



Nanofluids for Automotive Radiators: A Review of Thermophysical Properties, Stability, Heat Transfer Performance, and Future Research Directions

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ARTICLE HISTORY

Received: 18 May 2026

Revised: 2 June 2026

Accepted: 4 June 2026

KEYWORDS

Nanofluids

Automotive radiator

Thermal conductivity

Hybrid nanofluid

Heat transfer enhancement

Stability

Viscosity

Thermophysical properties

ABSTRACT– The persistent demand for compact, high-efficiency automotive cooling systems has driven significant research into nanofluids as next-generation coolants. This review critically examines recent advances in mono, hybrid, and ternary nanofluids applied to automotive radiators, synthesizing over experimental and numerical studies published during last decade. Key thermophysical properties comprising thermal conductivity, dynamic viscosity, density, and specific heat capacity are discussed alongside the principal factors governing their variation with nanoparticle concentration, temperature, particle geometry, and base fluid composition. Nanofluid preparation methodologies (one-step and two-step) and strategies for stabilising colloidal dispersions including surfactant addition, ultrasonication, pH control, and zeta potential management are evaluated against practical longevity requirements. Empirical correlations for property estimation are tabulated and critically compared. Heat transfer performance data from radiator studies are synthesised, revealing that carbon-based nanofluids (graphene, MWCNTs) consistently outperform metal-oxide counterparts in thermal conductivity enhancement (up to 161.8%), while hybrid and ternary formulations demonstrate superior combined performance due to synergistic inter-particle effects. Practical challenges including erosion, clogging, agglomeration, and increased pumping power requirements are assessed with emphasis on long-term system reliability. The review concludes with a structured agenda for future research, highlighting the need for standardised testing protocols, machine-learning-assisted property prediction, and compatibility studies with modern radiator materials.

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Introduction

Internal combustion engines (ICEs) convert only approximately 35% of fuel chemical energy into useful crankshaft work, with the remaining energy dissipated primarily through exhaust gases and the engine cooling system [1]. Temperatures within the combustion chamber routinely exceed 2700 K, necessitating robust thermal management to prevent component failure while simultaneously maintaining the elevated operating temperatures required for optimal thermodynamic efficiency [1–3]. The radiator, functioning as a liquid-to-air heat exchanger, is the primary mechanism through which excess heat is rejected from the coolant circuit to the atmosphere.

Conventional engine coolants comprising water (WT), ethylene glycol (EG), propylene glycol (PG), and their binary blends have long served as the dominant working fluids in automotive cooling circuits. Water offers high specific heat and thermal conductivity (0.69 W/mK at 25°C) but is limited by its narrow liquid range (0–100°C at atmospheric pressure), corrosive tendencies, and incompatibility with aluminium

alloys at elevated pH. EG extends the operational range substantially (freezing point –11°C, boiling point 197°C) but introduces thermal conductivity penalties (0.30 W/mK), while PG, preferred in environmentally sensitive applications, exhibits even lower conductivity (0.15 W/mK) [3,4]. These intrinsic limitations have become increasingly untenable as modern engine designs demand higher specific power densities and tighter thermal envelopes.

Nanofluids engineered with colloidal suspensions of metallic, metal-oxide, or carbon-based nanoparticles (1–100 nm) in conventional base fluids which emerged from the pioneering work of Choi and Eastman at Argonne National Laboratory in the 1990s as a compelling route to enhanced thermal performance without hardware modification. Based on Maxwell's effective medium theory, the inherently higher thermal conductivity of solid nanoparticles relative to liquids endows nanofluids with superior heat conduction capability, enabling improved engine cooling at reduced or equivalent coolant flow rates, thereby reducing radiator size, weight, and parasitic power demands [3–6].

The body of literature on nanofluid applications in automotive radiators has expanded dramatically over the past decade and a half. However, earlier review works were largely confined to mono-component nanofluids with limited thermophysical scope [7-8]. The comprehensive review by Güllüm et al. [3] substantially advances the field by systematically integrating mono, hybrid, and ternary nanofluid data, and providing critical analyses of empirical models, stability mechanisms, and preparation methods. This review builds on earlier work with three main points: (i) a clear method for reviewing with set criteria; (ii) a detailed explanation of how property trends relate to physical behaviors in nanofluids; and (iii) a look at the difference between lab stability data and real-world conditions. Modern vehicle thermal systems are complex, with features like electric drivetrains, turbocharged engines, and strict thermal management. This makes it important to organize nanofluid data to help with engineering decisions and further investigations.

A. Review Methodology

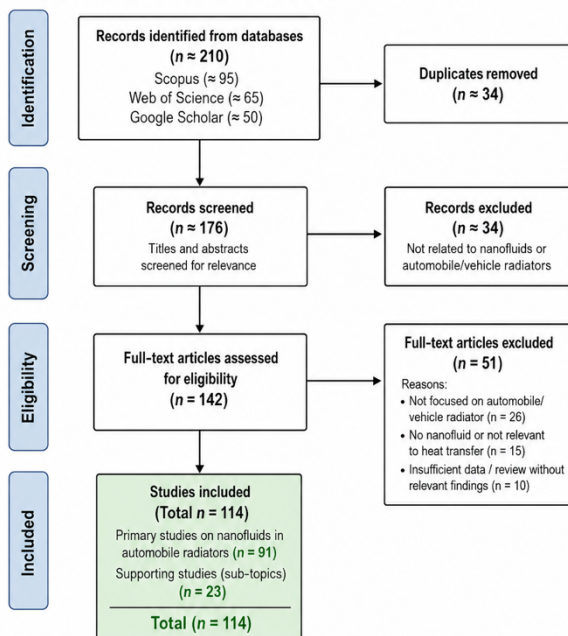


Figure 1. PRISMA-style screening flow diagram

This review was conducted using a structured literature search approach consistent with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, adapted for engineering review articles.

This review is organised as follows: the preparation methodologies are first discussed, followed by the fundamentals of thermophysical properties and colloidal stability. The review then examines heat transfer performance in radiator applications, discusses practical challenges, presents a structured comparison of nanofluid classes, and identifies priority directions for future research.

Preparation Methods of Nanofluids

The preparation method fundamentally determines the degree of nanoparticle dispersion, agglomeration tendency, long-term stability, and consequently the realised

thermophysical properties of the nanofluid. Two principal preparation routes have been established in the literature: the two-step method and the single-step method [7,9–13].

A. Two-Step Method

The two-step method remains the most widely adopted approach, primarily due to its scalability and cost-effectiveness. Nanoparticles are first synthesised as a dry powder via gas-phase condensation in an inert atmosphere of argon or nitrogen to prevent oxidation and subsequently dispersed into the selected base fluid. For metal-oxide nanoparticles, oxygen may be incorporated as a reactive gas during synthesis. Dispersion of the dry powder into the base fluid represents the critical quality-determining step, as the strong van der Waals attractive forces between nanoparticles promote cluster formation that degrades both thermal conductivity and suspension stability [14–19].

Post-synthesis dispersion is typically augmented through a combination of mechanical stirring, probe or bath ultrasonication, surfactant addition, and pH adjustment. Ultrasonication, particularly using probe-type sonicators, generates cavitation bubble collapse events that produce highly localised pressure and temperature transients sufficient to disintegrate nanoparticle clusters. However, excessive sonication can shorten carbon nanotubes and modify particle morphology, with potentially adverse effects on property enhancement [20]. The two-step method is most effective for oxide-based nanoparticles and at volume fractions exceeding approximately 0.2%; it is less suitable for metallic nanoparticles due to oxidation during the dispersion stage [7,9-14].

B. Single-Step Method

The single-step method integrates nanoparticle synthesis and dispersion in a single operation, typically using physical vapour deposition (PVD) or liquid-phase chemical reduction directly into the flowing base fluid VEROS (vacuum evaporation onto a running oil substrate) in which metallic vapour condenses directly into a continuously flowing low-vapour-pressure base fluid, bypassing the intermediate dry powder stage entirely. By eliminating intermediate storage, drying, and transfer steps, the single-step approach minimises agglomeration and substantially enhances suspension stability. It is particularly advantageous for metallic nanofluids where oxidation during handling is a concern [14–19]. Its principal drawbacks are restriction to base fluids with low vapour pressure, higher equipment cost, and limited scalability beyond laboratory volumes.

A comparative perspective of both methods highlights a fundamental trade-off: the two-step method offers industrial scalability at the expense of dispersion quality, while the single-step method provides superior stability at higher complexity and cost. Surface functionalisation of nanoparticles which is applicable in both methods introduces electrostatic and/or steric repulsion through covalent attachment of functional groups, providing an important route

to long-term stability enhancement in either approach [14–19].

