

Review on Nanofluids: Preparation, Properties, Stability, and Thermal Performance Augmentation in Heat Transfer Applications

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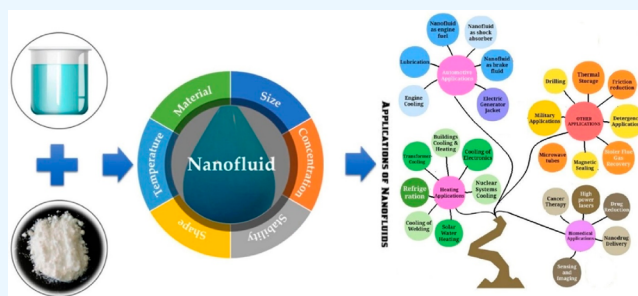
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ABSTRACT: Nanoparticles play a crucial role in enhancing the thermal and rheological properties of nanofluids, making them a valuable option for increasing the efficiency of heat exchangers. This research explores how nanoparticle characteristics, such as concentration, size, and shape, impact the properties of nanofluids. Nanofluids' thermophysical properties and flow characteristics are essential in determining heat transfer efficiency and pressure loss. Nanoparticles with high thermal conductivity, such as metallic oxides like MgO, TiO₂, and ZnO, can significantly improve the heat transfer efficiency by around 30% compared to the base fluid. The stability of nanofluids plays a crucial role in their usability.

Various methods, such as adding surfactants, using ultrasonic mixing, and controlling pH, have been employed to enhance the stability of nanofluids. The desired thermophysical properties can be achieved by utilizing nanofluids to enhance the system's heat transfer efficiency. Modifying the size and shape of nanoparticles also considerably improves thermal conductivity, affecting nanofluid viscosity and density. Equations for determining heat transfer rate and pressure drop in a double-pipe heat exchanger are discussed in this review, emphasizing the significance of nanofluid thermal conductivity in influencing heat transfer efficiency and nanofluid viscosity in impacting pressure loss. This Review identifies a trend indicating that increasing nanoparticle volume concentration can enhance heat transfer efficiency to a certain extent. However, surpassing the optimal concentration can reduce Brownian motions due to higher viscosity and density. This Review offers a viable solution for enhancing the thermal performance of heat transfer equipment and serves as a fundamental resource for applying nanofluids in heat transfer applications.



1. INTRODUCTION

The revolutionary impact of nanotechnology, with its distinctiveness compared to conventional scales, has garnered significant attention. This exponential growth has been fueled by its diverse applications across various sectors, such as medicine, agriculture, engineering, and industry.^{1–5} As a scientific discipline, nanotechnology delves into the properties of materials at the nanoscale.

Nanotechnology facilitates the manipulation of materials at the nanolevel, where particles are one billionth of a meter or 10⁻⁹ meters. For instance, materials like alumina and titanium oxide, with relatively high thermal conductivity, can be engineered into small nanosized particles. These nanosized particles are integrated into base fluids for heat transfer, forming a stable colloidal solution. When added to base fluids with low thermal conductivity, they can enhance the fluids' heat transfer characteristics. This innovative concoction, known as nanofluid, represents one of the recent advancements in nanotechnology. Notably, nanofluid introduces new heat transfer characteristics, contributing to energy conservation akin to downsizing heat transfer equipment.⁶

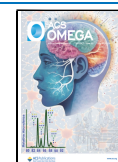
Industries like chemicals, food, oil, and gas utilize double-pipe HX for various purposes like pasteurization, sterilization, reheating, preheating, digester heating, and effluent heating. These heat exchangers are also common in renewable energy systems like solar energy, waste heat recovery, geothermal, combustion, latent heat energy storage, and air conditioning. The advantage of double-pipe HX lies in their modest design and ease of maintenance. They are typically compact in size and can be easily installed in various locations. Additionally, double-pipe HX are cost-effective and have a high thermal efficiency, making them an attractive option for many industrial applications. One of the key benefits of double-pipe heat exchangers is their versatility. They can be used for both liquid-to-liquid and gas-to-liquid HX processes, making

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them appropriate for various applications. Also, double-pipe HX can handle various temperatures and Δp conditions, making them suitable for use in demanding industrial environments.

Thermal energy management relies heavily on the use of HX. In reply to the energy crunch, there is a growing demand for efficient HX to support the growth of energy-saving technologies in various industries. Researchers are concentrating on enhancing equipment design and the thermal characteristics of working fluids to attain optimal energy efficiency. This focus on energy optimization is crucial as conventional fuel sources have limitations. Improving the performance of HX can lead to significant energy savings. Numerous forms of HX, like plate-type HX, double-pipe HX, HP, and mini-channel/heat sinks, offer compactness, effectiveness, flexibility, and high thermal performance. Plate-type HX was initially designed to meet the needs of dairy industries and has since found numerous applications in engineering sectors, including heat recovery, HVAC, cooling, power generation, and refrigeration. Double-pipe HX is commonly used in power plants for electricity generation, with heaters and economizers being key components.⁷ The simplicity, ease of cleaning, and low cost of double-pipe HX have made them popular in various applications.⁸ Portable devices like laptops and mobile phones require efficient cooling solutions, which has led to the development of mini/micro channels and HP. While improved HT in HX leads to greater efficiency, it also increases pumping power requirements, necessitating a balance between enhanced HT and associated Δp .⁹ The primary issue concerning nanoliquids is the substance used for the solid particles. A wide range of metals, metal oxides, and carbon-based materials are accessible, all of which are suitable options for improving HT and have good mechanical properties. The main emphasis is finding the most effective material with minimal drawbacks compared to other options while still performing well in all key areas. It may seem logical to prioritize materials with high thermal conductivity, like silver or copper, to set a standard for other nanoliquid materials. However, this is not always the case. In addition to thermal properties, the long-term stability of the nanoliquid is crucial. As an outcome, extensive research has been shown to address stability issues, including various chemical and physical treatments to maintain stability.

The most recent research reviews the capabilities of nanoliquid employed in HX with extended surfaces. Since these techniques are rarely used together, limited information is available on this dual approach. The novelty of this research lies in the lack of comprehensive evidence or reviews discussing the use of nanofluid with extended surfaces. This paper delves deeper into this concept by examining the effectiveness and characteristics of various kinds of fins and nanofluid particles found in existing literature, consolidating this information into a single paper. This review aims to be a cutting-edge assessment of the combined use of nanofluid and extended surfaces in enhancing heat transfer, highlighting key differences in studies, applications, and working conditions. This comprehensive understanding of the impact of key parameters is crucial for improving heat transfer. In contrast to other reviews focused on specific applications, this review explores a variety of applications for both methods, such as solar collectors, car radiators, and nuclear fuel rods, to emphasize the effects of critical parameters like particle concentration and flow patterns on thermal performance. Therefore, it is essential to conduct this review to advance

knowledge in the field. This review primarily focuses on improving h_m , Nu , HT rates, TPF, and other related enhancements that can be impacted by using nanofluid. By suggesting new avenues for exploration, this review aims to promote further research that can significantly contribute to the field of HT augmentation. Ultimately, this research may serve as a valuable resource for researchers seeking to understand and enhance HT using nanofluids.

Below are essential points elucidated in this review article. Categorization of nanofluids.

- Recent advancements in engineering thermal application owing to innovative HT mediums (nanofluid).
- Several significant parameters need to be considered while selecting and preparing nanofluids.
- Impact of integrating passive methods on HT and Δp efficiency of heat transfer applications.
- Elaboration of significant factors that play a vital part in enhancing heat transfer characteristics of nanofluid.
- Different models are used for calculating the thermodynamic properties of nanofluid.

