Thermal Conductivity Enhancement in Nanofluids: A Critical Review of Influencing Parameters, Hybrid Formulations, and Heat Transfer Applications

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ABSTRACT

This review examines experimental investigations into thermal-conductivity enhancement in conventional and hybrid nanofluids, with emphasis on nanoparticle composition, concentration, temperature, particle characteristics, base-fluid composition, and dispersion stability. This review presents a comprehensive overview of recent advances in thermal conductivity enhancement in nanofluids, incorporating relevant studies published between 2024 and 2026. Particular emphasis is placed on graphene oxide (GO)-based mono- and hybrid nanofluids, GO/MXene dispersions in water–ethylene glycol mixtures, and CuO–GO hybrid formulations. Recent developments in hybrid-nanofluid stability, thermophysical property measurement, and thermal performance are critically discussed in relation to findings from earlier studies. The review further examines the key parameters governing thermal conductivity enhancement, the challenges associated with stability and measurement reliability, and the potential of nanofluids for heat-transfer applications. Finally, existing research gaps are identified to guide future investigations toward the development of stable and thermally efficient nanofluids. Materials considered include metal oxides such as Al_2O_3 and CuO, carbon-based dispersions such as GO, and hybrid formulations combining different nanoparticles. Across the studies reviewed, thermal conductivity commonly increases with nanoparticle loading and, in many formulations, with temperature. However, the magnitude of enhancement varies with the nanoparticle–fluid combination, concentration basis, particle dimensions and morphology, preparation procedure, measurement technique, and stability of the suspension. Hybrid nanofluids can provide useful combinations of material properties, but their performance should not be assumed to exceed that of every corresponding mono-nanofluid without matched-condition comparisons. In addition, conductivity enhancement alone is insufficient to establish improved system-level heat-transfer performance because viscosity, pumping requirements, flow conditions, and long-term stability also affect practical outcomes. The review identifies the need for standardized reporting, reliable measurement and uncertainty assessment, matched comparisons of mono- and hybrid nanofluids, and application-specific evaluation.

Keywords: Nanofluids; thermal conductivity; hybrid nanofluids; graphene oxide; copper oxide; ethylene glycol–water; heat transfer; dispersion stability.

INTRODUCTION

Heat-transfer fluids play a central role in the performance of thermal power systems, refrigeration and air-conditioning equipment, electronic cooling, automotive radiators, heat exchangers, solar thermal systems and other energy technologies. The heat transport capability of a fluid is determined by the fluid thermophysical properties and the operating conditions and geometry of the system. Thermal conductivity is an important

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property as it characterizes conductive heat transport within the fluid but the convective heat-transfer coefficient is influenced by viscosity, density, specific heat, flow velocity, flow regime and surface geometry.

Nanofluids are conventional base fluids containing nanoscale particle suspensions. The materials studied were metal oxides, metals, carbon-based materials and mixtures of different particles. They have a potential advantage that the dispersed phase may improve the effective thermal conductivity of the suspension. The enhancement so obtained is not universal and depends on the particle and fluid properties, concentration, temperature, particle morphology, dispersion quality and measurement protocol. Also, the effective properties may change over time due to particle aggregation or sedimentation.

Previous works have investigated water-, ethylene glycol- and water–ethylene glycol (W–EG) based nanofluids containing CuO, Al_2O_3, ZnO, GO and hybrid mixtures. The reported enhancements vary from small increases at low loading to larger increases at higher concentrations, but values from different studies cannot be directly compared unless concentration definitions, temperatures, base-fluid compositions and measurement methods are taken into account. Therefore, the objective of this review is to synthesize trends reported in the literature provided, identify factors that help explain differences among results, and outline research priorities for reliable thermal-conductivity enhancement.

Scope and approach of the review

This paper presents a critical review of published research on thermal conductivity enhancement in nanofluids, with particular emphasis on reported enhancement trends and their relevance to heat-transfer applications. The review examines findings from experimental investigations and recent literature to discuss the influence of key parameters, including nanoparticle concentration, temperature, base-fluid composition, and hybrid nanoparticle formulations.