Thermophysical Properties of Nanofluids

A. Thermal Conductivity

Thermal conductivity is the most intensively studied thermophysical property of nanofluids and the primary driver of their heat transfer advantage over conventional fluids. Enhancement mechanisms include: (i) Brownian motion of nanoparticles and the associated microconvection in the surrounding fluid layer; (ii) nanolayer formation at the solid-liquid interface, which creates a high-conductivity pathway for phonon transport; (iii) nanoparticle clustering effects that form percolating thermal networks; and (iv) ballistic phonon transport across nanoparticle aggregates [21–24].

Carbon-based nanomaterials exhibit the most substantial enhancements. Graphene nanoplatelets in water at 1 vol% and 90°C produce a thermal conductivity enhancement of up to

161.8% which is highest reported in the reviewed literature [25]. MWCNT-based nanofluids in EG-WT blends at 1 vol% show enhancements of 34.7% at 50°C [26]. Metal-oxide nanoparticles (Al_2O_3 , CuO, TiO_2 , MgO, ZnO) typically deliver more modest enhancements in the range of 8–70% depending on concentration, temperature, and base fluid [27–29]. Hybrid and ternary formulations can exceed the performance of individual components: CuO-MgO- TiO_2 in water at 0.5 vol% and 50°C achieves 50.78% thermal conductivity enhancement [30], while SiC-MWCNT hybrids in EG at 0.4 vol% deliver a 32.01% improvement [31].

Thermal conductivity exhibits a consistent positive dependence on both nanoparticle volume concentration and temperature across virtually all reported systems, the latter trend being attributed to the temperature-dependence of Brownian motion intensity [21–24]. The transient hot-wire technique is the preferred measurement method due to its speed, accuracy, and minimal convection interference.

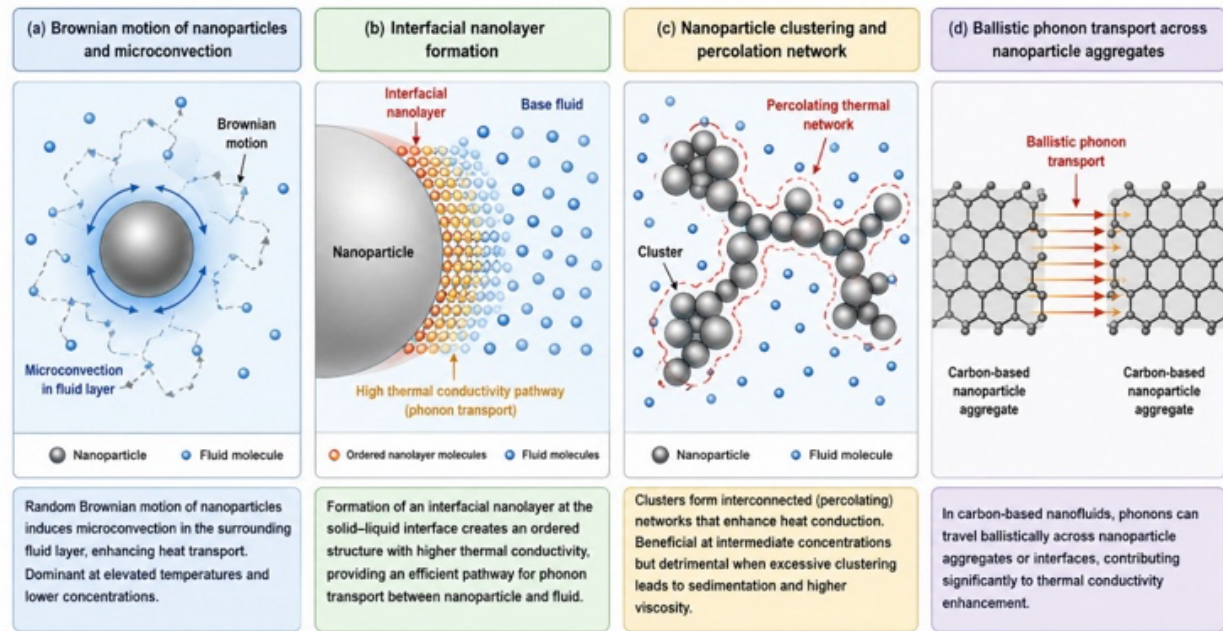


Figure 2. Principal mechanisms of thermal conductivity enhancement in nanofluids.

Table 1. Representative thermal conductivity enhancement data for mono, hybrid, and ternary nanofluids in automotive radiator applications

Nanofluid System	Base Fluid	Conc. (vol%)	Temp. (°C)	Max TC Enhancement	Ref.
Graphene (mono)	Water	1.0	90	161.8%	[25]
MWCNTs (mono)	EG-WT (40:60)	1.0	50	34.7%	[26]
SiC (mono)	EG-WT (40:60)	0.5	50	53.81%	[32]
CuO (mono)	Water	3.0	25	71.67%	[28]
Al_2O_3 (mono)	EG-WT (20:80)	1.5	60	32.26%	[27]
CuO-MgO- TiO_2 (ternary)	Water	0.5	50	50.78%	[30]
SiC-MWCNTs (hybrid)	EG	0.4	—	32.01%	[31]

B. Dynamic Viscosity

Dynamic viscosity is a critical counter-performance parameter in nanofluid applications: while nanoparticles enhance thermal transport, the concomitant viscosity increase raises pressure drop and pumping power requirements, partially offsetting thermal gains. The viscosity increase arises from two concurrent mechanisms: hydrodynamic particle-fluid interaction that increases effective fluid density, and inter-particle colloidal forces that create structured clusters offering additional flow resistance. At higher temperatures, weakening intermolecular forces reduce base fluid viscosity while simultaneously intensifying Brownian motion, reducing inter-particle clustering both effects lower nanofluid viscosity, following an approximate Arrhenius relationship for most systems [34–36]. Conversely, viscosity decreases with temperature as intermolecular cohesive forces weaken and Brownian motion increases, following an Arrhenius-type relationship for most base fluids [36].

Nanoparticle type exerts a strong influence on dynamic viscosity for example WO_3 -crude oil nanofluids showed a 320% viscosity increase at moderate concentrations, compared to 40% for TiO_2 in the same base [37]. Particle size is inversely correlated with viscosity in α -SiC-WT systems, with smaller particles producing higher viscosity due to the greater surface area available for hydrodynamic interaction [38]. Surfactant addition generally reduces nanofluid viscosity by disrupting inter-particle attraction; SDBS addition to Al_2O_3 -WT and CuO -WT systems reduced viscosity by 4–6% [39]. Einstein's [43] dilute-suspension model ($\mu_{eff} = \mu_{bf}(1 + 2.5\phi)$) consistently underestimates viscosity at practical concentrations and is particularly deficient for non-spherical particles comprising carbon nanotubes, where entanglement effects are significant [40]. More physically complete models incorporating Brownian motion, aggregation, and particle geometry [42] provide better agreement across broader concentration ranges.

C. Density and Specific Heat Capacity

Nanofluid density is accurately predicted by the classical mixture rule (Pak and Cho, 1998): $\rho_{nf} = \phi\rho_{np} + (1 - \phi)\rho_{bf}$, [44] with the extension to hybrid systems proposed by Takabi and Salehi (2014) accommodating two nanoparticle species [44–45]. Since most nanoparticles possess densities substantially higher than the base fluid, density increases linearly with concentration. Density decreases with increasing temperature, consistent with thermal expansion of the continuous phase [46–47].

Specific heat capacity of nanofluids typically decreases with increasing nanoparticle concentration when the nanoparticle C_p is lower than that of the base fluid which is the most common scenario for inorganic nanoparticles dispersed in water-glycol systems [48–49]. The effect of temperature on C_p is less predictable and system-specific, with some studies reporting increases and others decreases with temperature, depending on the relative temperature-dependence of constituent C_p values [50]. Si_3N_4 nanoparticles in liquid argon represent a notable exception,

showing C_p enhancement with volume fraction, attributable to interfacial phonon scattering effects [51]. In automotive radiator applications, the reduction in specific heat capacity has a direct practical consequence: a lower C_p means less energy is absorbed per unit mass per degree of temperature rise, reducing the coolant's thermal buffering capacity. System designers must therefore account for this trade-off while thermal conductivity improvements enhance heat rejection rates, the simultaneous reduction in C_p may require higher mass flow rates to achieve equivalent coolant-side temperature control, particularly under transient engine load conditions comprising cold start or rapid acceleration.