2. NANOFUIDS: FUNDAMENTALS, SYNTHESIS, STABILITY, AND PROPERTIES

Nanoparticles within nanofluids are minute solid particles dispersed throughout the base fluid, exhibiting a specific motion. They function as heat carriers, directly conveying energy.¹⁰ Additionally, they can be likened to “stirrers,” generating microconvection currents that augment the effective thermal conductivity of the base fluid. This enhancement primarily stems from the heightened motion of molecules, consequently increasing their collision frequency and facilitating greater heat transfer through conduction. In contrast to microsized particles, nearly 20% of the total atoms within a nanoparticle (with sizes <20 nm) reside on the surface, enabling efficient absorption and heat transfer. Conversely, microsized particles predominantly harbor their atoms beneath the surface, limiting their involvement in heat transfer processes.

Several hypotheses encompassing the principles of heat conduction in nanofluids offer insights that could aid in understanding and verifying mechanisms for enhancing thermal conductivity. These include nanoparticle Brownian motion, nanoparticle aggregation, the formation of a liquid nanolayer surrounding nanoparticles, ballistic transport and nonlocal effects, thermophoresis, and near-field radiation (see Figure 1). Although all these mechanisms have the potential to explain the increase in thermal conductivity, there is a considerable likelihood that they may not apply uniformly across all nanofluid systems. This is primarily due to the diverse behavior exhibited by a wide range of nanomaterials when interacting with different base fluids.¹¹

2.1. Selection of Nanoparticles Based on the Base Fluid. The primary determinant of nanofluid thermal conductivity lies in the foundational fluid, which constitutes the predominant portion of its composition. While nanoparticles contribute to improving thermal conductivity, the foundational fluid exerts the greatest influence. Thus, selecting the foundational fluid is equally crucial to choosing nanoparticles. A diverse array of foundational fluids suitable for deployment includes water, ethylene glycol, natural and synthetic oils, ionic liquids, and refrigerants. Nanofluids formulated with foundational fluids possessing high thermal

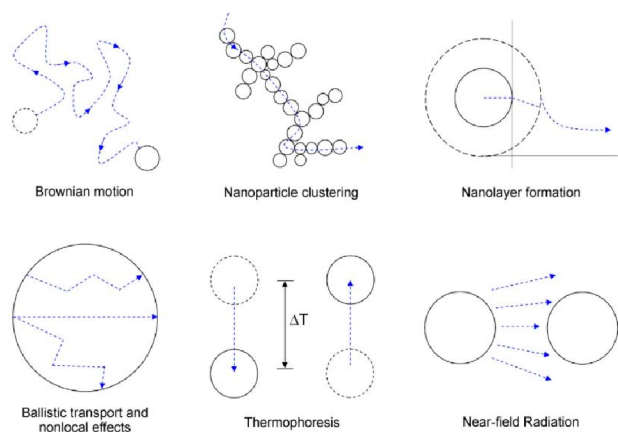


Figure 1. HT mechanisms of nanofluids. Reproduced with the permission of Bhanvase and Barai.¹⁰ Copyright 2021 Elsevier Inc.

conductivity exhibit superior thermal conductivity compared to those formulated with lower thermal conductivity. Despite ethylene glycol's thermal conductivity being three times inferior to water's, it demonstrates a greater enhancement in thermal conductivity. An endeavor to elucidate this phenomenon relates to the dispersibility of nanoparticles in different foundational fluids illustrated in Figure 2; nanofluids

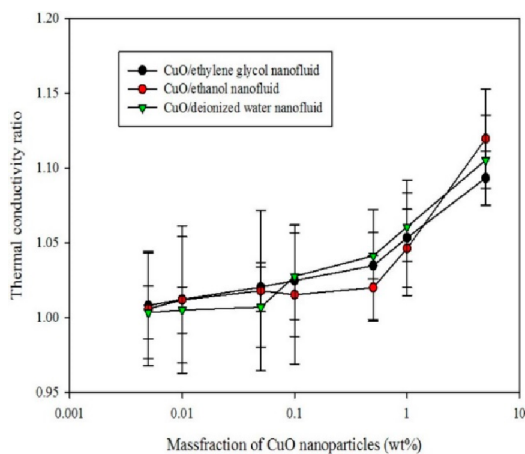


Figure 2. Thermal conductivity of CuO nanofluid (5 wt %) as a function of temperature using water, ethanol, and ethylene glycol as base fluids. Reproduced with the permission of Dehkordi and Abdollahi.¹² Copyright 2018 Elsevier Ltd.

containing identical nanoparticles display varying rates of thermal conductivity ratio augmentation with temperature elevation owing to differences in foundational fluids.¹²

Nanoparticle-infused fluids are seen as an innovative solution for enhancing HT in various engineering settings, offering a versatile and effective approach. Due to their small size, they can be utilized in microscale devices, showing promise in industries such as automotive,^{13,14} HVAC, and electronics.¹⁵ This technology could be used as a unique form of coolant for cars, leading to better thermal performance and benefits like improved fuel efficiency, reduced pollution, and enhanced engine performance.¹⁶ They could also improve coolants in small-scale environments with limited cooling space.¹⁷ Recently, adding nanoparticles to PCM has reduced melting time, resulting in nanoparticle-enhanced PCM for better thermal energy storage.^{18–20} However, it is essential to

acknowledge that the use of nanoparticle-infused fluids can alter the liquid's physical properties, increasing density and viscosity in an unfavorable manner.²¹ This can lead to the formation of nanoparticle clusters that may block flow channels during turbulent movements. Additionally, due to the potential instability of nanoparticle-infused fluids, using high concentrations of the main liquids is not advisable. Therefore, maintaining stability and nanoparticle concentration in these fluids is crucial and is an area of ongoing research to develop reliable products for industrial use.

Different types of nanofluids are categorized into three key categories based on the materials present. The first category, Group A, consists of mononanofluids containing only one type of nanoparticle, such as metals like Al, metal oxides like Al₂O₃, or carbon-based nanoparticles like GNPs. A few of them are shown in Table 1.

Table 1. k_p of Group A Nanoparticles and Base Fluids

material	thermal conductivity (W/mK)	ref
silver	424	22
aluminum	273	22
iron	80	22
copper	398	22
steel	46	23
Al ₂ O ₃	40	24
TiO ₂	8.37	25
CuO	77	26
ZnO	29	27
SiO ₂	1.2	28
diamond	3300	29
graphite	2000	30
CNT	2000	31
water	0.608	32
ethylene glycol	0.257	22
40:60% EG/W	0.404	33

The second category, Group B, includes nanofluids combining two or more different solid nanoparticles.^{34,35} Lastly, Group C comprises hybrid nanofluids comprising polymeric, metallic, or nonmetallic materials with significant differences in solids or phase change materials.^{36,37} Various efficient techniques must be employed for their preparation to ensure the stability of nanofluids and minimize sedimentation and changes in chemical composition. These techniques may involve adjusting the pH of the suspension, using surfactants as dispersants, or employing ultrasonic vibration.³⁸ The main objective of implementing these methods is to modify the surface physiognomies of nanoparticles, enhance their dispersibility within the base fluid, and avert particle agglomeration.³⁹ Equations 1–4 describe the governing equations linking nanofluids' hydraulic and thermophysical properties and base fluids based on nanoparticle ν_f . Equations 5 to (9) are essential HT equations used for data analysis to study the THP. A few of Group C are shown in Table 2.

$$k_{\text{nano}} = \frac{k_{\text{nanoparticle}} + 2k_{\text{base fluid}} + 2\varphi(k_{\text{nanoparticle}} - k_{\text{base fluid}})}{k_{\text{nanoparticle}} + 2k_{\text{base fluid}} - \varphi(k_{\text{nanoparticle}} - k_{\text{base fluid}})} k_{\text{base fluid}} \quad (1)$$

