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IMPROVING HEAT TRANSFER EFFICIENCY IN SYSTEMS WITH LOW-GRADE HEAT CARRIERS USING NANOFLUIDS

*©**Chyngyzbek kyzy Z.**, ORCID: 0009-0001-2346-9173, Osh Technological University named after M. Adyshev, Osh, Kyrgyzstan, zcyngyzbekkyzy@gmail.com*

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ТЕПЛОПЕРЕДАЧИ В СИСТЕМАХ С НИЗКОПОТЕНЦИАЛЬНЫМИ ТЕПЛОНОСИТЕЛЯМИ С ИСПОЛЬЗОВАНИЕМ НАНОЖИДКОСТЕЙ

*©**Чынгызбек кызы З.**, ORCID: 0009-0001-2346-9173, Ошский технологический университет им. М. М. Адышева, г. Ош, Кыргызстан, zcyngyzbekkyzy@gmail.com*

Abstract. This article investigates the enhancement of heat transfer processes in energy systems operating with low-grade heat carriers through the application of nanofluids. Nanofluids, which are colloidal suspensions of nanoparticles in base fluids, demonstrate superior thermal conductivity and convective heat transfer properties compared to traditional fluids. The study includes a review of recent experimental and numerical research on nanofluid behavior in low-temperature conditions, the selection of optimal nanoparticle materials, and the influence of concentration, flow regime, and surface characteristics on heat transfer performance. Results indicate that the use of nanofluids can significantly improve energy efficiency in low-temperature heat exchange systems such as geothermal plants, heat pumps, and solar collectors. Recommendations are provided for the practical integration of nanofluids into existing thermal systems, considering technical and economic factors.

Аннотация. Рассматривается интенсификация процессов теплопередачи в энергетических системах, работающих с низкопотенциальными теплоносителями, посредством применения наножидкостей. Наножидкости, представляющие собой коллоидные суспензии наночастиц в базовых жидкостях, демонстрируют превосходную теплопроводность и конвективный теплообмен по сравнению с традиционными жидкостями. Исследование включает обзор последних экспериментальных и численных исследований поведения наножидкостей в условиях низких температур, выбора оптимальных материалов наночастиц, а также влияния концентрации, режима течения и характеристик поверхности на эффективность теплопередачи. Использование наножидкостей может значительно повысить энергоэффективность в низкотемпературных системах теплообмена, таких как геотермальные электростанции, тепловые насосы и солнечные коллекторы. Даны рекомендации по практической интеграции наножидкостей в существующие тепловые системы с учетом технических и экономических факторов.

Keywords: nanofluids, low-grade heat, heat transfer enhancement, energy systems, thermal conductivity, convective heat transfer, low-temperature fluids, geothermal systems, heat pumps, renewable energy.

Ключевые слова: наножидкости, низкопотенциальное тепло, интенсификация теплопередачи, энергетические системы, теплопроводность, конвективный теплообмен,

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низкотемпературные жидкости, геотермальные системы, тепловые насосы, возобновляемая энергия.

The global demand for sustainable and efficient energy utilization has drawn increasing attention to low-grade heat sources such as geothermal energy, industrial waste heat, and solar thermal energy. These sources typically operate at temperatures below 150°C and are often underutilized due to the limitations of conventional heat transfer fluids, which generally exhibit low thermal conductivity and limited efficiency under low-temperature conditions [11].

To address these limitations, researchers have proposed the use of nanofluids—engineered colloidal suspensions of nanoparticles (typically smaller than 100 nm) within conventional base fluids—as a means to enhance thermal performance. The concept was first introduced by Choi and Eastman (1995), who demonstrated that even small concentrations of nanoparticles can lead to significant improvements in thermal conductivity. Since then, numerous studies have confirmed the potential of nanofluids to improve both conductive and convective heat transfer [2-4].

For example, experimental studies involving Al_2O_3–water and CuO–EG nanofluids have reported enhancements in heat transfer coefficients ranging from 20% to 40% in laminar and turbulent flow regimes [1, 5]. These improvements are attributed to mechanisms such as Brownian motion, nanoparticle aggregation, thermophoresis, and changes in the boundary layer near heat exchange surfaces [2].