Stability of Nanofluids

A. Stability Assessment Methods

Long-term colloidal stability is prerequisite for reliable nanofluid performance in operational radiator circuits. Three principal characterisation methods are employed: (i) Sedimentation/visual observation which is the most straightforward approach, tracking particle settling by direct photography or measurement of supernatant concentration over time; (ii) Zeta potential analysis by using the Smoluchowski equation applied to electrophoretic mobility data from Zeta Sizer Nano instruments, with $|\zeta| > 40$ mV indicating stable systems and $|\zeta| > 60$ mV considered excellent stability [52]; and (iii) UV-Vis spectrophotometry by exploiting the linear relationship between nanoparticle concentration and absorbance intensity in the 190–1100 nm range to provide precise, time-resolved stability quantification [52].

Quantitative stability benchmarks from the literature indicate that SiC nanofluids in engine coolant (40:60 EG-WT) show minimal sedimentation for up to 30 days, with noticeable particle settling between 30 and 45 days [32]. MWCNT-WT nanofluids stabilised with sodium dodecyl benzene sulphonate (SDBS) surfactant remain stable without visible sedimentation for over 3 months [40]. Al_2O_3 nanofluids prepared without surfactant show consistent stability up to two months at lower concentrations [53], while synthesis route significantly impacts the sedimentation onset; in-situ prepared Al_2O_3 shows markedly superior stability versus commercial powder-based preparations [54].

It is important to note that the stability benchmarks discussed above are derived predominantly from static or quiescent laboratory conditions. Real automotive radiator circuits impose additional destabilising factors including repeated thermal cycling (engine start-stop cycles), mechanical vibration from the engine and drivetrain, continuous turbulent flow through narrow fin passages, and exposure to dissolved oxygen and corrosion products. These factors can significantly accelerate particle agglomeration and sedimentation relative to laboratory observations, and their effects are not currently captured by standard nanofluid stability characterisation protocols representing a critical gap between laboratory findings and practical field performance.

B. Stability Enhancement Strategies

Surfactant addition is the most widely employed chemical stabilisation strategy. Anionic surfactants (SDBS, SDS), cationic surfactants (CTAB, DTAB), and non-ionic surfactants (PVP, oleic acid) each address different aspects of inter-particle interaction. CTAB demonstrated the most effective stabilisation performance among SDS, OA, and CTAB for $\text{Mg}(\text{OH})_2$ -WT nanofluids in a direct comparative study using 30-day sedimentation photography [55]. However, excess surfactant introduces foaming during thermal cycling, potential contamination of the heat transfer medium, and thermal interfacial resistance at the adsorbed surfactant layer, all of which can partially or fully negate thermal enhancement [52,56].

pH control modifies nanoparticle surface charge, enabling formation of electrostatic double layers that generate repulsive forces opposing aggregation. Optimal pH stability windows of 7.5–8.9 for Al_2O_3 and approximately 7.6 for Cu-based nanofluids have been identified; departure below pH 7 induces rapid agglomeration [57]. The DLVO theory (Derjaguin-Landau-Verwey-Overbeek) provides the theoretical framework for understanding the balance between van der Waals attraction and electrostatic repulsion governing colloidal stability, with suspension stability assured when repulsive interactions dominate [58–59].

Mechanical methods comprising magnetic stirring and ultrasonication provide temporary dispersion enhancement by physically disrupting agglomerates. Probe sonication is consistently more effective than bath sonication; optimal sonication durations are system-specific, with excessive processing potentially reducing particle aspect ratio in CNT systems and causing re-agglomeration [60–61].

Heat Transfer Performance in Automotive Radiators

A. Mono Nanofluids

The preponderance of experimental evidence confirms that mono nanofluids enhance heat transfer coefficients, Nusselt numbers, and overall thermal performance relative to base fluids in automotive radiator applications, though the magnitude varies substantially with nanoparticle chemistry, concentration, flow regime, and radiator geometry. Al_2O_3 -WT nanofluids, the most extensively studied system, show heat transfer coefficient enhancements of 45–45.87% at 1 vol% [62–63], with radiator effectiveness improvements of up to 40% at the same concentration [64]. TiO_2 -based systems at lower concentrations (0.2–0.3 vol%) yield 22–42.5% heat transfer rate improvements [65–67]. ZnO nanofluids show a 46% heat transfer enhancement at 0.2 vol% in a Suzuki Mehran radiator [68–69].

These metal-oxide enhancements are primarily attributable to increased thermal conductivity and secondary Brownian motion effects. The relatively modest magnitudes (compared to carbon-based systems) reflect the lower intrinsic thermal conductivity of oxide nanoparticles and their

tendency to form dense clusters that reduce active surface area.

Carbon-based mono nanofluids consistently outperform metal-oxide counterparts at equivalent concentrations. This superiority stems from the extremely high intrinsic thermal conductivity of graphitic carbon structures (graphene: ~ 5000 W/mK; MWCNTs: ~ 3000 W/mK), high aspect ratios that create extended thermal conduction pathways, and strong Brownian motion contributions at the low concentrations studied. Graphene nanoplatelet suspensions at 0.3 vol% achieve 275% thermal performance improvement [70], while MWCNTs at 0.5 vol% demonstrate Nu number enhancement exceeding 196% [71]. GO and reduced graphene oxide (RGO) in water-EG blends show 236% and 320% heat transfer coefficient improvements respectively [72]. These exceptional values are attributable to the extremely high intrinsic thermal conductivity of graphitic carbon structures, high aspect ratios providing extended thermal pathways, and strong Brownian motion contributions at the concentrations studied.

B. Hybrid and Ternary Nanofluids

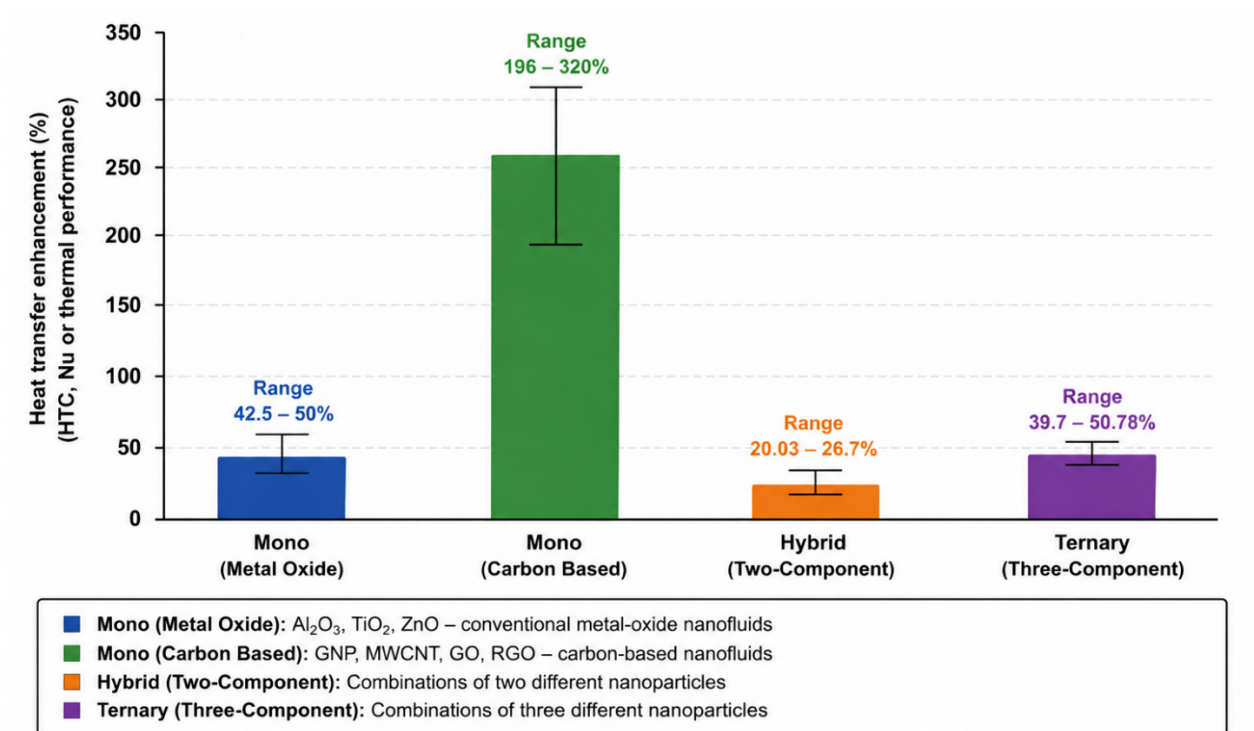
Hybrid nanofluids which are formed by dispersing two or more nanoparticle species simultaneously exhibit synergistic thermal performance that frequently surpasses the additive contribution of individual components. This synergy can be rationalised through three mechanisms: (i) complementary particle geometries producing more effective percolation networks a spherical oxide combined with a high-aspect-ratio CNT fills spatial gaps that neither particle alone would occupy; (ii) inter-particle thermal interface effects that reduce phonon scattering resistance at particle-fluid boundaries when dissimilar materials are in proximity; and (iii) improved long-term stability arising from electrostatic complementarity between particles with different surface charge characteristics, reducing agglomeration tendency. The RGO-CuO hybrid in 1:1 EG-WT at 0.01 vol% produces an 88.82-fold increase in Nusselt number [73], the highest enhancement factor reported in the reviewed literature. ZnO- Al_2O_3 - SiO_2 tri-hybrid nanofluids at approximately 1 vol% in 20:80 EG-WT demonstrate optimal cooling performance across idle, urban, and highway driving cycles [74]. Al_2O_3 - TiO_2 - SiO_2 ternary hybrid (0.3 vol% in 40:60 EG-WT) delivers 39.7% heat transfer coefficient enhancement on the coolant side [75].