40

$$\rho_{\text{nanofluid}} = (1 + \varphi)\rho_{\text{base fluid}} \quad (2)$$

41

Table 2. Few Group C Nanofluids

investigators	nanoparticles	base liquid
Suresh et al. ⁴⁴	Al ₂ O ₃ -Cu	H ₂ O
Esfe et al. ⁴⁵	MWCNT-ZnO	oil
Esfe et al. ⁴⁶	Cu-TiO ₂	H ₂ O/EG
Abbasi et al. ⁴⁷	Al ₂ O ₃ /MWCNT	H ₂ O
Afrand ⁴⁸	fMWCNT-MgO	EG
Gürbüz et al. ⁴⁹	CuO-Al ₂ O ₃	H ₂ O
Ahmed ⁵⁰	Al ₂ O ₃ -graphene	H ₂ O
Chen et al. ⁵¹	Fe ₂ O ₃ /MWCNT	H ₂ O
Esfe et al. ⁵²	Ag-MgO	H ₂ O
Chopkar et al. ⁵³	Al ₂ Cu/Ag ₂ Al	H ₂ O/EG
Martin et al. ⁵⁴	Fe-CuO	H ₂ O
Minea ⁵⁵	SiO ₂ /TiO ₂ /Al ₂ O ₃	H ₂ O
Asadi and Asadi ⁵⁶	MWCNT-ZnO	oil
Gürbüz et al. ⁵⁷	ZnO-Al ₂ O ₃	ammonia/water
Nine et al. ⁵⁸	Cu-CuO ₂	H ₂ O
Jana et al. ⁵⁹	CNT-Au	H ₂ O
Baghbazadeh et al. ⁶⁰	silicon-MWCNT	H ₂ O
Paul et al. ⁶¹	Al-Zn	EG
Munkhbayar et al. ⁶²	Ag-MWCNT	H ₂ O
Batmunkh et al. ⁶³	Ag-TiO ₂	H ₂ O
Arani and Pourmoghadam ⁶⁴	Al ₂ O ₃ /MWCNT	EG
Farajzadeh et al. ⁶⁵	Al ₂ O ₃ /TiO ₂	H ₂ O
Esfe et al. ⁶⁶	MgO-SWCNT	EG
Giwa et al. ⁶⁷	γ-Al ₂ O ₃ /MWCNT	H ₂ O
Giwa et al. ⁶⁸	MgO-ZnO	H ₂ O

$$\mu_{\text{nanofluid}} = (1 + 2.5\phi + 6.25\phi^2)\mu_{\text{base fluid}} \quad (3)$$

42

$$C_{p,\text{nanofluid}} = \frac{[(1 - \phi)\rho_{\text{base fluid}} \cdot C_{p,\text{base fluid}} + \phi\rho_{\text{nanofluid}} \cdot C_{p,\text{nanofluid}}]}{\rho_{\text{nanofluid}}} \quad (4)$$

43

$$Re_h = \frac{\rho U D_h}{\mu} \quad (5)$$

$$Pr = \frac{C_p \mu}{k} \quad (6)$$

$$Nu = \frac{h D_h}{k} \quad (7)$$

$$\Delta P = f \frac{L}{D} \frac{\rho V^2}{2} \quad (8)$$

$$PEC = \frac{Nu}{Nu_{\text{smooth}}} \left(\frac{f}{f_{\text{smooth}}} \right)^{-1/3} \quad (9)$$

2.2. Nanofluid Preparation. The perfect colloidal suspension containing nanoparticles requires even distribution and excellent stability. However, because of these particles' high surface area and energy, they tend to clump together and settle in the liquid, impacting the HT properties of the fluid.⁶⁹ Therefore, achieving a stable suspension of nanofluids is crucial. The stability of these fluids is subjective to the preparation process, whether it be a one-step approach^{70,71} or a two-step process.⁷²⁻⁷⁴

In Figure 3, the single-step process involves the thermal breakdown of nanoparticles under reduced pressure.^{75,76} This

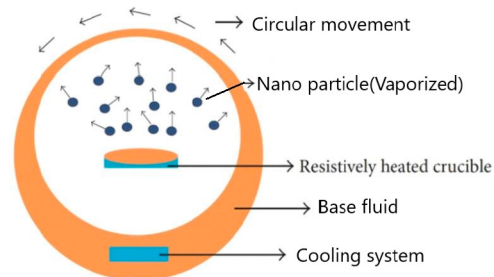


Figure 3. Single-step method. Reprinted with the permission of Kong et al.⁷⁶ Copyright 2017 from the Royal Society of Chemistry.

approach simplifies the conversion of nanoparticles into liquid form without requiring multiple preparatory steps.⁷⁷ Highlighted as a benefit, the single-step method eradicates the need for drying, storing, transporting, dispersing, and oxidizing, resulting in enhanced stability while reducing particle aggregation.

A more commonly utilized method for producing nanofluids is the two-step process (Figure 4), which is deemed simpler

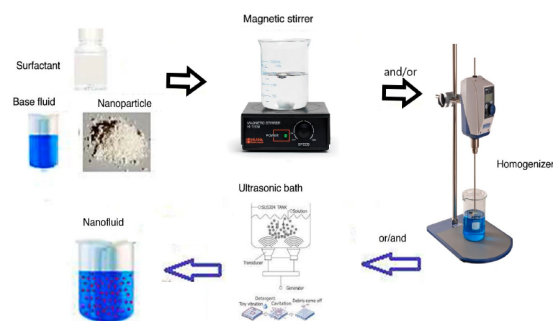


Figure 4. Two-step process.

and more cost-efficient. This technique is preferred for creating nanofluids composed of oxides.⁷⁸ The process entails converting nanoparticles into a powdered form using chemical, physical, or biological methods and then dispersing the powder in a base liquid. Uniform and stable nanofluids are typically achieved through ultrasonic agitation, ball milling, and magnetic stirring.⁷⁹ Due to the straightforward and economical nature of producing nanopowders, this method is potentially suitable for commercial industrial applications. However, the two-step process often leads to poor dispersion of the nanoparticles. Thus, researchers have introduced additional steps to enhance dispersion quality and minimize aggregation.⁷⁵ These supplementary measures may involve the use of surfactants^{80,81} surface modification or functionalization,^{82,83} pH adjustment,⁸⁴ and others. Many experiments have utilized this approach due to its potential in commercial and industrial settings.⁸⁵⁻⁸⁹ Challenges, however, are present with the two-step approach, such as swift settlement, additional stages, and elevated surface energy.⁹⁰ The difference in the above to nanofluid preparation has been depicted in Figure 5.

The assessment of colloidal suspensions involves a range of characterization examinations, including Scanning Electron Microscopy, Transmission Electron Microscopy, Differential Scanning Calorimetry, and other analyses aimed at studying the configuration, composition, and attributes of the nanoparticles.⁸⁷ In addressing the issue of nanoparticles' instability, stability assessments are crucial, as clustering could potentially

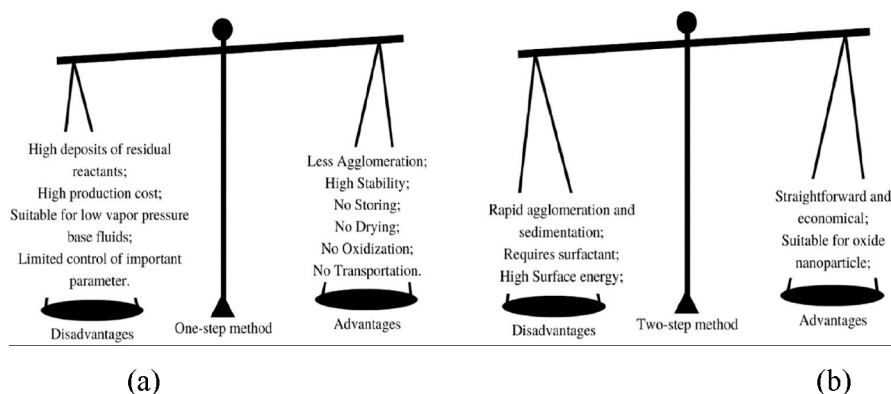


Figure 5. Advantages and disadvantage of (a) one-step and (b) two-step nanofluid preparation. Reprinted with the permission of Ho et al.⁸⁸ Copyright 2023 Elsevier Inc.

disrupt thermal mechanisms. To avert nanofluid agglomeration and guarantee peak efficiency, multiple stability tests must be conducted.