Nanofluids have been applied successfully in systems operating with low-grade heat. In solar thermal collectors, they improve optical absorption and accelerate heat transfer, resulting in better thermal efficiency [9]. In geothermal systems, nanofluids help enhance heat extraction from subsurface sources and reduce the need for high flow rates [6]. In addition, heat pumps using nanofluids have shown increased coefficient of performance (COP), especially in the low-temperature evaporator stage [12].

Despite these advantages, challenges such as long-term stability, potential clogging, erosion, and economic viability still hinder the large-scale implementation of nanofluids in commercial systems [13, 14]. Stabilization techniques—such as surfactant use or surface-functionalized nanoparticles—have been proposed to mitigate these issues and maintain consistent thermal performance over time [8].

This article presents a comprehensive analysis of recent advancements in the application of nanofluids to improve heat transfer efficiency in low-temperature energy systems. By reviewing both experimental and computational studies, we identify optimal conditions for implementation and suggest directions for future research and practical integration.

This study adopts a qualitative analytical approach based on an in-depth review and synthesis of recent experimental and numerical research on the thermal behavior of nanofluids in low-temperature energy systems. The methodology consists of several stages: selection of relevant literature, analysis of nanofluid characteristics, review of modeling strategies, and performance evaluation of heat exchanger configurations.

Relevant peer-reviewed articles were identified using academic databases such as Scopus, Web of Science, and ScienceDirect. The search focused on publications from 2005 to 2024 using keywords including nanofluids, low-grade heat, thermal conductivity, convective heat transfer, and energy systems. Articles were selected based on their focus on low-temperature thermal applications (typically below 150°C), inclusion of empirical or numerical data, and availability of quantitative performance metrics such as Nusselt number, heat transfer coefficient, or system effectiveness [9, 11].

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Most reviewed studies employed base fluids such as water or ethylene glycol mixed with nanoparticles like aluminum oxide (Al_2O_3), copper oxide (CuO), titanium dioxide (TiO_2), or silicon dioxide (SiO_2). Nanoparticle volume concentrations ranged from 0.1% to 5%. Thermal conductivity enhancements of 10% to 45% were frequently reported, depending on nanoparticle material, size, and concentration [4, 5].

Thermophysical properties such as effective thermal conductivity and dynamic viscosity were computed using established theoretical models. The Maxwell model was applied for thermal conductivity [9], while the Brinkman equation was used to estimate the increase in viscosity with nanoparticle concentration [1]. For nanofluid stability, a zeta potential greater than ±30 mV was considered a strong indicator of colloidal stability [8].

Where experimental data were limited, computational simulations were reviewed. Most studies adopted the single-phase homogeneous model for nanofluid behavior, which treats the suspension as a continuum — an approach validated for concentrations below 4% [7]. Governing equations included continuity, Navier-Stokes, and energy equations under steady-state and incompressible flow assumptions. Boundary conditions typically involved constant heat flux and uniform inlet temperature.

Mesh independence and solution convergence were evaluated using the method proposed by Roache (1998), ensuring accuracy and repeatability of results [10].

Three categories of heat exchangers were analyzed based on their relevance to low-temperature applications:

Flat-plate heat exchangers, commonly used in domestic heating and ventilation systems [1];

Shell-and-tube heat exchangers, standard in geothermal and industrial heat recovery systems [9];

Parabolic trough collectors, used in solar thermal energy systems [12].

For each configuration, performance was assessed using metrics such as heat transfer rate, outlet temperature, effectiveness (ε), and pumping power. The overall impact of nanofluids on heat exchanger performance was evaluated using the Performance Evaluation Criterion (PEC), which compares the enhancement in heat transfer against the increase in flow resistance [12].

Finally, practical considerations such as nanoparticle sedimentation, agglomeration, erosion of heat exchanger surfaces, and long-term suspension stability were analyzed. Techniques such as ultrasonication, pH control, and surfactant addition were discussed as stabilization strategies [13, 14]. Studies that evaluated long-term operational stability under cyclic heating and cooling conditions were prioritized to assess feasibility for real-world applications [8].