Nanofluid preparation and dispersion

Two-step method

In the two step method nanoparticles are produced separately and disperse in the selected base fluid. Magnetic stirring, ultrasonication and, where appropriate, surfactants may be employed to encourage dispersion. This route is widely employed because it is relatively simple and can accommodate commercially available powders. The main problem is the tendency of the ions to agglomerate or settle. The protocol of preparation and the time between preparation and measurement are important details to report.

One-step method

With the one-step method, nanoparticles are formed and dispersed in the base fluid in a single process. Skipping separate powder handling can help reduce agglomeration, though the method may require more complex synthesis and tighter process control. The best approach depends on the materials, production scale, cost, and desired stability.

For thermal-conductivity results to be reproducible, studies should report the particle supplier or synthesis method, purity, particle-size distribution, and morphology, when available. They should also specify the base-fluid composition, concentration basis, mixing and sonication conditions, surfactant type and amount, storage conditions, time elapsed before testing, and any stability assessment. Visual observations offer only qualitative evidence of short-term stability and should not be treated as a quantitative measure.

Factors influencing thermal conductivity

Nanoparticle material and morphology

Material choice shapes both the conductivity difference between the dispersed particles and the base fluid and the interactions at their interface. The studies reviewed here cover Al_2O_3, CuO, ZnO, copper, GO, and hybrid materials. Carbon-based materials such as GO may offer transport pathways and interfacial properties that differ

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from those of metal oxides, but their performance depends heavily on factors such as sheet size, oxidation state, dispersion, and orientation. Particle shape and morphology can also affect effective transport, so meaningful comparisons require well-characterized materials—not just their nominal names.

Nanoparticle concentration

Many of the cited studies find that thermal conductivity rises as particle concentration increases. This is a common pattern: with more dispersed particles present, a larger share of the material can help carry heat. The increase isn't necessarily linear, though, and its size may depend on factors such as particle aggregation, interfacial resistance, and how concentration is defined. Mass fraction and volume fraction are not interchangeable, so comparisons should always state which measure was used. Higher particle loadings can also raise viscosity or make the suspension less stable. As a result, the concentration that gives the highest conductivity may not be the best choice for a practical cooling system.

Temperature

Several studies reviewed here found that thermal conductivity increases as temperature rises, though the extent of the increase depends on the nanoparticle material and base-fluid composition. Changes in the base fluid's thermal conductivity, particle–fluid interactions, and suspension properties may all play a role. Because these effects vary by formulation, the temperature-dependent behaviour of one nanofluid should not be assumed to apply to others without experimental evidence.

Base-fluid composition

Water and ethylene glycol are widely used as base fluids, both separately and in mixtures. Water–ethylene glycol blends are especially useful when freeze protection or a specific operating-temperature range is needed, such as in automotive and thermal-management systems. Because the mixture ratio influences both thermal conductivity and viscosity, any reported percentage enhancement should be compared with the matching base fluid at the same temperature and composition.

Dispersion, aggregation, and measurement

Dispersion quality can affect both measured conductivity and the consistency of results. When particles aggregate, their effective size distribution changes, and they may settle out of the fluid. Surfactants can also alter fluid properties and interfacial behavior. Results may vary depending on the instruments and protocols used, so studies should report calibration, measurement temperature, equilibration time, repeat measurements, uncertainty, and the model or baseline used to calculate enhancement.

LITERATURE REVIEW

The studies reviewed generally show that thermal conductivity rises as nanoparticle concentration increases, and many also report higher conductivity at elevated temperatures. The extent of this improvement, however, depends on factors such as the nanoparticle material, base fluid, particle properties, operating conditions, and experimental setup. For this reason, results are best interpreted in the context of each material family and application, rather than as evidence for a universal ranking of nanofluids.

Ref	Author (s), year	Nanoparticle/basefluid	Experimental conditions or scope	Main reported result
[1]	Raja Sekhar and Sharma (2012)	Al_2O_3 / water	0.01–0.1 vol.%; 21–45 °C	Thermal conductivity increased with temperature, with enhancement up to 8%. Empirical prediction equations were developed.