2.3. Nanofluid Stability. Particles at the nanoscale in liquids experience intricate stress conditions and have a high level of surface activity, making them susceptible to self-polymerization when in basic liquids. Once aggregated particles reach a certain size, these nanoparticles settle, leading to an uneven dispersion of particles. This instability at a larger scale affects the flow behavior and HT properties of the liquid-containing nanoparticles. Over time, the polymerized particles settle out of the liquid. Techniques such as using the appropriate electrolyte as a dispersant, adding surfactants, and applying ultrasonic vibrations during dispersion help address nanofluids' suspension stability issues. In sedimentation testing, the suspension's stability is assessed by capturing sedimentation images in a tube using a camera. Although the settling process is visible, ultrasonic vibrations can disrupt the nanoparticle interactions. Dispersants create a repulsive force between particles, reducing their tendency to clump together and settle as particle swarms.⁷³ Stability issues stemming from interactions between particles and with the liquid are a significant concern for nanofluids; other factors, such as temperature and magnetic fields, can also impact nanofluids' stability.⁹¹

The intensity of the magnetic field is significant for nanofluids. Hong et al.⁹² studied how the strength and duration of magnetic fields affect nanofluids' kp . When magnetic nanoparticles (Fe_2O_3) are subjected to a magnetic field, they create networks and align along the field's direction, increasing physical interaction and higher kp . They observed a 35% boost in thermal conductivity without a magnetic field. However, lengthy exposure to the magnetic field triggered the accumulation of large particle clusters over time, reducing kp . The magnetic field weakens the opposing force between suspended particles, causing them to clump together. Chang et al.⁹³ inspected the impact of magnetic fields on the stability of CuO nanofluids and found that stability deteriorated more quickly with a magnetic field present. This led to particle aggregation and the formation of larger particles.

Similarly, Zhang et al.⁹⁴ looked at how particle ϕ affects the stability of SiO_2 (water-based) nanofluids. They noted that higher ϕ led to poor initial stability, resulting in agglomeration and decreased efficiency in heat transfer.⁹⁵ The balance between van der Waals forces causing agglomeration and the electrical double-layer repulsion force separating particles

determines the stability of a nanofluid.^{96–98} Enhancing the repulsive forces between particles is essential for maintaining stability.

2.4. Stability Enhancement Methods. **2.4.1. Surfactant Addition.** A nanofluid liquid typically involves a pair of elements. These consist of nanoparticles and basic fluid. The stability of nanofluid depends on the kind of nanoparticles and the base fluid. Nanoparticles may be hydrophobic or hydrophilic, while base liquids might be polar or nonpolar. Different types of surfactants are shown in Figure 6.

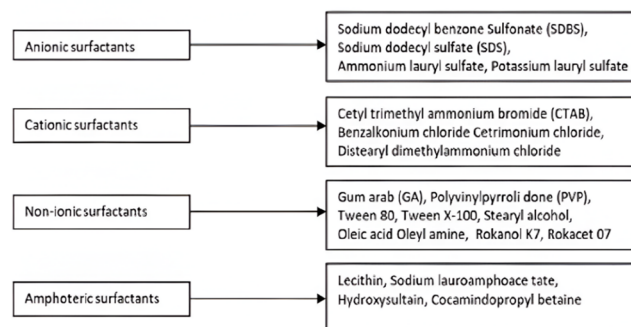


Figure 6. Types of surfactants.

Particles, generally hydrophilic like oxide particles, are easily mixed into polar fluids like water, and hydrophobic particles like CNT can be mingled into nonpolar base liquids such as oils without needing a third element. Nonetheless, surfactants must be included to anchor the nanoparticle if hydrophobic particles are blended into polar base fluids.

Surfactants are generally of four types: anionic, nonionic, cationic, and amphiphatic. Amphiphatic substances have positive and negative hydrophilic groups, which can create positive/negative elements according to the pH of the fluid. They possess germ-repelling qualities, resilience to water hardness, and little toxicity.⁹¹

The creation of bubbles is a drawback of surfactants, impacting the heat characteristics of the liquid. Introducing surfactant into the nanofluid may enhance its stability, but the adverse impact on the surfactant is magnified in high-temperature scenarios (Table 3).

Zeta potential measures the repulsion between nanoparticles, which is represented in millivolts. The particle's charge determines whether the zeta potential is positive or

Table 3. Effect of Different Surfactants on Stability

researchers	nanofluid	surfactant	zeta potential value (mV)
Chakraborty et al. ⁹⁹	Cu–Zn–Al/water	none	38.6
Wang et al. ¹⁰⁰	Al ₂ O ₃ /water	SDBS	–40.1
Sandhu et al. ¹⁰¹	Al ₂ O ₃ /water–EG	none	57
Ahammed et al. ¹⁰²	graphene/water	SDBS	–63.7
Srinivas et al. ¹⁰³	CNT/water	none	20.5
Hwang et al. ¹⁰⁴	carbon black/water	SDS	–26.9
Mostafizur et al. ¹⁰⁵	SiO ₂ /methanol	none	–40
Ghadimi et al. ¹⁰⁶	TiO ₂ /water	none	–33.3
Gupta and Sharma ¹⁰⁷	Cu–CNT/water	none	–46.6
Xian et al. ¹⁰⁸	TiO ₂ /water–EG	SDBS	–60
Li et al. ¹⁰⁹	Cu–water	CTAB	28.1
		SDBS	–43.8
		TX-10	–8.3
Khairul et al. ¹¹⁰	CuO/water	none	28
		SDBS	–85.1
Cacua et al. ¹¹¹	Al ₂ O ₃ –water	none	30
		SDBS	20
		CTAB	32
Choudhury et al. ¹¹²	Al ₂ O ₃ –water	none	14
		SDS	–30
Song et al. ¹¹³	stainless steel–water	SDBS	–70
		CTAB	60.1
Chakraborty et al. ¹¹⁴	Cu–Zn–Al–water	SDS	–50.6
		Tween 20	24.3
Ghadimi et al. ¹⁰⁶	TiO ₂ –water	None	–33.3
		SDS	–55
Jiang et al. ¹¹⁵	CNT/water	None	–30
		SDS	–40
Yilmaz Aydin et al. ¹¹⁶	Dolomite–water	SDBS	30
		Triton X-100	26

negative. Nanofluids with a high zeta potential are considered to be electrically stable. Precipitation occurs rapidly at zeta potentials between 15 and 30 mV, stability is achieved at 30 mV, and excellent stability is observed at 45 mV. Kim et al.¹¹⁷ created a nanofluid with gold/water without surfactants and assessed its stability through zeta potential measurements. The zeta potential for nanofluids with nanoparticle ϕ of 0.018 vol% showed –32.1 mV, and 0.0025 vol% showed –38.5 mV. Mondragon et al.¹¹⁸ investigated the consequence of ϕ of silica nanoparticles. Results indicate a –16 mV with a nanoparticle concentration of 2 wt % and –48.63 mV with a mass concentration of 20 wt %. Nanofluids with a concentration of 20 wt % showed stability for at least 48 h.