The superior performance of hybrid nanofluids over mono nanofluids can be rationalised through: (i) complementary particle geometries producing more effective percolation networks; (ii) inter-particle thermal interface effects that reduce phonon scattering; and (iii) improved long-term stability arising from electrostatic complementarity between different particle surfaces. However, hybrid system design introduces additional complexity in preparation, stabilisation, and property prediction, as existing empirical models developed for mono nanofluids inadequately capture synergistic effects [3].

Table 2. Comparative heat transfer enhancement performance of mono, hybrid, and ternary nanofluids in automotive radiator studies.

Nanofluid Type	System	Conc.	HTC Enhancement	Nu Enhancement	Ref.
Mono – oxide	Al ₂ O ₃ -WT	1 vol%	45.87%	44.83%	[62]
Mono – oxide	ZnO-WT	0.2 vol%	50% (overall HTC)	31%	[68]
Mono – oxide	TiO ₂ -PG-WT	0.35 vol%	42.5%	—	[66]
Mono – carbon	GNP-WT	0.3 vol%	275% (perf.)	—	[70]
Mono – carbon	MWCNT-EG-WT	0.5 vol%	196% (mean HTC)	—	[71]
Hybrid	Fe ₂ O ₃ -TiO ₂ /WT	0.009 vol%	26.7%	20.03%	[76]
Hybrid	RGO-CuO/EG-WT	0.01 vol%	—	88.82×	[33]
Ternary	CuO-MgO-TiO ₂ /WT	0.5 vol%	TC: 50.78%	—	[30]
Ternary	ZnO-Al ₂ O ₃ -SiO ₂	1 vol%	Best drive cycle	—	[74]

Note: HTC = convective heat transfer coefficient; Nu = Nusselt number; TC = thermal conductivity. Values are relative to respective base fluid at optimal test conditions. *'Best drive cycle' for ZnO-Al₂O₃-SiO₂ indicates the nanofluid outperformed all other tested formulations across idle, urban, and highway conditions.

**Figure 3.** Comparative maximum thermal conductivity enhancement across nanofluid categories compiled from reviewed studies

Practical Challenges and Limitations

A. Erosion, Corrosion, and Clogging

The introduction of hard, high-density nanoparticles into coolant circuits introduces material degradation risks that are particularly acute in turbulent flow regimes and at elevated operating temperatures. Erosion tests on common radiator

materials (aluminium, copper, stainless steel) in the European NanoHex project demonstrated that aluminium suffers partial to significant degradation depending on nanofluid type and operating conditions, while copper and stainless steel showed minimal degradation [77-78]. ZrO₂ and TiO₂ nanofluids exhibited the highest erosion rates among tested nanoparticles, while SiC-based formulations showed the least

erosive impact [79-80]. Chemical corrosion was identified as the dominant degradation mechanism even at elevated nanoparticle concentrations, with pH management emerging as the critical control parameter for material protection [77-78].

Clogging remains a significant operational concern, particularly in microchannels and narrow flat-tube radiator passages. Al₂O₃ nanoparticles in microchannel heat sinks induced surface fouling and cluster formation under two-phase flow conditions [81]. Nanocellulose in ethylene glycol radiator fluid showed increased erosion on flat tubes at flow rates exceeding recommended limits [82]. Long-term field studies confirming acceptable erosion rates under real automotive duty cycles are conspicuously absent from the literature, representing a major barrier to commercialisation.

The preponderance of experimental evidence confirms that mono nanofluids enhance heat transfer coefficients, Nusselt numbers, and The preponderance of experimental evidence confirms that mono nanofluids enhance heat transfer coefficients, Nusselt numbers, and

B. Viscosity Penalty and Pumping Power

The viscosity increase accompanying nanoparticle addition imposes a direct penalty on system energy balance through elevated pressure drop and pumping power requirements. Pak and Cho reported a 31% increase in pumping power at 3 vol% concentration at constant fluid velocity [44]. Al₂O₃ in engine oil (10W-40) showed viscosity enhancement of 132% at 2 vol% and 55°C [83]. The net thermal advantage of a nanofluid is therefore determined by the relative magnitudes of heat transfer enhancement and pumping power penalty provides a trade-off that is concentration-dependent and system-specific. At lower concentrations (≤0.5 vol%), heat transfer benefits generally

outweigh viscosity penalties; at higher concentrations, this balance often reverses.

C. Measurement Inconsistency and Data Reliability

Contradictory data in the nanofluid literature are pervasive and arise from: (i) non-standardised preparation protocols leading to different agglomeration states; (ii) instrument-specific systematic errors in transient hot-wire, oscillating plate, and laser flash measurements; (iii) temperature and shear-rate dependent behaviour not consistently controlled across studies; and (iv) incomplete characterisation of nanoparticle size distribution, surface chemistry, and aggregation state [3]. These inconsistencies severely limit cross-study comparability and impede the development of universal predictive correlations.

Ultimately, the commercial viability of nanofluids in automotive cooling circuits depends not on peak heat transfer enhancement alone, but on achieving a favourable balance across the full performance envelope: sustained heat transfer improvement over extended service life, acceptable viscosity penalty and pumping power, chemical compatibility with radiator materials, and cost-effective preparation and maintenance requirements that current laboratory-scale studies have not yet collectively demonstrated.

Comparison of Nanofluid Classes and Preparation Strategies

A structured comparison of the principal dimensions comprising preparation method, stabilisation strategy, and nanofluid type reveals that no single optimum configuration exists; the preferred choice is context-dependent and represents a multi-objective optimisation across thermal performance, stability, cost, scalability, and safety.

Table 3. Structured comparison of nanofluid preparation methods, stabilisation strategies, and nanofluid types across key performance dimensions.

Dimension	Single-Step	Two-Step	Mechanical Stab.	Chemical Stab.	Mono NF	Hybrid NF
Dispersion Quality	High	Lower	Temporary	Long-term	Moderate	Better
Cost & Scalability	High cost	Low cost	Low cost	Moderate	Simpler	Complex
TC Enhancement	High	Moderate	—	—	High	Higher
Viscosity Impact	Moderate	Variable	—	—	Moderate–High	Moderate
Stability Duration	Long	Short w/o additive	Short-term	Long-term	Moderate	Better

Note: All comparisons are qualitative and based on aggregate trends reported across the reviewed literature. Individual nanofluid formulations may deviate from these general trends depending on specific nanoparticle chemistry, base fluid, concentration, and preparation method. This table is intended as a decision-support guide and should not be used as a quantitative design specification.

Hybrid nanofluids represent the current performance frontier: their synergistic thermal effects, combined with greater inherent stability relative to single-component

systems at equivalent concentrations, positions them as the most promising candidates for advanced automotive cooling applications. However, the added complexity of dual-particle

preparation, the scarcity of validated hybrid property models, and limited long-term durability data mean that mono nanofluids at optimised low concentrations (0.1–0.5 vol%) remain the practical choice for near-term deployment.

Empirical Correlations: Status and Limitations

A substantial body of empirical correlations for nanofluid thermal conductivity, viscosity, density, and specific heat has been developed over the reviewed period. Maxwell's [89] effective medium theory provides a physically transparent baseline for spherical particles at low concentrations but systematically underestimates enhancement at higher concentrations and for non-spherical geometries. The Hamilton-Crosser model extends Maxwell's framework with a particle shape factor, while more recent correlations incorporate Brownian motion [85], aggregation state [38], and nanolayer geometry [86].