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[2]	Rahmati and Reiszadeh (2019)	CuO / EG–water (50:50)	0.05, 0.1, 0.2 and 0.3 vol.%; 40–70 °C	Thermal conductivity increased with nanoparticle concentration and temperature.
[3]	Kavitha et al. (2022)	CuO / water	Up to 0.04 vol.%; parallel-flow double-pipe heat exchanger	Average heat-transfer coefficient increased with CuO concentration. This is an application-level heat-transfer result, not a reported conductivity percentage.
[4]	Chaichan et al. (2022)	CuO / water–EG (75:25)	2.0 vol.%; photovoltaic/thermal system	Approximately 140% thermal-conductivity increment was reported. Electrical and thermal efficiencies increased by 6.76% and 39.6%, respectively.
[5]	Yu et al. (2016)	CuO / glycol	0.25–1.5 vol.%; constant heat flux	At higher CuO concentrations, wall temperature decreased while Nusselt number and heat-transfer performance increased.
[6]	Kiani et al. (2019)	CuO / water	Automobile radiator application	Heat-transfer coefficient increased with nanoparticle volume fraction.
[7]	Serebryakova (2015)	Al_2O_3 / EG–water (90:10)	1.5 vol.%; particle diameter 13 nm	Thermal conductivity increased by up to 5% compared with the base fluid.
[8]	Yu (2009)	ZnO / ethylene glycol	5 vol.%	Thermal conductivity enhancement of 26.5% was reported. Enhancement varied non-linearly with volume fraction.
[9]	Ramadhan (2020)	Tri-hybrid nanoparticles / water–EG	Conditions not specified in the reviewed manuscript	The study investigated thermophysical properties of tri-hybrid nanofluids. A numerical conductivity enhancement is not available in the current literature description.
[10]	Garg et al. (2008)	Copper nanoparticles / ethylene glycol	Copper nanoparticles / ethylene glycol	Thermal conductivity was reported to be substantially higher than the Maxwell model prediction. The exact enhancement relative to the base fluid should be checked in the original paper.
[11]	Rahmatineja d et al. (2021)	Al_2O_3 and CuO / water- and EG-based fluids	1, 2, 3 and 4 vol.%; 20–50 °C	Thermal conductivity increased with concentration and temperature; smaller nanoparticle diameters produced higher conductivity.
[12]	Yadav et al. (2022)	GO / ethylene glycol	0.25 mass%	Thermal conductivity increased by up to 36.72%. Conductivity also increased with temperature and GO mass concentration.
[13]	Prasanna Shankara et al. (2022)	GO / EG–water (60:40)	0.1% GO; radiator application	Maximum heat-transfer enhancement of 71.1% and maximum Nusselt number of 192 were reported.

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[14]	Zennifer et al. (2015)	CuO / ethylene glycol	1 vol.%; 26 °C as stated in the manuscript	Thermal conductivity enhancement of 11% was reported.
[15]	Rostami et al. (2019)	CuO–GO / water–EG (50:50)	0.1–1.6 vol.%; 25–50 °C	Thermal conductivity enhancement of 43.4% was reported. Conductivity depended on nanoparticle concentration and temperature.
[16]	Nayebpashaee et al. (2022)	Graphene–Al_2O_3 / EG–water	2.5 vol.%; 263 and 303 K	Thermal-conductivity ratios increased by approximately 4.07% at 263 K and 44.02% at 303 K.
[17]	Singh et al. (2020)	GO–CuO / distilled water	0.03, 0.1 and 0.3 wt.%; 30, 45 and 60 °C	At 0.3 wt.% and 60 °C, conductivity increased by 12.4% for CuO, 51.6% for GO and 30% for the GO–CuO hybrid.
[18]	Shaik et al. (2023)	Cu–graphene / water	Low nanoparticle concentrations	Thermal conductivity and viscosity enhancement were reported compared with water. Numerical enhancement values are not specified in the reviewed manuscript.
[19]	Nabil et al. (2018)	TiO_2–SiO_2 (50:50) / water–EG (60:40)	3 vol.%	Thermal conductivity increased by 22.8% at 80 °C compared with the base fluid.
[20]	Akhgar et al. (2018)	TiO_2–MWCNT (50:50) / water–EG (50:50)	Different temperatures and volume fractions	Thermal conductivity increased with temperature and volume fraction; maximum enhancement of 38.7% was reported.
[21]	Saidur et al. (2011)	Review of different nanofluids	Various thermal-management applications	Reviewed nanofluid applications in electronics cooling, automotive radiators, heat exchangers, refrigeration, solar systems and other thermal-management applications.
[22]	Barai et al. (2023)	Review of nanofluids in heat exchangers	Various nanofluid systems	Reviewed the heat-transfer performance of nanofluids in heat exchangers. No single experimental enhancement value applies to this review.
[23]	Jin et al. (2024)	GO–MXene (1:1) / EG–water (50:50)	0.01–0.3 wt.%; 20–60 °C	Maximum thermal-conductivity increment of 33.49% at 0.3 wt.% and 60 °C. The nanofluid also maintained relatively low viscosity and good dispersion stability.
[24]	Kanti et al. (2024)	SiO_2, GO, TiO_2 and their hybrids / water	0–1 vol.%; 30–60 °C	GO nanofluid showed a maximum thermal-conductivity ratio increase of 52% at 1 vol.% and 60 °C. The maximum viscosity-ratio increase reported was 177% at 1 vol.% and 30 °C.