2.4.2. Ultrasonication. The ultrasonic mixing technique utilizing ultrasonic waves in a nanofluid improves its stability by overcoming the force of gravity acting on the nanoparticles. To extend the enduring lifespan of nanofluids, ultrasonication has garnered widespread adoption and is recognized as a pivotal stage in nanofluid production via the two-step method. Nevertheless, there remains a lack of standardized protocols for nanofluid preparation, particularly regarding the optimal duration for achieving homogeneity, the requisite power amplitude of the sonicator, and the appropriate types or durations of pulse modes to be employed. Researchers have encountered conflicting findings regarding the impact of ultrasonication duration on the colloidal dispersion of nanoparticles. While some argue that longer ultrasonication durations are advantageous for achieving proper nanoparticle dispersion, others suggest that prolonged sonication may harm

the surfactants in nanofluids or that the size of nanoparticles could decrease with increased sonication time. A few proposed guidelines include utilizing a cooling bath, operating in pulse mode, and employing cylindrical-shaped flat-bottom beakers.

Nanofluid with gold/water was created by Chen and Wen¹¹⁹ by varying the sonication periods from 10 to 60 min, and a reduction in agglomerated particles was noted as the sonication time increased. However, no change in particle size was observed after 45 min. Mahbubul et al.¹²⁰ applied ultrasonication for various durations (30, 60, 90, 120, 150, and 180 min) to TiO₂/water nanofluids and determined that the optimal sonication time for maximum stability is 150 min. Exceeding 150 min of sonication led to nanoparticles reagglomerating. Azmi et al.¹²¹ agitated a TiO₂/water-ethylene glycol (60:40) nanofluid on a magnetic stirrer for 30 min tailed by 2 h in an ultrasonic bath. They confirmed the stability of the nanofluid for over 7 months through stability analysis using FESEM and TEM. Mahbubul et al.¹²² dispersed 0.5 vol.% of Al₂O₃ nanoparticles in water using ultrasonication for varying durations from 0 to 5 h and examined the nanoparticle distribution through electron microscopy. The scholars observed that longer ultrasonication times were necessary to attain improved stability and decreased viscosity. TEM analysis indicated superior particle dispersal after 2 h of ultrasonication. Additionally, an external force like ultracentrifugation is employed for the separation and purification of nanoparticles, relying on particle deposition induced by the centrifugal force from the rotation of the ultracentrifuge.¹²³ Figure 7 represents microstructure after 1 h of ultrasonication with different vol%.

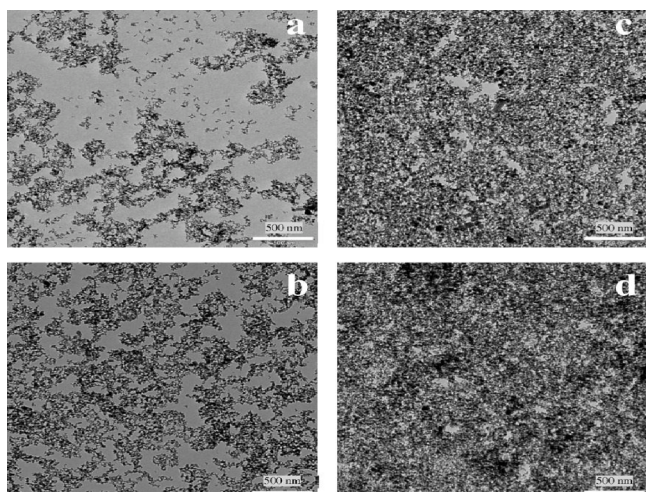


Figure 7. TEM images showing the microstructure of 1 h ultrasonicated Al₂O₃–water nanofluids of (a) 0.01, (b) 0.1, (c) 0.5, and (d) 1 vol.% concentrations. Reprinted with the permission of Mahbulul et al.¹²³ Copyright 2015 Elsevier B.V.

2.4.3. pH Control. Nanoparticles tend to aggregate more readily because of their elevated surface energy, posing challenges for achieving uniform dispersion within fluids. Hence, mitigating nanoparticle aggregation in the liquid has emerged as a crucial concern for facilitating stable nanofluid formation, which is essential for efficient HT. In addition to

adding a surfactant, another method to enhance the stability of nanofluids involves pH control. Adjusting the pH of the nanofluid can result in a stable suspension by manipulating strong repulsive forces.

Adjusting the pH of a nanofluid can be achieved by adding an appropriate nonreactive acidic or alkaline solution.¹²⁴ Changes in flow patterns occur with fluctuations in nanofluid pH. However, pH alterations in nanofluids have other effects as well. Recent studies have indicated that pH variation is crucial for improving nanofluid stability, k_p , and μ .

Azizian et al.¹²⁴ studied how pH affects TiO₂/water nanofluid stability and k_p , noting particle aggregation as a key factor in thermal enhancement. Zhang et al.¹²⁵ suggested adding NaOH or HNO₃ to control the pH of TiO₂/water nanofluids.

Wang et al.¹²⁶ explored the impact of pH on Al₂O₃/water and Cu/water nanofluids, determining pH levels of 8 and 9.5 as optimal for each respectively. At these ideal pH levels, k_p improvements of up to 15% for Al₂O₃/water and 18% for Cu/water nanofluids were achieved at a 0.8% weight fraction. Zhu et al.¹²⁷ investigated pH's impact on Al₂O₃/H₂O nanofluid behavior, noting a 10.1% increase in effective k_p at a pH of 8 with a 0.15 wt % particle concentration. Said et al.¹²⁸ applied pH-treated Al₂O₃/water nanofluids to a solar collector, observing improved energy and exergy efficiency.

Various techniques for preparing stable nanofluids have been compared, showing that the effectiveness of these methods may vary based on the nanoparticle type, base fluid type,