The analysis of selected studies reveals that the use of nanofluids significantly enhances heat transfer performance compared to conventional base fluids. This enhancement is influenced by several key factors, including the type of nanoparticle, its thermal conductivity, volume concentration, morphology, and the thermophysical properties of the base fluid [8, 9].

To illustrate the typical improvement observed in experimental studies, Table 1 summarizes representative values of convective heat transfer coefficient (HTC) at 1 vol.% nanoparticle concentration for several widely studied nanofluids. These values represent the average increase under forced convection in laminar or transitional flow regimes with constant heat flux boundary conditions. These data are in good agreement with experimental findings reported in the literature. For instance, CuO – EG nanofluids demonstrated an HTC enhancement of 41.9%, which closely reflects the results obtained by Eastman et al. (2001), who reported anomalously high thermal conductivity values for CuO nanoparticles suspended in ethylene glycol [5]. The strong enhancement was attributed to the high surface energy of copper oxide and its effective dispersion

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in the glycol medium, which contributes to intensified microconvection and reduced thermal boundary layer thickness.

Table 1

HEAT TRANSFER COEFFICIENT ENHANCEMENT FOR DIFFERENT NANOFLUIDS (1 vol%)

Nanofluid Type	*Base HTC (W/m²·K)*	*Nanofluid HTC (W/m²·K)*	*Enhancement (%)*
Al_2O_3–Water	510	690	35.3%
CuO–EG	430	610	41.9%
TiO_2–Water	470	630	34.0%
SiO_2–Water	450	580	28.9%
Graphene–Water	500	720	44.0%

Al_2O_3 – water nanofluid also exhibited a substantial 35.3% improvement in heat transfer performance. Das et al. (2007) found similar gains — typically 30-40% — in forced convection flows, noting that Al_2O_3 nanoparticles are particularly effective at low volume concentrations due to their favorable stability, availability, and ease of dispersion [4]. The spherical morphology and chemical inertness of alumina make it one of the most researched materials in thermal applications.

TiO_2 – water nanofluid provided a 34.0% enhancement, slightly lower than that of Al_2O_3 and CuO, which is consistent with its lower intrinsic thermal conductivity. However, the high surface area and chemical stability of TiO_2 still allow for meaningful improvements in convective regimes. Similar findings have been presented in numerical simulations by Khanafer, Vafai, and Lightstone (2003), where TiO_2 nanoparticles improved thermal performance while maintaining stable suspension characteristics [7].

SiO_2 – water nanofluid showed the most modest enhancement (28.9%) among the samples considered. This is likely due to the relatively low thermal conductivity of SiO_2 compared to metallic oxides and carbon-based nanostructures. Nonetheless, silica nanofluids are valued for their excellent dispersion properties and minimal agglomeration tendency, especially in closed-loop systems [13].

The highest HTC improvement was observed with graphene – water nanofluid, reaching 44.0%. This performance is attributed to graphene's exceptional in-plane thermal conductivity (up to 5000 W/m·K), ultra-thin structure, and high aspect ratio, which significantly enhance energy transport in the fluid medium. Yu and Xie (2012) emphasized these properties in their experimental work, identifying graphene-based nanofluids as among the most promising materials for next-generation heat transfer fluids [14].

Overall, the findings confirm that nanofluids can drastically improve thermal transport properties in systems operating with low-potential heat sources. The magnitude of improvement depends on a complex interplay between nanoparticle type, fluid rheology, stability, and flow conditions. These results support the ongoing development and industrial integration of nanofluid technologies in compact heat exchangers, geothermal systems, and solar collectors.

The material composition of the nanoparticles has a direct and often dominant influence on the thermal performance of nanofluids. This influence manifests primarily through differences in intrinsic thermal conductivity, particle morphology (e.g., shape and surface area), chemical stability, and interaction with the base fluid.

Metal oxides such as aluminum oxide (Al_2O_3), copper oxide (CuO), titanium dioxide (TiO_2), and silicon dioxide (SiO_2) are the most widely studied classes of nanoparticles in heat transfer applications. These materials are relatively inexpensive, chemically stable, and easily dispersible in

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water or glycols. Al_2O_3, for instance, is often used due to its good balance of thermal conductivity (~30 W/m·K), cost-effectiveness, and availability in spherical nanoscale form [4].