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[25]	Das et al. (2024)	Review of single and hybrid nanofluids	Preparation, stabilization and applications	Reviewed preparation and stabilization methods and their influence on the properties and practical applications of nanofluids. No single experimental conductivity enhancement value applies.
[26]	Rahman et al. (2024)	Review of different nanofluid systems	Preparation, properties, stability and heat-transfer applications	Reviewed nanofluid preparation, stability, thermophysical properties and thermal-performance enhancement. No single experimental conductivity enhancement value applies.
[27]	Manimaran et al. (2025)	Water-based hybrid nanofluids	Critical review of stability and thermal conductivity	Highlighted the relationship between dispersion stability and thermal conductivity, including the influence of aggregation, sedimentation and preparation conditions. No single experimental enhancement value applies.
[28]	Soleimanzadeh et al. (2025)	Al_2O_3–GO / water–EG (50:50)	0.1–1.6 vol.%; 25–50 °C	Thermal conductivity increased with concentration and temperature, with a maximum enhancement of approximately 38% at 1.6 vol.%.
[29]	Diabis and Abu Talib (2026)	GO–CuO / water-based hybrid nanofluid	0.15–0.75 vol.% as reported in the reviewed study; up to 50 °C	Maximum thermal-conductivity gain of 8.8% at 0.75 vol.% and 50 °C. A correlation was also proposed for predicting conductivity.

Overall, the studies reviewed suggest that adding nanoparticles usually increases nanofluid thermal conductivity. The degree of improvement, however, varies with the nanoparticle material, base fluid, concentration, temperature, and experimental setup. Both mono and hybrid nanofluids can improve thermal performance, though hybrid formulations do not always perform better. For practical applications, thermal conductivity should also be considered alongside viscosity, stability, and heat-transfer performance. When comparing reported enhancement percentages, it is also important to account for differences in concentration units (volume or weight fraction), base-fluid composition, temperature, and experimental conditions.

Hybrid nanofluids: opportunities and limitations

Hybrid nanofluids contain two types of particles, such as a metal oxide paired with a carbon-based material or two different oxides. They are designed to combine complementary properties or strike a practical balance among thermal transport, stability, cost, and ease of handling. Examples in the cited literature include CuO–GO, graphene–Al_2O_3, TiO_2–SiO_2, and TiO_2–MWCNT systems. While several studies report higher conductivity at increased concentrations, using two particle types alone does not prove a synergistic benefit.

To convincingly demonstrate a hybrid advantage, compare the hybrid fluid with the base fluid and each corresponding mono-nanofluid under the same conditions: total particle volume fraction, temperature, preparation protocol, and measurement method. Clearly state the ratio of the two particle types by mass or volume. Studies should also report viscosity, stability, and measurement uncertainty, since higher conductivity alone does not necessarily mean better overall thermal-hydraulic performance.