Table 4. A Few k_p Mathematical Equations of Nanofluids

author	mathematical equation	conclusions
Maxwell ¹²⁹	$k_{nf} = \frac{(k_p + 2k_f + 2\Phi(k_p - k_f))k_f}{(k_p + 2k_f - 2\Phi(k_p - k_f))k_f}$	spherical nanoparticles of various v_f
Hamilton and Crosser ¹³⁰	$k_{nf} = \frac{k_p + (n-1)k_f + (n-1)\Phi(k_p - k_f)}{k_p + (n-1)k_f - \Phi(k_p - k_f)}$	cylindrical and spherical nanoparticles
Bruggeman ¹³¹	$\frac{k_{nf}}{k_f} = \frac{(3\Phi - 1)\frac{k_p}{k_f} + [3(1 - \Phi) - 1] + \sqrt{\Delta}}{4}$	effective k_{nf} of mixed bodies from isotropic substances
Patel et al. ¹³²	$\frac{k_{eff}}{k_f} = 1 + \frac{k_p d_f \Phi}{k_f d_p (1 - \Phi)} \left[1 + c \frac{2k_B T d_p}{\pi \alpha \mu_f d_p^2} \right]$	microconvection model for k_f of nanofluids
Rea et al. ¹³³	$k_{nf} = k_f (1 + 4.5503\Phi)$	model obtained using experimental data
Eastman et al. ¹³⁴	$\frac{k_{eff}}{k_f} = \left[1 + \frac{k_p \Phi d_f}{k_f (1 - \Phi) d_p} \right]$	a generic model
Evans et al. ¹³⁵	$\frac{k_{eff}}{k_f} = 1 + \Phi \frac{k_p}{P 3k_f}$	a model established on particle k_f
Singh et al. ¹³⁶	$k_{nf} = k_f (1 + 4\Phi)$	modified Hamilton–Crosser model
Khanafer and Vafai ¹³⁷	$\frac{k_{nf}}{k_f} = 1 + 1.0112\Phi + 2.4375\Phi \left(\frac{47}{d_p(nm)} \right) - 0.0248\Phi \left(\frac{k_p}{0.613} \right)$	based on experimental works
Lu and Lin ¹³⁸	$\frac{k_{eff}}{k_f} = 1 + a\Phi_p + b\Phi_p^2$	composites with oriented spheroidal particle
Wang et al. ¹³⁹	$\frac{k}{k_f} = 1 + \frac{3f\phi(p)/P_0}{1 - f\phi(p)/P_0}$	based on the size of the nanoparticle, v_f shape, nanolayer, and interaction between nanoparticles
Sundar et al. ²⁹	$k_{nf} = k_{bf} (1 + 10.5\Phi)^{0.10515}$	effective for the Fe ₂ O ₃ nanoparticle within a specified temperature range and v_f range
Wang et al. ¹⁴⁰	$\frac{k_{eff}}{k_f} = \frac{(3\Phi - 1)\frac{k_p}{k_f} + [3(1 - \Phi) - 1] + \sqrt{\Delta_B}}{4}$	a hypothetical model for estimating the efficient coefficient of flow of a solution containing nanoparticles
Afrand et al. ¹⁴¹	$\frac{k_{nf}}{k_{bf}} = 0.7575 + 0.3\varphi^{0.323} T^{0.245}$	a model developed by curve fitting of data and based on a magnetic nanofluid
Khndher et al. ¹⁴²	$\frac{k_{nf}}{k_{bf}} = 1.268 \left(\frac{T}{80} \right)^{-0.0074} \left(\frac{\varphi}{100} \right)^{0.036}$	based on temperature or particle v_f
Zaraki et al. ¹⁴³	$\frac{k_{nf}}{k_{bf}} = 1 + N_f \phi$	a low v_f nanoparticle model was constructed using experimental data ($\varphi < 5\%$)

Table 5. Nanoparticle v_f Impact on HT Features

articles	v_f	findings
Reza et al. ¹⁵⁷	$0\% \leq \phi \leq 20\%$	introducing more nanoparticles in the flow lowers the shear stress and enhances the HT rate
Fares et al. ¹⁵⁸	$0\% \leq \phi \leq 8\%$ $10^3 \leq Ra \leq 10^6$	raising the v_f of nanoparticles increments the average Nu , especially for high Ra values
Parvin et al. ¹⁵⁹	$0\% \leq \phi \leq 15\%$ $Gr = 10^4$ $Pr = 6.2$	increasing the nanoparticle v_f accelerates heat transmission
Mebarek-Oudina ¹⁶⁰	$0\% \leq \phi \leq 10\%$ $Ra = 10^4$	incrementing the v_f of nanoparticles in various base fluids improves the h_m and yields a strong HT
Zaim et al. ¹⁶¹	$0\% \leq \phi \leq 4\%$ $10^3 \leq Ra \leq 10^6$	HT performance is at its highest for important nanoparticle v_f when conduction drives the flow, the effect of nanoparticles is more prominent
Chamkha et al. ¹⁶²	$0\% \leq \phi \leq 10\%$	although HT is boosted when increasing the nanoparticle v_f , the ratio of entropy to Nu appears to increase as well
Ganesh et al. ¹⁶³	$0\% \leq \phi \leq 8\%$	the strength of the Nu number and HT is related to the nanoparticle v_f
Raza et al. ¹⁶⁴	$1\% \leq \phi \leq 10\%$	altering the solid concentration of nanoparticles can adjust the nanofluid temperature
Dogonchi et al. ¹⁶⁵	$0\% \leq \phi \leq 4\%$	improving the Nu number requires a high kp that can be obtained by enhancing the nanoparticle v_f
Chamkha et al. ¹⁶⁶	$0\% \leq \phi \leq 5\%$ $Ra = 10^5$	enhancement of HT is achieved by the incorporation of nanoparticles, resulting in an increased average Nu
Mebarek-Oudina et al. ¹⁶⁷	$0\% \leq \phi \leq 5\%$ $Ra = 10^4$	the growth of the HT rate is led by the dispersion of nanoparticles, especially those with high thermal conductivity

nanoparticle concentrations, and sonication duration.¹⁴⁴ Increasing sonication time or power reduces cluster size and increases particle suspension stability.

Nevertheless, very high and prolonged sonication power may not show the same results. Ultrasonic devices can elevate nanofluid temperature, but ambient temperature also plays a role, resulting in diverse nanofluid products based on location and weather conditions. Therefore, determining the optimal sonication period and power level that enhances nanofluid stability is crucial. Surface modification methods are complex and expensive, so they are not ideal for industrial use. Establishing stable nanofluids through pH management is simpler and more cost-effective.

In nanofluids, extremely low or high pH levels can originate either acidity or alkalinity, damaging HT equipment and restricting practical applications.¹⁴⁵ Surfactants connect nanoparticles with base fluids, enhancing nanoparticle dispersion by reducing base fluid surface tension. The presence of surfactants in nanofluids at elevated temperatures can lead to foaming and blockages in pipes. Over time, using nanofluids containing surfactant at extremely high temperatures leads to malfunctions in thermal devices.

2.5. Characteristics Concerning the Transfer of Heat in Nanofluids. Recently, there has been a growing trend toward using novel types of working fluids that incorporate particles of nanoscale materials dispersed within the base liquid (such as water, deionized water, ethylene glycol, etc.) for HT purposes. This is because these nanofluids have a significant impact on the thermal characteristics of the base fluid. Different nanomaterials influence the base fluids' thermal properties in varying ways. Factors like nanoparticle size, shape, and ϕ are vital factors that can significantly alter the thermal properties.¹⁴⁶

2.5.1. Thermal Conductivity. The key factor for efficient HT systems is nanofluids' kp , which surpasses traditional fluids. Nanoparticles in nanofluids exhibit greater kp due to their Brownian motion, where collisions with fluid molecules enhance thermal properties. Nanoparticle size and forming a nanolayer near solid particles influence this phenomenon. The base fluid's thermal properties affect the nanofluid's kp . Various methods, including hot wire, transient plane welding, temper-

ature swing, parallel plate, and optical techniques, can assess nanofluid kp . Multiple factors affect kp , including nanoparticle ϕ , nanolayer presence, nanoparticle size, temperature, and type of base fluid. Several theoretical models have been devised to predict the kp of nanofluids, some of which are listed in Table 4. These models are constructed based on classical theories like Maxwell¹²⁹ and Hamilton-Crosser models,¹³⁰ considering the conductive properties of spherical and nonspherical particles within the mixtures. Experimental models like the Rea¹³³ model and Afrand¹⁴¹ correlation have also been designed to estimate the kp ratios of specific nanofluids under varying conditions. Overall, the effectiveness of these models in predicting kp relies on factors like particle ϕ , temperature, and base fluid properties. Further research and experimentation are needed to enhance our understanding of the thermal behavior of nanofluids and optimize their applications in HT systems. kp can be altered by changing factors like size/shape and type of the nanoparticles/basefluid.

2.5.2. Nanoparticle ϕ Effect on k_p of Nanofluids. The thermal efficiency of thermal systems can be enriched by incorporating nanoparticles of an optimal size. However, particle agglomeration can begin as the ϕ of particles increases, leading to a decrease in kp . Higher v_f and larger particle size can contribute to agglomeration and sedimentation, increasing μ intensifying HT surface fouling. This fouling phenomenon and increased μ can lead to higher Δp and greater pumping power demand, ultimately reducing the overall THP compared to conventional fluids.^{147–149} To achieve high HT with minimal Δp , it is crucial to determine the ideal v_f of nanoparticles with high kp . Maintaining maximum HT efficiency and minimizing pumping power demand is essential for designing energy-efficient thermal systems.