For dynamic viscosity, Einstein's linear model ($\mu_{eff} = \mu_{bf}(1 + 2.5\phi)$) provides a useful lower bound but is valid

only for $\phi \leq 0.02$ and spherical particles, consistently underestimating practical nanofluid viscosities particularly for CNT-based systems [43]. The Krieger-Dougherty model, incorporating a maximum packing fraction parameter, offers the broadest applicability across nanoparticle types and concentration ranges [41].

Collectively, existing correlations are constrained by the assumptions of monodisperse spherical particles, perfect dispersion, and stable suspensions — conditions rarely met in practice. Their accuracy degrades markedly for hybrid nanofluids where cross-particle interactions create synergistic effects not captured by linear mixing rules. Machine learning approaches such artificial neural networks (ANNs), gradient boosting regressors, and Gaussian process regression have demonstrated superior predictive accuracy for complex nanofluid property datasets compared to analytical correlations, and represent a priority direction for future development.

Table 4. Summary of key empirical correlations for nanofluid thermal conductivity and dynamic viscosity.

Model	Property	Expression (simplified)	Applicability
Maxwell [84]	Thermal conductivity	$k_{nf}/k_{bf} = f(k_{np}, k_{bf}, \phi)$	Spherical particles; low ϕ ; good balance of accuracy and simplicity
Hamilton-Crosser	Thermal conductivity	Extends Maxwell with shape factor n	Non-spherical particles; shape factor $n=3/\psi$
Feng et al. [86]	Thermal conductivity	Incorporates $\lambda = tp/rp$ (thickness-to-radius ratio)	Accounts for nanoparticle geometry and nanolayer
Corcione [85]	Thermal conductivity	$k_{nf} = f(Re, Pr, T/T_{ref}, k_n/k_{bf}, \phi)$	T: 294–324 K; d_p : 10–150 nm; ϕ : 0.002–0.9%
Pak and Cho [44]	Thermal conductivity	$k_{nf}/k_{bf} = 1 + 7.47\phi$	General; includes diameter and surface resistance
Einstein [43]	Viscosity	$\mu_{eff} = \mu_{bf}(1 + 2.5\phi)$	Dilute suspensions; $\phi \leq 0.02$; spherical particles only
Brinkman [42]	Viscosity	$\mu_{eff} = \mu_{bf}(1 - \phi)^{-2.5}$	ϕ up to 0.04; spherical particles
Krieger-Dougherty [41]	Viscosity	$\mu_{eff} = \mu_{bf}(1 - \phi/\phi_m)^{(-[\eta]\phi_m)}$	Broadest applicability; wide concentration range
Batchelor [via [3]]	Viscosity	$\mu_{eff} = \mu_{bf}(1 + 2.5\phi + 6.5\phi^2)$	Includes particle-particle interaction effects

Note: This table provides a condensed summary of key correlations for design reference. Full mathematical expressions and fitting constants are available in the cited sources. All correlations were developed for mono nanofluids; their accuracy for hybrid and ternary systems is substantially reduced due to unaccounted synergistic effects.

Future Research Directions

A. Standardisation of Preparation and Characterisation Protocols

The most pressing need in the field is the establishment of universally adopted protocols for nanofluid preparation

(sonication energy, duration, sequence), characterisation (instrument calibration, sample conditioning, measurement interval), and reporting (full particle size distribution, zeta potential, pH, concentration verification). Without such standards, inter-laboratory data comparability will remain

severely limited and universal models cannot be developed with confidence.

B. Machine Learning for Property Prediction

The high-dimensional parameter space of nanofluid systems comprising nanoparticle type, size, shape, concentration, base fluid composition, temperature, pH, surfactant type/concentration, preparation history are ideally suited to data-driven modelling approaches. Taguchi-assisted Design of Experiments combined with Grey Relational Analysis and gradient boosting or deep neural network architectures can efficiently map the property space with reduced experimental burden, providing reliable predictions for untested formulations.

C. Hybrid and Ternary Nanofluid Optimisation

While hybrid nanofluids demonstrate superior performance, systematic parametric studies of particle ratio, combined concentration, and base fluid composition using Taguchi L9/L27 orthogonal arrays remain limited. Rigorous optimisation of hybrid formulations using multi-objective approaches (Pareto front analysis) that simultaneously maximise heat transfer enhancement while minimising viscosity penalty and cost would provide actionable design guidance.

D. Long-term Durability and Material Compatibility

Extended field tests (minimum 1000 hours) in operational automotive radiator circuits are needed to assess: (i) nanoparticle stability evolution under thermal cycling; (ii) erosion and corrosion rates on modern radiator alloys (Al 3003, Al 6061) and polymer pump components under realistic duty cycles; and (iii) fouling behaviour in louvered-fin radiator geometries typical of passenger vehicles.

E. Environmental, Health, and Safety Assessment

The aquatic toxicity, biodegradability, and disposal pathways of nanoparticle-laden coolants have received insufficient attention relative to performance studies. Lifecycle assessment (LCA) of nanofluid-based cooling systems by incorporating nanoparticle synthesis energy, operational gains in fuel efficiency, and end-of-life disposal impacts are essential for establishing whether the thermal performance advantages translate to a net environmental benefit.

F. Integration with Advanced Thermal Management Architectures

Next-generation vehicle thermal management systems by incorporating heat pump circuits, waste heat recovery (thermoelectric generators, ORC), and combined cooling of battery-electric drivetrains which create new application domains for nanofluids beyond the conventional ICE radiator. Nanofluid integration within phase-change material (PCM) thermal storage systems (nano-enhanced PCMs) and absorption cooling circuits represents a particularly promising research frontier for EV and hybrid vehicle applications.

Conclusions

This review has synthesised the state of the art in nanofluid research for automotive radiator applications, encompassing peer-reviewed studies from 2009 to 2025. The following principal conclusions are drawn:

1. Carbon-based nanofluids (graphene, MWCNTs, GO, RGO) consistently deliver the highest thermal conductivity enhancements (up to 161.8%) and heat transfer improvements, outperforming metal-oxide counterparts at equivalent concentrations due to intrinsically higher nanoparticle thermal conductivity and beneficial geometry effects.
2. Hybrid and ternary nanofluids exhibit synergistic thermal performance exceeding predictions from single-component models. ZnO-Al₂O₃-SiO₂ and CuO-MgO-TiO₂ ternary systems demonstrate exceptional combined performance in radiator heat transfer studies, confirming that multi-particle formulations represent the current performance frontier.
3. Colloidal stability governed by zeta potential, pH, surfactant selection, Brownian motion, and particle size is the critical practical constraint on nanofluid deployment. The SDBS surfactant provides stability exceeding 3 months for MWCNT-based systems; most unsurfacted nanofluids require pH management to achieve stability beyond 30 days.
4. Existing empirical correlations for thermal conductivity and viscosity prediction are insufficient for hybrid nanofluids and at elevated concentrations therefore use of machine learning methods which offer a superior route to reliable property prediction across the multi-dimensional nanofluid parameter space should be utilized.
5. The practical deployment of nanofluids in commercial automotive cooling circuits requires resolution of erosion, clogging, long-term stability, manufacturing cost, and environmental disposal challenges. It is found that none of them are adequately addressed by current literature. Standardised testing protocols are urgently needed to enable cross-study data comparability and accelerate commercialisation.

The convergence of advanced nanofluid formulations with machine-learning-aided design, improved stabilisation chemistry, and integration into next-generation vehicle thermal architectures positions nanofluids as a highly promising candidate technology for next-generation automotive thermal management, contingent on resolution of stability, durability, and commercialisation challenges.

Competing Interest

The author declares that there are no competing interests related to this work.

