach captures nanoparticle-base-fluid slip and concentration-dependent property modulation within a tractable CFD framework [16,17], while the fixed 1% total loading targets the commonly reported effective window for stability and performance in electronics cooling [17–19]. The chosen flux/velocity pairs bracket EV-relevant duty cycles, enabling direct comparison of HNF pairings under identical spray hydraulics.

$$\nabla.\left(\rho_m \overrightarrow{V_m}\right) = 0 \qquad [1]$$

$$\nabla.\left(\rho_m \overrightarrow{V_m}\ \overrightarrow{V_m}\right) = -\nabla p + \nabla.\left(\mu_m \nabla \overrightarrow{V_m}\right) + \rho_m \vec{g} + \nabla.\left(\sum_{k=1}^{n} \varphi_k \rho_k \overrightarrow{V_{dr,k}}\ \overrightarrow{V_{dr,k}}\right) \qquad [2]$$

$$\nabla.\sum_{k=1}^{n}\left(\varphi_k \overrightarrow{v_k}\left(\rho_k H_k + p_m\right)\right) = \nabla.\left(k_m \nabla T\right) \qquad [3]$$

$$\nabla.\left(\varphi_{np}\rho_{np}\overrightarrow{V_m}\right) = -\nabla.\left(\varphi_{np}\rho_{np}\overrightarrow{V_{dr,k}}\right) \qquad [4]$$

$$\overrightarrow{V_m} = \frac{\sum_{k=1}^{n}\varphi_k \rho_k \overrightarrow{V_k}}{\rho_m};\quad \overrightarrow{V_{dr,k}} = \overrightarrow{V_k} - \overrightarrow{V_m} \qquad [5]$$

$$f_{drag} = \begin{cases} 1 + 0.15 Re_p^{0.687} & Re_p \le 1000 \\ 0.0183 Re_p & Re_p > 1000 \end{cases} \qquad [6]$$

The boundary conditions and the assumptions used for the current numerical investigation are that the incompressible, continuum, and steady fluid was considered. The heat transfer through radiation was neglected. No-slip conditions were considered at the wall, and at the inlet, the velocity remains constant. Moreover, zero-gauge pressure was considered at the outlet.

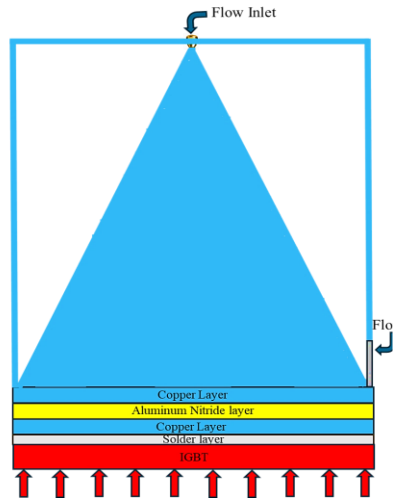

Fig. 1 Spray distribution within the fluid domain

Also, a steady heat flux of 1000 W/cm^2 and 500 W/cm^2 was provided on the electronic chip, shown in Fig.1. The left and right sides of the electronic chip were given an adiabatic boundary condition. A rigorous mesh based sensitivity study was conducted to ensure numerical accuracy. A high-quality tetrahedral mesh (characteristic element size of 1.34×10^{-4} meters; target aspect ratio$\approx$1) was generated as represented in Fig. 2a. Four meshes, approximately 3, 5, 7, and 9 million elements were evaluated for grid independence. The solution change between the 9 million and 7 million meshes were 0.47%, indicating mesh independence at the 7 million scale. Accordingly, the production mesh with 7,174,774 elements and 1,241,360 nodes was adopted for all simulations. Model validation was performed against the experimental data of Siddiqui et al. [4] using a non-metal/metal hybrid nanofluid (GNP-Ag) at a total volume fraction of 1% and a mixing ratio of 0.1-0.9. Chip surface temperature was compared over imposed heat-flux levels from 520 to 545 W/cm^2 as shown in Fig. 2b. The numerical predictions reproduced the experimental trends with a maximum deviation < 1%, confirming that the model accurately captures the relevant spray-cooling physics under EV-relevant high-heat-flux conditions.