In an experimental study by Goodarzi et al.,¹⁵⁰ the thermal efficiency and Δp in a double pipe HX were analyzed using nitrogen-doped graphene (NDG) nanofluids at different ϕ of nanosheets (0.01–0.06%). The outcome exhibited that adding nanosheets with water improved the HT rate of the nanofluid, achieving a 15.86% augmentation at a 0.06% ϕ of nanoparticles in NDG nanofluid. The researchers established that higher Re and particle percentages could increase the f , leading to elevated Δp and demand for pumping power. Akhavan-

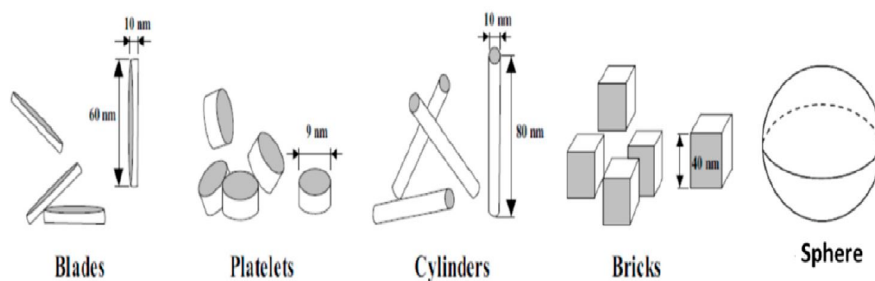


Figure 8. Different nanoparticle shapes generally added to the base fluid. Reprinted with the permission of Mahian et al.¹⁷⁰ Copyright 2014 Elsevier B.V.

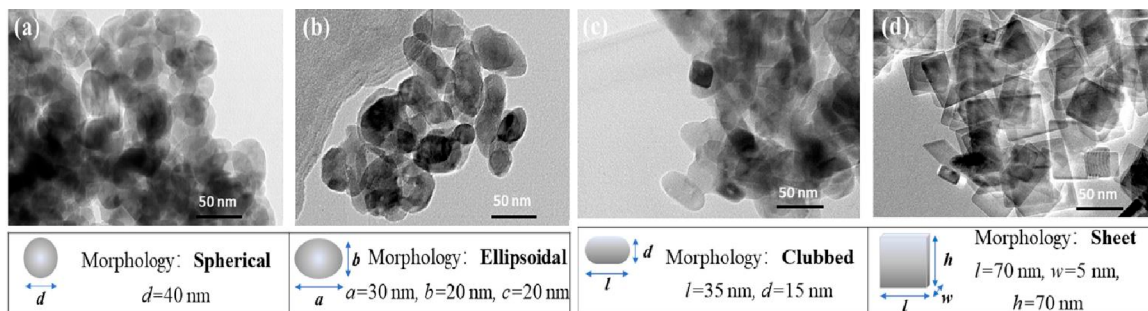


Figure 9. TEM image showing the morphology of TiO₂ nanoparticles of different shapes: (a) spherical, (b) elliptical, (c) cubed, (d) sheet. Reprinted with the permission of Cui et al.¹⁷¹ Copyright 2021 Elsevier B.V.

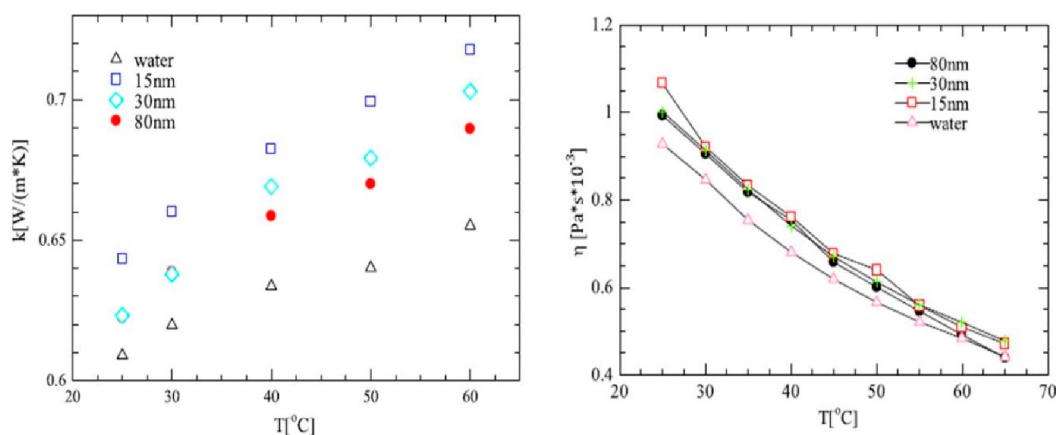


Figure 10. Variations in (a) kp and (b) μ of the SiO₂–water nanofluids as a function of temperature and particle size. Reprinted with the permission of Zhang et al.¹⁶⁹ Copyright 2021 American Chemical Society.

Behabadi et al.¹⁵¹ studied the HT and Δp in an HX using nanofluid (MWCNTs–water) of various particle ϕ (0.05–0.2%). They noted that the h_m of the nanofluid surpassed that of the base fluid and rose with higher particle ϕ .

Ezekwem and Dare¹⁵² created SiC/DW and SiC/EG nanofluids with v_f ranging between 0.5 to 5 vol %. The kp of the nanofluids was assessed, showing enhanced kp with increased nanoparticle ϕ . Further, Suresh et al.¹⁵³ concluded from their study that nanoparticle ϕ of hybrid nanofluids (Al₂O₃–Cu/water) directly impacts kp .

In a study by Akhavan-Zanjani et al.,¹⁵⁴ it was found that even small amounts of graphene at a concentration of 0.02 vol % could boost water's kp by more than 10%. Kiyomura et al.¹⁵⁵ examined the performance of boiling HT on surfaces coated with Fe₂O₃ nanoparticles in Fe₂O₃ nanofluid (water-based) at high ϕ (0.29 g/L) and low ϕ (0.029 g/L). The research indicated that the maximum kp values were observed on

copper surfaces coated with a low mass ϕ , with an increase in ϕ leading to a surge in surface roughness. In another study by Garbadeen et al.,¹⁵⁶ the free convection using nanofluids (water–MWCNT) in a square duct with differentially heated side walls was experimentally investigated, showing a significant improvement in HT with an optimal nanoparticle v_f of 0.1 vol %. A few of the research on ϕ effect on HT can be accessed in Table 5.

2.5.3. Effect of Nanoparticle Size and Shape on the Thermal Conductivity of Nanofluids. The size of nanoparticles impacts the viscosity, thermal conductivity, and density of nanofluids. Reducing nanoparticle size improves the thermophysical properties of nanofluids.^{168,169} Furthermore, the primary factors that influence the thermophysical properties of nanofluids encompass nanoparticle morphology and concentration.