References

- [1] F. Abbas, H. M. Ali, T. R. Shah, H. Babar, M. M. Janjua, U. Sajjad, and M. Amer, "Nanofluid: Potential evaluation in automotive radiator," *J. Mol. Liq.*, vol. 297, pp. 1–25, 2020, doi: 10.1016/j.molliq.2019.112014.
- [2] W. W. Pulkrabek, *Engineering Fundamentals of the Internal Combustion Engine*. New Jersey, NJ, USA: Prentice Hall, 1997.
- [3] M. Gülüm, A. Çakmak, and S. Osman, "Nanofluids for automotive radiators: Thermophysical properties, opportunities, challenges, and research trends: A review," *Propuls. Power Res.*, vol. 14, no. 3, pp. 484–526, 2025, doi: 10.1016/j.jprr.2025.08.002.
- [4] R. A. Urthi, M. A. Islam, and M. N. A. Siddiki, "Comparative heat transfer analysis using synthesized nanofluids of SiO₂, Al₂O₃, CuO, and MgO of a car radiator," *Therm. Adv.*, vol. 3, p. 100049, 2025, doi: 10.1016/j.thradv.2025.100049.
- [5] G. A. Oliveira, E. M. C. Contreras, and E. P. B. Filho, "Experimental study on the heat transfer of MWCNT/water nanofluid flowing in a car radiator," *Appl. Therm. Eng.*, vol. 111, pp. 1450–1456, 2017, doi: 10.1016/j.applthermaleng.2016.05.086.
- [6] M. K. Abdolbaqi, N. A. C. Sidik, M. F. A. Rahim, R. Mamat, W. H. Azmi, M. N. A. W. M. Yazid, and G. Najafi, "Experimental investigation and development of new correlation for thermal conductivity and viscosity of BioGlycol/water based SiO₂ nanofluids," *Int. Commun. Heat Mass Transf.*, vol. 77, pp. 54–63, 2016, doi: 10.1016/j.icheatmasstransfer.2016.07.001.
- [7] W. E. Ukwueje, F. I. Abam, and A. Obi, "A perspective review on thermal conductivity of hybrid nanofluids and their application in automobile radiator cooling," *J. Nanotechnol.*, vol. 2022, pp. 1–51, 2022, doi: 10.1155/2022/2187932.
- [8] M. H. S. Bargal, A. N. Allam, A. M. Zaki, M. E. Zayed, L. M. Alhems, and H. M. Ali, "Thermohydraulic performance augmentation and heat transfer enhancement of automotive radiators using nanocoolants: A critical review," *J. Therm. Anal. Calorim.*, pp. 1–53, 2025, doi: 10.1007/s10973-025-14101-2.
- [9] P. Kumar and R. M. Sarviya, "Recent developments in preparation of nanofluid for heat transfer enhancement in heat exchangers: A review," *Mater. Today Proc.*, vol. 44, pp. 2356–2361, 2021, doi: 10.1016/j.matpr.2020.12.434.
- [10] A. Asadi et al., "Recent advances in preparation methods and thermophysical properties of oil-based nanofluids: A state-of-the-art review," *Powder Technol.*, vol. 352, pp. 209–226, 2019, doi: 10.1016/j.powtec.2019.04.054.
- [11] F. Mashali, E. M. Languri, J. Davidson, D. Kerns, W. Johnson, K. Nawaz, and G. Cunningham, "Thermophysical properties of diamond nanofluids: A review," *Int. J. Heat Mass Transf.*, vol. 129, pp. 1123–1135, 2019, doi: 10.1016/j.ijheatmasstransfer.2018.10.033.
- [12] H. M. Ali, H. Babar, T. R. Shah, M. U. Sajid, M. A. Qasim, and S. Javed, "Preparation techniques of TiO₂ nanofluids and challenges: A review," *Appl. Sci.*, vol. 8, no. 4, p. 587, 2018, doi: 10.3390/app8040587.
- [13] S. K. Das, S. U. Choi, W. Yu, and T. Pradeep, *Nanofluids: Science and Technology*, 1st ed. Hoboken, NJ, USA: John Wiley & Sons, 2007.
- [14] B. M. Praveenkumara, H. M. S. Murthy, B. S. Gowda, A. C. Dixith U, D. Shrinivasa, and E. Amruth, "Effect of low-concentration CuO and RGO hybrid nanofluids on thermal performance of automotive radiator: An experimental study and correlations development," *J. Therm. Anal. Calorim.*, 2025, doi: 10.1007/s10973-025-14129-4.
- [15] O. O. Oyeleke, O. S. Ohunakin, D. S. Adelekan, O. E. Atiba, M. O. Nkiko, and G. Jatinder, "Recent advancements in the development of nanofluid technology in heat transfer applications," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1107, no. 1, p. 012209, 2021, doi: 10.1088/1757-899X/1107/1/012209.
- [16] A. Ghadimi, R. Saidur, and H. S. C. Metselaar, "A review of nanofluid stability properties and characterization in stationary conditions," *Int. J. Heat Mass Transf.*, vol. 54, no. 17–18, pp. 4051–4068, 2011, doi: 10.1016/j.ijheatmasstransfer.2011.04.014.
- [17] P. Keblinski, J. A. Eastman, and D. G. Cahill, "Nanofluids for thermal transport," *Mater. Today*, vol. 8, no. 6, pp. 36–44, 2005, doi: 10.1016/S1369-7021(05)70936-6.
- [18] X. Q. Wang and A. S. Mujumdar, "Heat transfer characteristics of nanofluids: A review," *Int. J. Therm. Sci.*, vol. 46, no. 1, pp. 1–19, 2007, doi: 10.1016/j.ijthermalsci.2006.06.010.
- [19] Y. Li, J. E. Zhou, S. Tung, E. Schneider, and S. Xi, "A review on development of nanofluid preparation and characterization," *Powder Technol.*, vol. 196, no. 2, pp. 89–101, 2009, doi: 10.1016/j.powtec.2009.07.025.
- [20] R. Sadri, G. Ahmadi, H. Togun, M. Dahari, S. N. Kazi, E. Sadeghinezhad, and N. Zubir, "An experimental study on thermal conductivity and viscosity of nanofluids containing carbon nanotubes," *Nanoscale Res. Lett.*, vol. 9, pp. 1–16, 2014, doi: 10.1186/1556-276X-9-151.
- [21] S. Yan, F. Wang, Z. Shi, and R. Tian, "Heat transfer property of SiO₂/water nanofluid flow inside solar collector vacuum tubes," *Appl. Therm. Eng.*, vol. 118, pp. 385–391, 2017, doi: 10.1016/j.applthermaleng.2017.02.108.
- [22] G. M. Moldoveanu, A. A. Minea, G. Huminic, and A. Huminic, "Al₂O₃/TiO₂ hybrid nanofluids thermal conductivity: An experimental approach," *J. Therm. Anal. Calorim.*, vol. 137, pp. 583–592, 2019, doi: 10.1007/s10973-018-7974-4.
- [23] M. H. Esfe, S. Saedodin, W. M. Yan, M. Afrand, and N. Sina, "Study on thermal conductivity of water-based nanofluids with hybrid suspensions of CNTs/Al₂O₃ nanoparticles," *J. Therm. Anal. Calorim.*, vol. 124, pp. 455–460, 2016, doi: 10.1007/s10973-015-5104-0.