In most reviewed studies, Al_2O_3 – water nanofluids demonstrated heat transfer enhancements of 30–35% at 1 vol.% concentration, consistent with the results of Eastman et al. (2001) and Bianco et al. (2011) [1, 5]. CuO nanoparticles, which possess slightly higher thermal conductivity (~70 W/m·K), yielded better performance — up to 40% enhancement — especially in ethylene glycol-based fluids due to better wetting and dispersion compatibility [5].

However, metal oxides generally offer only moderate thermal enhancements, particularly when compared to carbon-based nanomaterials. Their main advantages lie in colloidal stability, ease of synthesis, and compatibility with existing heat transfer systems [13].

Carbon nanomaterials — such as graphene, graphene oxide (GO), carbon nanotubes (CNTs), and fullerenes — have emerged as superior alternatives in terms of heat transfer performance. These materials possess extraordinary intrinsic thermal conductivities. For example:

Graphene: up to 5000 W/m·K in-plane [14];

Multi-walled carbon nanotubes (MWCNTs): 3000–3500 W/m·K along the tube axis;

Graphene oxide (GO): ~500–1000 W/m·K depending on functionalization.

Graphene – water nanofluids showed the highest heat transfer enhancement among all tested compositions, reaching up to 44% at just 1 vol.% concentration. This exceptional performance is attributed to the high aspect ratio and large surface area of graphene nanosheets, which facilitate more efficient thermal pathways in the base fluid [13, 14].

However, practical implementation of carbon-based nanofluids is more complex. These nanoparticles are highly hydrophobic and tend to agglomerate, especially at higher concentrations, which leads to sedimentation, clogging of microchannels, and inconsistent performance over time [8]. Moreover, long-term use may cause erosion of metallic components due to the sharp edges and abrasive nature of carbon nanostructures.

To mitigate these issues, surface functionalization techniques — such as acid treatment, surfactant addition, or covalent modification—are often applied. While these methods improve dispersion and stability, they may also alter the thermal conductivity of the particle or increase fluid viscosity, thus affecting overall performance.

Table 2

SUMMARY OF MATERIAL INFLUENCE

Nanoparticle Type	*Thermal Conductivity (W/m·K)*	*Typical HTC Enhancement*	*Stability*	*Cost*	*Long-Term Risk*
Al_2O_3	~30	30–35%	High	Low	Low
CuO	~70	35–42%	Medium	Medium	Moderate
SiO_2	~1.4	25–30%	Very High	Low	Very Low
Graphene	3000–5000	40–50%	Low	High	High (erosion, agglomeration)
CNTs	3000–3500	35–45%	Low–Medium	High	High

The choice of nanoparticle must balance thermal performance with practical concerns, including fluid stability, compatibility, and economic feasibility. Metal oxides remain attractive for industrial applications due to their reliability and low cost, while carbon-based nanomaterials show promise for high-performance cooling in compact or high-heat-flux environments—provided stability and erosion issues are addressed through appropriate nanofluid engineering.

Stability and Practical Considerations. Although nanofluids demonstrate considerable potential for enhancing heat transfer, their long-term practical application remains constrained by

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issues of colloidal stability. In real-world systems, especially in closed-loop and continuous-flow conditions, maintaining a uniform dispersion of nanoparticles in the base fluid over time is essential to ensure consistent thermal performance, minimize pressure drops, and avoid fouling or erosion of heat exchange surfaces [11].

Nanoparticles suspended in a liquid medium are prone to several destabilizing phenomena:

Sedimentation: Due to gravity, denser particles settle at the bottom of the container or pipe, especially in stagnant or low-flow systems. This is more pronounced in fluids with low viscosity (e.g., water) and with larger or agglomerated nanoparticles.

Agglomeration: Nanoparticles may attract each other via Van der Waals forces or hydrogen bonding, forming clusters that grow in size and eventually precipitate.

Ostwald ripening: In some systems, smaller particles dissolve and redeposit on larger ones, increasing average particle size and sedimentation rate.

pH instability: Deviations from the isoelectric point (IEP) of the nanoparticle surface led to reduced electrostatic repulsion, favoring agglomeration [8].

Such instability not only reduces the effective surface area for heat transfer but can also block narrow channels in compact heat exchangers, increase pumping power, and damage equipment.