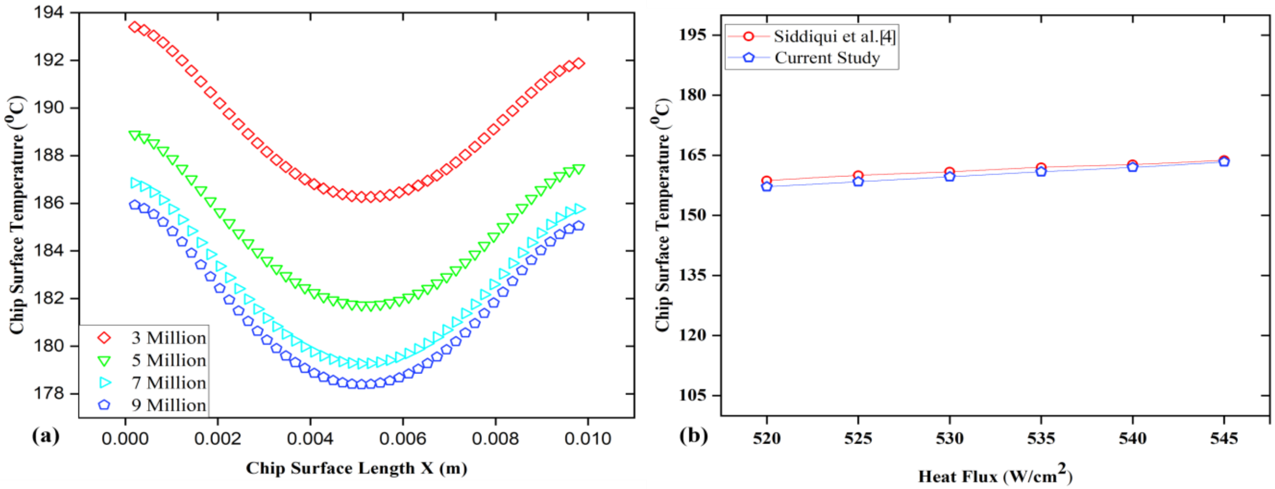

Fig. 2 (a) Mesh sensitivity test, (b) Validation

Table 1 Thermophysical characteristics and dimensions of the electronic chip module

Component Layer	Material	Density ρ (kg/m^3)	Heat capacity C_p (J/kg.k)	Thermal Conductivity K (W/m.k)
DBC layer	Copper	8700	385	400
	Aluminum nitride	170	780	170
	Copper	8700	385	400
IGBT chip	Silicon	2329	700	130
Solder layer	60Sn-40Pb	9000	150	50

Table 2 Nanoparticles characteristics

Physical Properties	Ag	Al_2O_3	GNP	SWCNT
Density (kg/m^3)	10500	3970	2267	2600
Heat capacity (J/kg.K)	235	765	900	425
Thermal Conductivity (W/m.k)	429	40	4000	6600
Particle size (nm)	90	13	8	1-2

3. RESULTS AND DISCUSSION

The semi-analytical framework used to predict the heat transfer coefficient (HTC) for hybrid nanofluids using mixing ratios of 0.1-0.9 and 0.9-0.1 is shown in Fig. 3. The model utilized the density ratios, temperature, heat capacities, thermal conductivity, and velocity ratios of hybrid nanofluids at two different mixing ratios to predict the HTC. Moreover, the model was developed by using four different velocities (5 m/s, 10m/s, 20 m/s, and 30 m/s) using heat fluxes of 500 W/cm^2 and 1000 W/cm^2, respectively. Furthermore, by raising the velocity of the hybrid nanofluids, the HTC also increases. This is because at higher velocities the corresponding boundary layer becomes progressively thinner, more particles come in contact that resulting in effective heat dissipation. The graph also illustrates that non-metal-metal oxide (CNT-Al_2O_3) at mixing ratios of 0.1-0.9 has a higher HTC compared to all other hybrid nanofluids. This is because the Nusselt number for that hybrid nanofluid combination is higher than for other combinations, which results in higher heat dissipation. In addition to that, metal-nonmetal (Ag-CNT) hybrid nanofluids at a mixing ratio of 0.1-0.9 show lower HTC because of a lower Nusselt number compared to all other hybrid nanofluids combinations at two different mixing ratios. Moreover, the mixing ratios also affect HTC; it was observed that 0.1 CNT-0.9 Al_2O_3 has higher HTC compared to 0.9 CNT-0.1 Al_2O_3.