- [24] G. M. Moldoveanu, C. Ibanescu, M. Danu, and A. A. Minea, "Viscosity estimation of Al_2O_3 , SiO_2 nanofluids and their hybrid: An experimental study," *J. Mol. Liq.*, vol. 253, pp. 188–196, 2018, doi: 10.1016/j.molliq.2018.01.061.
- [25] L. K. L. Toh and T. W. Ting, "Numerical simulation of graphene-nanoplatelet nanofluid convection in millimeter-sized automotive radiator," *CFD Lett.*, vol. 16, pp. 32–52, 2024, doi: 10.37934/cfdl.16.6.3252.
- [26] M. Soltanimehr and M. Afrand, "Thermal conductivity enhancement of COOH-functionalized MWCNTs/ethylene glycol-water nanofluid for application in heating and cooling systems," *Appl. Therm. Eng.*, vol. 105, pp. 716–723, 2016, doi: 10.1016/j.applthermaleng.2016.03.089.
- [27] L. S. Sundar, E. V. Ramana, M. K. Singh, and A. C. M. Sousa, "Thermal conductivity and viscosity of stabilized ethylene glycol and water mixture Al_2O_3 nanofluids for heat transfer applications: An experimental study," *Int. Commun. Heat Mass Transf.*, vol. 56, pp. 86–95, 2014, doi: 10.1016/j.icheatmasstransfer.2014.06.009.
- [28] M. S. A. Khan, "Analytical examination of nano-fluid-assisted cooling rate enhancement in a car radiator," *Am. Int. J. Sci. Eng. Res.*, vol. 6, pp. 1–14, 2023, doi: 10.46545/aijser.v6i1.310.
- [29] B. C. Sahoo, D. K. Das, R. S. Vajjha, and J. R. Satti, "Measurement of the thermal conductivity of silicon dioxide nanofluid and development of correlations," *J. Nanotechnol. Eng. Med.*, vol. 3, no. 4, p. 041006, 2012.
- [30] A. Kumar and M. A. Hassan, "Heat transfer in flat tube car radiator with CuO-MgO-TiO_2 ternary hybrid nanofluid," *Powder Technol.*, vol. 434, pp. 1–20, 2024, doi: 10.1016/j.powtec.2023.119275.
- [31] X. Li, H. Wang, and B. Luo, "The thermophysical properties and enhanced heat transfer performance of SiC-MWCNTs hybrid nanofluids for car radiator system," *Colloids Surf. A Physicochem. Eng. Asp.*, vol. 612, pp. 1–10, 2021, doi: 10.1016/j.colsurfa.2020.125968.
- [32] X. Li, C. Zou, and A. Qi, "Experimental study on the thermo-physical properties of car engine coolant (water/ethylene glycol mixture type) based SiC nanofluids," *Int. Commun. Heat Mass Transf.*, vol. 77, pp. 159–164, 2016, doi: 10.1016/j.icheatmasstransfer.2016.08.009.
- [33] G. L. Dushyanthkumar, B. M. Praveenkumara, R. Shivashankar, and D. S. P. Muthuraju, "Experimental investigation of the enhancement of heat transfer rate in automobile radiator using low concentration hybrid nanofluids," *J. Mines Met. Fuels*, vol. 72, pp. 1187–1202, 2024, doi: 10.18311/jmmf/2024/46001.
- [34] A. T. M. Amin, W. A. W. Hamzah, and A. N. Oumer, "Thermal conductivity and dynamic viscosity of mono and hybrid organic- and synthetic-based nanofluids: A critical review," *Nanotechnol. Rev.*, vol. 10, no. 1, pp. 1624–1661, 2021, doi: 10.1515/ntrev-2021-0086.
- [35] J. M. Munyalo and X. Zhang, "Particle size effect on thermophysical properties of nanofluid and nanofluid based phase change materials: A review," *J. Mol. Liq.*, vol. 265, pp. 77–87, 2018, doi: 10.1016/j.molliq.2018.05.129.
- [36] L. S. Sundar, K. V. Sharma, M. K. Singh, and A. C. M. Sousa, "Hybrid nanofluids preparation, thermal properties, heat transfer and friction factor—A review," *Renew. Sustain. Energy Rev.*, vol. 68, pp. 185–198, 2017, doi: 10.1016/j.rser.2016.09.108.
- [37] H. Attari, F. Derakhshanfard, and M. H. K. Darvanjooghi, "Effect of temperature and mass fraction on viscosity of crude oil-based nanofluids containing oxide nanoparticles," *Int. Commun. Heat Mass Transf.*, vol. 82, pp. 103–113, 2017, doi: 10.1016/j.icheatmasstransfer.2017.02.007.
- [38] E. V. Timofeeva, D. S. Smith, W. Yu, D. M. France, D. Singh, and J. L. Routbort, "Particle size and interfacial effects on thermo-physical and heat transfer characteristics of water-based $\alpha\text{-SiC}$ nanofluids," *Nanotechnology*, vol. 21, no. 21, pp. 1–10, 2010, doi: 10.1088/0957-4484/21/21/215703.
- [39] M. A. Khairul, K. Shah, E. Doroodchi, R. Azizian, and B. Moghtaderi, "Effects of surfactant on stability and thermo-physical properties of metal oxide nanofluids," *Int. J. Heat Mass Transf.*, vol. 98, pp. 778–787, 2016, doi: 10.1016/j.ijheatmasstransfer.2016.03.079.
- [40] V. Kumaresan and R. Velraj, "Experimental investigation of the thermophysical properties of water-ethylene glycol mixture based CNT nanofluids," *Thermochim. Acta*, vol. 545, pp. 180–186, 2012, doi: 10.1016/j.tca.2012.07.017.
- [41] I. M. Krieger and T. J. Dougherty, "A mechanism for non-Newtonian flow in suspensions of rigid spheres," *Trans. Soc. Rheol.*, vol. 3, no. 1, pp. 137–152, 1959, doi: 10.1122/1.548848.
- [42] H. C. Brinkman, "The viscosity of concentrated suspensions and solutions," *J. Chem. Phys.*, vol. 20, no. 4, p. 571, 1952, doi: 10.1063/1.1700493.
- [43] A. Einstein, "A new determination of molecular dimensions," *Ann. Phys.*, vol. 4, no. 19, pp. 37–62, 1906.
- [44] B. C. Pak and Y. I. Cho, "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles," *Exp. Heat Transf.*, vol. 11, no. 2, pp. 151–170, 1998, doi: 10.1080/08916159808946559.
- [45] B. Takabi and S. Salehi, "Augmentation of the heat transfer performance of a sinusoidal corrugated enclosure by employing hybrid nanofluid," *Adv. Mech. Eng.*, vol. 6, pp. 1–16, 2014, doi: 10.1155/2014/14705.
- [46] Z. Said et al., "Enhancing the performance of automotive radiators using nanofluids," *Renew. Sustain. Energy Rev.*, vol. 112, pp. 183–194, 2019, doi: 10.1016/j.rser.2019.05.052.
- [47] B. Singh and S. Sood, "Hybrid nanofluids preparation, thermo-physical properties, and applications: A review," *Hybrid Adv.*, vol. 6, p. 100192, 2024, doi: 10.1016/j.hybadv.2024.100192.
- [48] S. D. Pandey and V. K. Nema, "Experimental analysis of heat transfer and friction factor of nanofluid as a