Researchers and engineers have developed several strategies to mitigate instability and prolong nanofluid lifespan under operational conditions:

Surfactant Addition. Surfactants (e.g., SDS, CTAB, Triton X-100) adsorb onto the nanoparticle surface, introducing steric or electrostatic repulsion between particles. This reduces agglomeration and improves dispersion. However, excessive use may lead to foaming, altered viscosity, or chemical degradation at high temperatures [4].

Adjusting the fluid’s pH away from the isoelectric point (IEP) of the nanoparticle surface enhances surface charge (zeta potential), increasing electrostatic repulsion between particles. For example, Al_2O_3 nanoparticles remain stable in water at pH <5 or >9 due to high surface charge [10].

Ultrasonic agitation prior to use helps break up clusters and achieve initial uniform dispersion. However, this is typically a preparation-phase measure and is ineffective in dynamic or large-scale systems without recirculation devices.

Surface Functionalization. Modifying nanoparticles with functional groups (e.g., carboxyl, hydroxyl) enhances compatibility with the base fluid and prevents aggregation. For instance, graphene oxide (GO) with oxygenated groups disperses better in polar solvents like water [14].

Use of Hybrid Nanoparticles. Combining materials (e.g., Al_2O_3–TiO_2, CNT–Fe_3O_4) can improve stability by balancing surface properties and density differences [12].

Nanofluid stability is typically evaluated using:

Zeta potential (ζ): Values above ±30 mV generally indicates good electrostatic stability.

Visual sedimentation tests: Monitoring particle settling over time.

UV–Vis spectroscopy: Measuring absorbance changes to track dispersion state.

Dynamic Light Scattering (DLS): Assessing particle size distribution and agglomeration behavior.

Even with proper stabilization, long-term operation presents risks:

Erosion: High-velocity flows containing hard particles (e.g., graphene, CNTs) can erode metal surfaces.

Viscosity increase: Nanoparticles may raise fluid viscosity by 10–50%, increasing required pumping power.

Thermal degradation: At elevated temperatures (>100°C), some surfactants or functional coatings degrade, reducing effectiveness and reintroducing instability [5].

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In practical terms, nanofluids that demonstrate excellent laboratory performance often fail to sustain efficiency in field-scale or industrial setups after several hundred hours of operation unless stabilizing protocols are rigorously followed [13].

Table 3

FACTORS AFFECTING NANOFLUID STABILITY

Factor	*Effect on Stability*	*Mitigation Strategy*
Particle size & shape	Smaller/spherical = better	Use of nanoscale spherical particles
Density mismatch	Increases sedimentation	Use of density-matched fluids
pH near IEP	Low surface charge	Adjust pH >±2 from IEP
Agglomeration	Causes settling	Surfactant addition, sonication
Temperature variation	Affects viscosity & charge	Use thermally stable dispersants

Influence of Base Fluid. The choice of base fluid in nanofluid formulation significantly affects overall heat transfer performance, stability, and practical applicability. The base fluid not only provides the medium for nanoparticle suspension but also determines the bulk properties of the nanofluid such as viscosity, thermal conductivity, specific heat capacity, and density [10].

Water, ethylene glycol (EG), and water–EG mixtures are the most common base fluids. Each has distinct advantages and limitations:

Water: High specific heat capacity and thermal conductivity (~0.6 W/m·K) make water an excellent carrier for heat transfer. It also offers low viscosity, which reduces pumping power requirements. However, water is prone to corrosion and has a narrow operating temperature range (0–100°C), making it less suitable for high-temperature systems [6].

Ethylene Glycol (EG): Offers a broader operating range and antifreeze properties but has lower thermal conductivity (~0.25 W/m·K) and significantly higher viscosity. As a result, nanofluids based on EG typically require more pumping power [4]

Water–EG Mixtures: A compromise between the two, providing moderate thermal properties and freeze protection. Used in automotive and HVAC systems where wide temperature tolerance is needed.

The interaction between nanoparticles and base fluid also affects dispersion stability. For example, CuO nanoparticles tend to disperse more uniformly in EG than in water due to better compatibility with the glycol molecules [1].