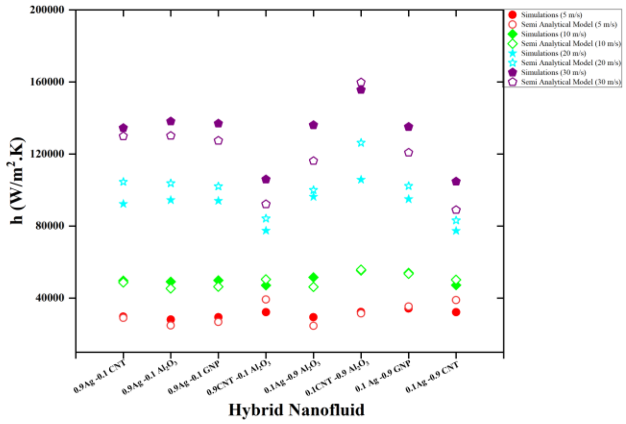

Fig. 3 Semi-analytical framework using HNF spray cooling

This is because the heat capacity of CNT nanoparticles is higher compared to Al_2O_3, which enables it to absorb more heat. The graph also indicates a strong relationship between numerically computed and developed predicted semi-analytical model, as the adjusted R^2 and R^2 were 94.5% and 95.4% respectively. Also, the measured ***'P'*** values for each coefficient were 0 (0.335), 0 (-2.022), 0.0001 (0.315), 0 (0.308), and 0.067 (3.554). This reflects that a stronger correlation exists between the coefficients in predicting HTC.

4. CONCLUSIONS

The dissipation of heat flux in modern high-power electronics becomes a serious concern because higher temperatures result in thermal breakdown that ultimately reduces the life span of the electronic devices. To tackle the current rising issue, spray cooling of different hybrid nanofluids combinations, including metal-metal oxide, non-metal-metal, and non-metal-metal oxide were investigated at mixing ratios of 0.1-0.9 and 0.9-0.1, respectively. Based on numerical investigations, the thermal semi-analytical model for HTC was developed. Following are the findings of the current investigation:

- The developed semi-analytical model accurately predicts the HTC for hybrid nanofluids, providing maximum adjusted R^2 and R^2 of 97.96% and 98.16% respectively.
- It was also observed that by varying the mixing ratios of the hybrid nanofluids, the HTC also varies. The non-metal and metal-oxide hybrid nanofluids combination at a mixing ratio of 0.1-0.9 provides higher HTC compared to all other hybrid nanofluids combinations and mixing ratios.
- Critical heat flux (CHF) is the limitation of the current study. The future research will be done by taking the current study and developing a semi-analytical model for spray using hybrid nanofluids.

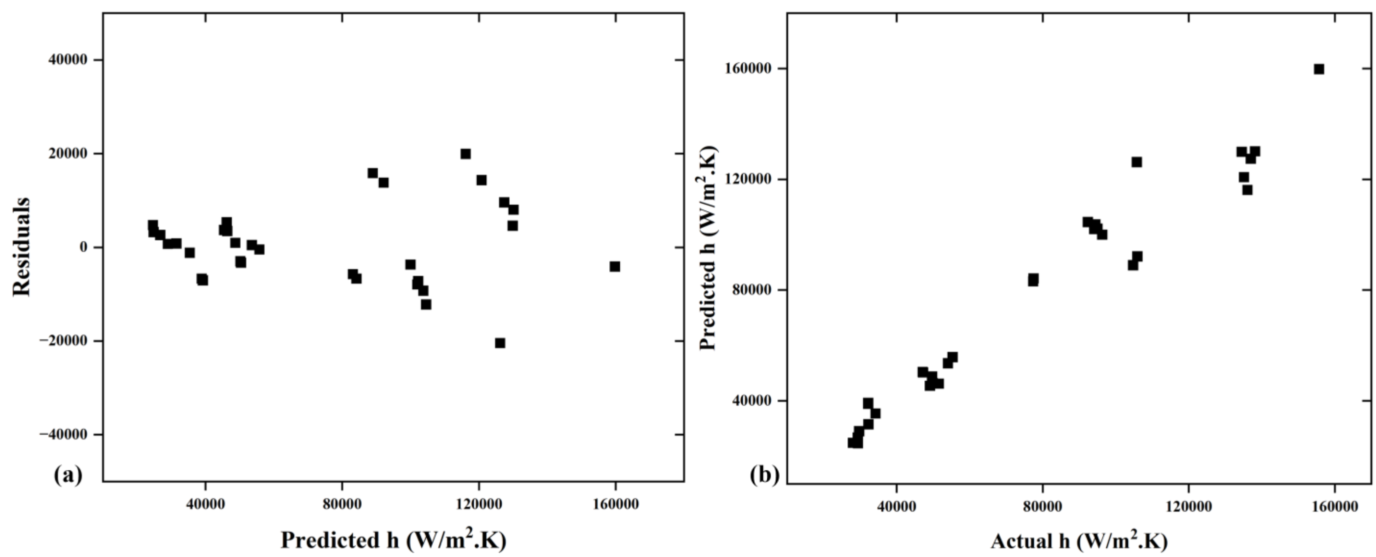

Fig. 5 (a) Predicted "h" vs Residuals, (b) Actual Vs Predicted "h"

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