- coolant in a corrugated plate heat exchanger,” *Exp. Therm. Fluid Sci.*, vol. 38, pp. 248–256, 2012, doi: 10.1016/j.expthermflusci.2011.12.013.
- [49] D. P. Kulkarni, R. S. Vajjha, D. K. Das, and D. Oliva, “Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant,” *Appl. Therm. Eng.*, vol. 28, no. 14–15, pp. 1774–1781, 2008, doi: 10.1016/j.applthermaleng.2007.11.017.
- [50] E. D. Robertis, E. H. H. Cosme, R. S. Neves, A. Y. Kuznetsov, A. P. C. Campos, S. M. Landi, and C. A. Achete, “Application of the modulated temperature differential scanning calorimetry technique for the determination of the specific heat of copper nanofluids,” *Appl. Therm. Eng.*, vol. 41, pp. 10–17, 2012, doi: 10.1016/j.applthermaleng.2012.01.003.
- [51] A. Mohebbi, “Prediction of specific heat and thermal conductivity of nanofluids by a combined equilibrium and non-equilibrium molecular dynamics simulation,” *J. Mol. Liq.*, vol. 175, pp. 51–58, 2012, doi: 10.1016/j.molliq.2012.08.010.
- [52] W. Yu and H. Xie, “A review on nanofluids: Preparation, stability mechanisms, and applications,” *J. Nanomater.*, vol. 2012, no. 1, pp. 1–17, 2012, doi: 10.1155/2012/435873.
- [53] H. W. Chiam, W. H. Azmi, N. A. Usri, R. Mamat, and N. M. Adam, “Thermal conductivity and viscosity of Al_2O_3 nanofluids for different based ratio of water and ethylene glycol mixture,” *Exp. Therm. Fluid Sci.*, vol. 81, pp. 420–429, 2017, doi: 10.1016/j.expthermflusci.2016.09.013.
- [54] S. Lee and S. U. S. Choi, “Application of metallic nanoparticle suspensions in advanced cooling systems,” in *Proc. ASME Int. Mech. Eng. Congr. Expo.*, 2023, pp. 227–234, doi: 10.1115/IMECE1996-0161.
- [55] A. Asadi, M. Asadi, M. Siahmargoi, T. Asadi, and M. G. Andarati, “The effect of surfactant and sonication time on the stability and thermal conductivity of water-based nanofluid containing $\text{Mg}(\text{OH})_2$ nanoparticles: An experimental investigation,” *Int. J. Heat Mass Transf.*, vol. 108, pp. 191–198, 2017, doi: 10.1016/j.ijheatmasstransfer.2016.12.022.
- [56] L. Chen, H. Xie, Y. Li, and W. Yu, “Nanofluids containing carbon nanotubes treated by mechanochemical reaction,” *Thermochim. Acta*, vol. 477, no. 1–2, pp. 21–24, 2008, doi: 10.1016/j.tca.2008.08.001.
- [57] W. Xian-Ju and L. Xin-Fang, “Influence of pH on nanofluids’ viscosity and thermal conductivity,” *Chin. Phys. Lett.*, vol. 26, no. 5, p. 056601, 2009, doi: 10.1088/0256-307X/26/5/056601.
- [58] T. Missana and A. Adell, “On the applicability of DLVO theory to the prediction of clay colloids stability,” *J. Colloid Interface Sci.*, vol. 230, no. 1, pp. 150–156, 2000, doi: 10.1006/jcis.2000.7003.
- [59] I. Popa, G. Gillies, G. Papastavrou, and M. Borkovec, “Attractive and repulsive electrostatic forces between positively charged latex particles in the presence of anionic linear polyelectrolytes,” *J. Phys. Chem. B*, vol. 114, no. 9, pp. 3170–3177, 2010, doi: 10.1021/jp911482a.
- [60] S. Witharana, I. Palabiyik, Z. Musina, and Y. Ding, “Stability of glycol nanofluids—The theory and experiment,” *Powder Technol.*, vol. 239, pp. 72–77, 2013, doi: 10.1016/j.powtec.2013.01.039.
- [61] A. Ghadimi and I. H. Metselaar, “The influence of surfactant and ultrasonic processing on improvement of stability, thermal conductivity and viscosity of titania nanofluid,” *Exp. Therm. Fluid Sci.*, vol. 51, pp. 1–9, 2013, doi: 10.1016/j.expthermflusci.2013.06.001.
- [62] A. Gulhane and S. P. Chincholkar, “Experimental investigation of convective heat transfer coefficient of Al_2O_3 /water nanofluid at lower concentrations in a car radiator,” *Heat Transf. Asian Res.*, vol. 46, pp. 1119–1129, 2017, doi: 10.1002/hjt.21264.
- [63] S. M. Peyghambarzadeh, S. H. Hashemabadi, M. S. Jamnani, and S. M. Hoseini, “Improving the cooling performance of automobile radiator with Al_2O_3 /water nanofluid,” *Appl. Therm. Eng.*, vol. 31, pp. 1833–1838, 2011, doi: 10.1016/j.applthermaleng.2011.02.029.
- [64] R. A. Bhogare and B. S. Kothawale, “Performance investigation of automobile radiator operated with Al_2O_3 based nanofluid,” *IOSR J. Mech. Civ. Eng.*, vol. 11, no. 3, pp. 23–30, 2014.
- [65] S. A. Ahmed, M. Ozkaymak, A. Sözen, T. Menlik, and A. Fahed, “Improving car radiator performance by using TiO_2 -water nanofluid,” *Eng. Sci. Technol., Int. J.*, vol. 21, no. 5, pp. 996–1005, 2018, doi: 10.1016/j.jestch.2018.07.008.
- [66] K. Jagadishwar and S. S. Babu, “Performance investigation of water and propylene glycol mixture based nano-fluids on automotive radiator for enhancement of heat transfer,” *Int. J. Mech. Eng. Technol.*, vol. 8, pp. 822–833, 2017.
- [67] S. Devireddy, C. S. R. Mekala, and V. R. Veerredhi, “Improving the cooling performance of automobile radiator with ethylene glycol water based TiO_2 nanofluids,” *Int. Commun. Heat Mass Transf.*, vol. 78, pp. 121–126, 2016, doi: 10.1016/j.icheatmasstransfer.2016.09.002.
- [68] M. Qasim, M. S. Kamran, M. Ammar, M. A. Jamal, and M. Y. Javaid, “Heat transfer enhancement of an automobile engine radiator using ZnO water base nanofluids,” *J. Therm. Sci.*, vol. 29, pp. 1010–1024, 2020, doi: 10.1007/s11630-020-1263-9.
- [69] H. M. Ali, H. Ali, H. Liaquat, H. T. B. Maqsood, and M. A. Nadir, “Experimental investigation of convective heat transfer augmentation for car radiator using ZnO -water nanofluids,” *Energy*, vol. 84, pp. 317–324, 2015, doi: 10.1016/j.energy.2015.02.103.
- [70] H. N. Hao, T. T. Wei, L. T. K. Lik, and N. H. Jong, “Experimental study on convective heat transfer enhancement of automotive radiator with graphene-nanoplatelet suspension,” *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 101, pp. 60–72, 2023, doi: 10.37934/arfm.101.2.6072.
- [71] B. M’hamed, N. A. C. Sidik, M. F. A. Akhbar, R. Mamat, and G. Najafi, “Experimental study on thermal

- performance of MWCNT nanocoolant in Perodua Kelisa 1000cc radiator system,” *Int. Commun. Heat Mass Transf.*, vol. 76, pp. 156–161, 2016, doi: 10.1016/j.icheatmasstransfer.2016.05.024.
- [72] M. Sandhya, D. Ramasamy, K. Sudhakar, K. Kadirgama, and W. S. W. Harun, “Heat transfer performance of a radiator with and without louvered strip by using graphene-based nanofluids,” *J. Therm. Eng.*, vol. 7, pp. 1315–1328, 2021, doi: 10.18186/thermal.989959.
- [73] A. A. Mohammed, H. I. Dawood, and H. N. Onyeaka, “Experimental investigation of heat transfer enhancement using MWCNT/DW nanofluid as coolant for cars radiator,” *AIP Conf. Proc.*, vol. 3211, no. 1, p. 050001, 2025, doi: 10.1063/5.0257849.
- [74] F. Dika, M. Dagbasi, M. Adedeji, and H. Adun, “Performance analysis of a wavy fin-and-tube automobile radiator operating on ethylene glycol and water based ternary nanofluids,” *Heliyon*, vol. 11, p. e41509, 2025, doi: 10.1016/j.heliyon.2024.e41509.
- [75] A. I. Ramadhan, W. H. Azmi, and R. Mamat, “Heat transfer characteristics of car radiator using tri-hybrid nanocoolant,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 863, p. 012054, 2020, doi: 10.1088/1757-899X/863/1/012054.
- [76] F. Abbas et al., “Towards convective heat transfer optimization in aluminum tube automotive radiators: Potential assessment of novel Fe_2O_3 - TiO_2 /water hybrid nanofluid,” *J. Taiwan Inst. Chem. Eng.*, vol. 124, pp. 424–436, 2021, doi: 10.1016/j.jtice.2021.02.002.
- [77] R. Bubbico, G. P. Celata, F. D’Annibale, B. Mazzarotta, and C. Menale, “Experimental analysis of corrosion and erosion phenomena on metal surfaces by nanofluids,” *Chem. Eng. Res. Des.*, vol. 104, pp. 605–614, 2015, doi: 10.1016/j.cherd.2015.10.004.
- [78] S. Vaschetto, M. A. Darmani, A. Cavagnino, and A. Tenconi, “Nanofluids for rotating electrical machines cooling: Perspectives and challenges,” in *Proc. 21st Eur. Conf. Power Electron. Appl. (EPE’19 ECCE Europe)*, 2019, pp. 1–10, doi: 10.23919/EPE.2019.8915554.
- [79] O. Mahian, A. Kianifar, S. A. Kalogirou, I. Pop, and S. Wongwises, “A review of the applications of nanofluids in solar energy,” *Int. J. Heat Mass Transf.*, vol. 57, no. 2, pp. 582–594, 2013, doi: 10.1016/j.ijheatmasstransfer.2012.10.037.
- [80] N. Ullah and J. Ahmad, “Heat transfer augmentation in engineering thermal devices by incorporating nanofluid as heat transfer medium: An extensive review study,” Ph.D. dissertation, Dept. Mech. Prod. Eng., Islamic Univ. Technol., Bangladesh, 2018.
- [81] J. Lee and I. Mudawar, “Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels,” *Int. J. Heat Mass Transf.*, vol. 50, no. 3–4, pp. 452–463, 2007, doi: 10.1016/j.ijheatmasstransfer.2006.08.001.
- [82] I. Naiman, D. Ramasamy, and K. Kadirgama, “Effect of nanocellulose with ethylene glycol for automotive radiator application,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 788, p. 012096, 2020, doi: 10.1088/1757-899X/788/1/012096.
- [83] M. H. Esfe, M. Afrand, S. Gharehkhani, H. Rostamian, D. Toghraie, and M. Dahari, “An experimental study on viscosity of alumina-engine oil: Effects of temperature and nanoparticles concentration,” *Int. Commun. Heat Mass Transf.*, vol. 76, pp. 202–208, 2016, doi: 10.1016/j.icheatmasstransfer.2016.05.013.
- [84] J. C. Maxwell, *A Treatise on Electricity and Magnetism*, vol. 2. Oxford, U.K.: Clarendon Press, 1873.
- [85] M. Corcione, “Empirical correlating equations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids,” *Energy Convers. Manag.*, vol. 52, no. 1, pp. 789–793, 2011, doi: 10.1016/j.enconman.2010.06.072.
- [86] Y. Feng, B. Yu, P. Xu, and M. Zou, “The effective thermal conductivity of nanofluids based on the nanolayer and the aggregation of nanoparticles,” *J. Phys. D: Appl. Phys.*, vol. 40, no. 10, pp. 3164–3171, 2007, doi: 10.1088/0022-3727/40/10/020.