Relevance to heat-transfer applications

The reviewed literature identifies several potential applications for nanofluids, including automotive radiators, heat exchangers, photovoltaic/thermal systems, electronics cooling, refrigeration and air conditioning, industrial

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cooling, solar thermal equipment, and some high-heat-flux systems. Studies on radiators and photovoltaic/thermal systems show that research is moving beyond property measurements. Still, application claims should clearly separate measured thermal conductivity from observed heat-transfer coefficients, Nusselt numbers, thermal efficiency, and system-level energy savings.

When selecting a fluid for engineering use, conductivity is only one factor to consider. Viscosity, pumping power, pressure drop, corrosion and material compatibility, long-term stability, operating temperature, and cost also matter. Experiments should compare the nanofluid with the base fluid under the same flow and thermal boundary conditions. Any system-level benefit should be demonstrated through measured performance, not assumed from improved conductivity alone.

RESEARCH GAPS AND RECOMMENDATIONS

- **Standardization of experimental reporting:** Standardize the reporting of nanoparticle size and morphology, concentration basis, base-fluid composition, nanofluid preparation procedures, and measurement protocols to facilitate meaningful comparisons among studies.
- **Measurement accuracy and uncertainty:** Report measurement uncertainty, replicate measurements, instrument calibration details, and temperature-control procedures to improve the reliability and reproducibility of experimental results.
- **Matched-condition comparison of mono- and hybrid nanofluids:** Compare mono- and hybrid nanofluids at identical total nanoparticle volume fractions and operating conditions before attributing improvements to synergistic effects.
- **Quantitative stability assessment:** Investigate the long-term dispersion stability of nanofluids using quantitative characterization methods wherever possible, rather than relying exclusively on visual observations.
- **Combined thermal and hydraulic performance:** Evaluate thermal conductivity alongside viscosity, pressure drop, pumping power, and convective heat-transfer performance to identify practically useful operating conditions.
- **Validation of prediction models:** Validate empirical correlations and theoretical models using independent experimental datasets, clearly specifying their applicable temperature ranges, concentration limits, nanoparticle types, and base-fluid compositions.
- **Practical feasibility of hybrid nanofluids:** Expand investigations into low-concentration hybrid nanofluids while considering preparation costs, surfactant effects, dispersion stability, and practical scalability.

CONCLUSIONS

The studies reviewed here suggest that adding nanoparticles can improve the effective thermal conductivity of base fluids. Conductivity generally rises as nanoparticle concentration increases, and many studies also report higher values at elevated temperatures. The degree of improvement, however, varies widely with factors such as nanoparticle composition, size and shape, the base-fluid formulation, concentration, dispersion quality, and experimental conditions. Researchers have examined CuO, Al_2O_3, ZnO, graphene oxide (GO), and a range of hybrid particles in water, ethylene glycol, and water–ethylene glycol mixtures, highlighting the potential of nanofluids in thermal applications.

Both mono- and hybrid nanofluids can improve thermal conductivity and heat transfer. Hybrid formulations may benefit from the properties of different nanoparticles, but the studies reviewed do not show that they consistently outperform their mono-nanofluid counterparts. Performance depends on the particle combination and mixing

ratio, as well as nanoparticle concentration, base-fluid composition, and operating conditions. Comparisons under matched conditions are therefore essential for determining whether a genuine synergistic effect exists.

The literature reviewed also shows that improving thermal conductivity alone is not enough to determine whether a nanofluid is practical. Its viscosity and dispersion stability, along with pressure drop, pumping demands, and overall heat-transfer performance, must also be taken into account. Reported enhancement percentages should be compared with care, since studies may use different concentration bases, temperature ranges, base-fluid compositions, and measurement methods.

Future research should prioritize reproducible measurements, thorough uncertainty analysis, and quantitative assessments of dispersion stability. It should also validate both theoretical and empirical prediction models. Studies tailored to specific applications must evaluate thermal and hydraulic performance together to identify nanofluids that improve heat transfer while remaining practical to use.

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