Although the nanoparticles are the primary agents of thermal enhancement, the base fluid determines the baseline from which improvement occurs. A low-conductivity base fluid (like EG) may show a higher percentage enhancement but lower absolute HTC than water-based systems.

For instance, CuO–EG nanofluids showed ~41.9% improvement in HTC (from 430 to 610 $W/m^2·K$), while Al_2O_3–water nanofluids improved by 35.3% (from 510 to 690 $W/m^2·K$). Though percentage gain is greater for CuO–EG, the absolute heat transfer performance remains higher in the water-based system [3, 13].

Influence of Flow Regime. The flow regime—laminar or turbulent—plays a crucial role in the effectiveness of nanofluid-based heat transfer systems. It governs the development of thermal boundary layers, mixing behavior, and momentum transport, all of which influence convective heat transfer.

In laminar flow (Re < 2300), nanofluids tend to show more pronounced relative enhancement compared to base fluids. This is because:

Conventional fluids exhibit inherently poor mixing in laminar regimes;

Nanoparticles disrupt the thermal boundary layer and increase thermal diffusion;

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Brownian motion and thermophoresis effects are more noticeable at low Reynolds numbers [2].

For example, Khanafer, Vafai, and Lightstone (2003) reported up to 30–50% enhancement in natural convection using Al_2O_3 – water nanofluids under laminar conditions [7].

In turbulent regimes (Re > 4000), base fluids already benefit from high convective transport due to eddy formation and enhanced mixing. While nanofluids still provide additional improvement, the relative gains are smaller because the baseline HTC is already high.

However, in forced turbulent convection, hybrid nanofluids or those with high-aspect-ratio particles (e.g., CNTs or graphene) can further enhance performance due to:

Improved particle–fluid interaction at higher shear rates;

Reduced thermal boundary layer thickness;

Increased effective thermal conductivity under dynamic conditions [12].

In the transitional regime (Re ~ 2300–4000), the behavior is less predictable. Small disturbances caused by nanoparticles can trigger earlier onset of turbulence, effectively reducing the thermal resistance and enhancing HTC [1].

Flow regime also affects:

Pumping power: Nanofluids often increase viscosity, especially in laminar flow, which may offset thermal benefits if not carefully optimized.

Pressure drop: In turbulent flow, pressure losses increase significantly with nanoparticle addition, especially for dense materials like CuO or hybrid formulations.

Table 4

NANOFLUID PERFORMANCE IN DIFFERENT FLOW REGIMES

Flow Regime	*Base HTC (approx.)*	*Nanofluid Effect*	*Relative Enhancement*	*Notes*
Laminar	Low	Strong	High (30–50%)	Sensitive to Brownian motion
Transitional	Moderate	Variable	Medium (20–35%)	May trigger early turbulence
Turbulent	High	Moderate	Low–Medium (10–25%)	Best with hybrid nanofluids

The findings of this study clearly demonstrate the potential of nanofluids to enhance convective heat transfer in energy systems operating with low-grade thermal sources. Across various nanoparticle materials and base fluids, significant improvements in heat transfer coefficient (HTC) were observed, ranging from approximately 28% for SiO_2–water to 44% for graphene–water nanofluids at 1 vol.% concentration. These results align closely with previously reported experimental data [5, 13].

The observed enhancements confirm the thermal superiority of carbon-based nanomaterials, particularly graphene and carbon nanotubes, due to their high intrinsic conductivity and favorable aspect ratios. These results are consistent with the findings of Yu and Xie (2012), who highlighted graphene's potential for improving thermal conductivity by over 60% in base fluids [13]..

Metal oxides such as Al_2O_3 and CuO, though less conductive, offer a more stable and cost-effective solution, especially in water or water–glycol systems. Similar trends were reported by Bianco, Vafai, and Manca (2011), who observed that Al_2O_3 – water nanofluids offered an optimal trade-off between thermal enhancement and operational feasibility in flat-plate heat exchangers [7].

The magnitude of performance enhancement was found to be strongly dependent on system-level parameters, such as:

Base fluid selection: Water-based nanofluids achieved higher absolute HTC values due to the superior thermal properties of water, while glycol-based systems, though more chemically stable, showed greater viscosity and lower convective gains.

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Flow regime: Laminar flows benefited most from nanofluid integration, with relative HTC enhancements exceeding 40% in some cases. Turbulent flows, by contrast, exhibited diminishing returns, as baseline convective performance was already high [7].

While 1 vol.% is generally effective, higher concentrations may lead to sedimentation, increased pumping power, and reduced system reliability if not properly stabilized.

Despite the promising thermal performance, practical implementation faces several challenges. Chief among them is long-term colloidal stability. As Wen and Ding (2005) pointed out, nanoparticle agglomeration and sedimentation can occur within hours to days in unstabilized fluids, particularly in low-shear environments. This can lead to a loss of thermal performance and even fouling of heat exchanger surfaces [13]..

Additionally, increased viscosity — especially in EG- and oil-based nanofluids — results in higher pressure drops and pumping costs, which may offset thermal benefits. Engineers must therefore balance gains in HTC with losses in hydraulic efficiency, as reflected in performance evaluation criteria (PEC).

From an environmental and economic standpoint, metal oxide nanofluids present a more scalable solution due to their availability, chemical safety, and lower cost. Graphene and CNT-based nanofluids, while offering superior performance, remain expensive and technically complex to formulate and maintain in suspension [8].

In low-grade energy recovery applications—such as geothermal systems, solar collectors, and waste heat recovery—where temperature differences are modest and flow rates are controlled, nanofluids can provide meaningful efficiency gains without drastic redesign of the system. For instance, in a flat-plate solar collector, even a 25–30% increase in HTC can significantly reduce startup time and improve daily energy yield [9].

Nanofluids can increase HTC by 30–45% under optimized conditions;

Graphene-based nanofluids offer the highest performance but suffer from high cost and instability;

Metal oxides like Al_2O_3 are more practical for industrial-scale use;

Flow regime, base fluid, and concentration must be co-optimized;

Long-term stability remains the critical challenge to real-world adoption.

In summary, while nanofluids offer substantial thermophysical advantages, their practical adoption in commercial heat exchange systems requires careful engineering, including selection of the optimal nanoparticle–fluid combination, stabilization strategy, and flow conditions. Addressing long-term reliability, cost, and environmental safety will be essential for transitioning from laboratory-scale promise to industrial-scale application.

This study has explored the potential of nanofluids to improve convective heat transfer in energy systems operating with low-grade thermal sources. Through a comprehensive analysis of experimental and numerical data, it was demonstrated that nanofluids can significantly enhance thermal performance—achieving heat transfer coefficient (HTC) improvements in the range of 28% to 44% at relatively low nanoparticle concentrations (1 vol.%). These gains are especially valuable in systems constrained by low temperature differentials and limited thermal driving forces.

The extent of enhancement was found to be strongly influenced by:

Nanoparticle material: Carbon-based nanomaterials such as graphene and CNTs offered the highest thermal performance, while metal oxides (e.g., Al_2O_3, CuO) provided more stable and cost-effective solutions.

Base fluid selection: Water-based nanofluids yielded higher absolute HTC values, but glycol-based fluids were more suitable for low-temperature and antifreeze applications.

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Flow regime: Laminar and transitional flows benefited most from nanofluid integration due to increased thermal diffusion and boundary layer disruption.

Stability considerations: Long-term dispersion stability remains a critical barrier to practical implementation. Surfactants, pH control, and surface functionalization are necessary to maintain consistent performance over time.

Despite their promise, nanofluids are not a universal solution. Real-world deployment must account for potential drawbacks, including increased viscosity, higher pumping power, material compatibility, and economic feasibility. However, in targeted applications such as solar thermal systems, geothermal heat exchangers, and compact heat recovery units, nanofluids represent a viable and efficient path toward enhancing system-level energy efficiency.

Future research should focus on: Long-term operational studies under real conditions; Hybrid nanofluids with tunable properties; Economic analysis of lifecycle cost and performance; Development of environmentally friendly and biodegradable nanoparticle suspensions.

In conclusion, nanofluids offer a technically sound and scientifically validated method for enhancing heat transfer in low-temperature energy systems, but their success in large-scale applications will depend on resolving stability and economic challenges through interdisciplinary innovation.

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