Table 6. A Few μ Models of Nanofluids

authors	mathematical equation	conclusions
Einstein ¹⁸⁰	$\mu_{\text{eff}} = \mu(1 + 2.5\phi)\phi < 0.05$	particles shaped like spheres with a volume concentration of 2% or below
Brinkman ¹⁸¹	$\frac{\mu_{\text{eff}}}{\mu_f} = \frac{\mu_{\text{eff}}}{(1-\phi)^{2.5}}$	extension of Einstein model
Bruijn ¹⁸²	$\frac{\mu_{\text{eff}}}{\mu_f} = 1 + 2.5\phi + 4.698\phi^2$	spherical particles
Batchelor ¹⁸³	$\mu_{\text{eff}} = \mu_0(1 + 2.5\phi + 6.5\phi^2)$	model developed keeping in mind the interaction taking place between particles
Wang et al. ¹⁸⁴	$\frac{\mu_{\text{eff}}}{\mu_f} = 1 + 7.3\phi + 123\phi^2$	a generic model
Dávalos-Orozco et al. ¹⁸⁵	$\mu_{\text{eff}} = \mu_f(1 + 2.5\phi + 6.17\phi^2)$	nanoparticles volume concentration involved
Nguyen et al. ¹⁸⁶	$\mu_{\text{eff}} = \mu_0(1 - 0.025\phi + 0.015\phi^2)$	statistical technique called curve fitting to analyze experimental data
Abedian et al. ¹⁸⁷	$\mu_{\text{eff}} = \frac{\mu_{\text{bf}}}{(1-2.5\phi)}$	model for suspended particles
Heyhat et al. ¹⁸⁸	$\mu_{\text{eff}} = \mu_0(T) \exp\left(\frac{5.989\phi}{0.278-\phi}\right)$	model for a specific range of temperatures, sizes of particles, and ϕ
Esfe et al. ¹⁸⁹	$\frac{\mu_{\text{nf}}}{\mu_{\text{bf}}} = 1 = (0.1008 \times \varphi^{0.69574} \times dp^{0.44708})$	developed considering the particle diameter of the Fe–water nanofluid
Hamid et al. ¹⁹⁰	$\mu = \frac{\mu_{\text{nf}}}{\mu_{\text{bf}}} = 1.42(1 + R)^{-0.1063} \left(\frac{T}{80}\right)^{0.2321}$	a chosen nanoparticle concentration and temperature range model
Zaraki et al. ¹⁴³	$\frac{\mu_{\text{nf}}}{\mu_{\text{bf}}} = 1 + N_v \times \phi$	a diluted nanofluid model was formulated, using N_v to represent the parameter of viscosity

They can be synthesized in various sizes ranging from 5 to 100 nm. The shapes of nanoparticles commonly employed in base fluids (as depicted in Figure 8) were demonstrated to directly influence solely the viscosity and thermal conductivity of the resultant nanomaterials.¹⁷⁰

Cui et al.¹⁷¹ conducted an experimental investigation into the thermal conductivity of nanofluids featuring various nanoparticle configurations, as depicted in Figure 9. The findings indicated that the relative thermal conductivity (RTC) of TiO₂/water nanofluids containing clubbed and sheet-shaped nanoparticles surpassed that of other shapes. Specifically, TiO₂ nanofluids containing sheet nanoparticles exhibited the highest RTC at 60 °C and a nanoparticle concentration of 4%.

Further, the effect of particle size by Zhang et al.¹⁶⁹ who examined how particle size influences the thermal transfer efficiency of SiO₂–water nanofluids. They meticulously crafted suspensions with commendable stability and dispersion and assessed their kp through the transient hot wire technique. The findings unveiled that the kp of SiO₂–water nanofluids with particle sizes measuring 15, 30, and 80 nm surpassed those of water by 7.80%, 4.90%, and 3.80%, respectively. Moreover, it was noted that smaller nanoparticle sizes in the nanofluid resulted in elevated dynamic viscosity values compared to the base fluid, as depicted in Figure 10.

2.5.4. Temperature Effect on the kp of Nanofluids. Research has indicated that temperature impacts kp , which rises as temperature increases. The overall μ of nanofluids comprises two components: static and dynamic. The Einstein model and the influence of nanolayer formation combine to create the static element of the nanofluid μ . The μ impact caused by the nanolayer surrounding a nanoparticle is heightened due to its 1 nm thickness. In contrast, the dynamic aspect is attributed to the μ influence due to Brownian motion associated with nanoparticles.¹⁷² A decrease in μ at elevated temperatures is a result of the expanding intermolecular distance within the base fluid at elevated temperatures. As nanoparticles heat up, their bond with the surrounding fluid weakens. The rise of μ in nanofluids rises more quickly with increasing temperatures than in the base fluid. This phenomenon is more pronounced at larger ϕ . A study by

Sundar et al.¹⁷³ revealed that a 2.0% vf at a temperature of 60 °C resulted in a rise 2.96 times higher than the original fluid. Furthermore, the μ enhancement can alter based on base fluid types. The μ boost declined as ethylene glycol percentage in the mixture increased.¹⁷⁴ Naik and Sundar¹⁷⁵ studied the temperature effect on the kp of CuO nanofluid utilizing a mixture of water and propylene glycol (30:70%) as the base liquid. They found that as the temperature rose from 298.15 to 338.15 K, so did the kp from 10.9% to 43.37% for a v_f of 1.2%. Buonomo et al.¹⁷⁶ studied the effects of temperature rise of nanofluid (Al₂O₃-water) on the kp at different levels of particle ϕ . They found that the enhancement in kp of the nanofluid became more pronounced as the temperature rose. Their results indicate that for particle ϕ of 0.5% at 25 °C, the increase in kp ranged from around 0.57% to approximately 8% at 65 °C. Additionally, with v_f of 4%, the rise in kp was from 7.6% to 14.4%, with a temperature rising between 25 to 65 °C.

2.6. Effect of μ . The role of μ in nanofluids is comparable to that of kp in HT applications. When nanoparticles are introduced, the μ of the base liquid undergoes changes. The greater μ of nanofluids causes a surge in the Δp during pumping. Several factors affect the μ of nanofluids, such as temperature, particle ϕ , size and shape of nanoparticles, shear stress, presence of surfactants, type of base liquid, tendency for nanoparticle agglomeration, and the specific type of nanoparticles used.¹⁷⁷ μ tends to decline with rising temperature due to changes in intermolecular forces. Adding surfactants can increase the μ of nanofluids.¹⁷⁸ Common techniques for measuring nanofluid μ include vibrating, rotating, capillary, orifice-type, and bubble viscometers.¹⁷⁹ Various models for predicting nanofluid viscosity can be found in Table 6.

2.6.1. Nanoparticle Size Affecting μ of Nanofluids. The impact of nanoparticle size in nanofluids on μ has produced varying results in various studies. Some research shows that nanofluid μ increases as particle size grows,^{191,192} whereas other studies suggest that viscosity rises as nanoparticle size decreases.^{193,194} He et al.¹⁹⁵ inspected how μ of nanofluids (TiO₂–water) of varying particle sizes and ϕ . They determined that as particle size and ϕ increased, the relative μ of nanofluids also increased. Nguyen et al.¹⁹⁶ utilized

nanoparticles (Al_2O_3) of 36 and 47 nm when creating a water-based Al_2O_3 nanofluid. The result indicates that particle size had a profound impact at higher V_f concentrations ($>4\%$), with nanofluid μ being higher using smaller nanoparticles than larger ones. This conclusion indicated that the μ of the nanofluid with 47 nm particle size at higher ϕ was greater than that of the nanofluid with 36 nm particles. They found that μ increased as particle size rose at higher ϕ . Anoop et al.¹⁹⁷ prepared a nanofluid (Al_2O_3 –water) using nanoparticles of 45 and 150 nm in an experimental study. The results of μ measurements revealed that the nanofluid with 45 nm particles had higher μ than the one with 150 nm particles. In summary, they suggested that smaller nanoparticles led to a greater increase in μ . Based on these studies, it can be determined that nanofluid μ is heavily influenced by particle size.

2.7. Heat Capacity. The C_n capacity is a critical factor for nanofluid that impacts its HT rate, as it is closely connected to energy storage, transfer, and the Pr . Both the base fluid and particles of a nanofluid play a role in determining its C_n capacity. Generally, the nanofluid's C_n capacity decreases as the nanoparticle concentration increases. Kumerasan and Velraj¹⁹⁸ experimented with MWCNT/EG–water nanofluid and observed that adding CNT to the base liquid surges the C_n capacity. However, they found that the C_n capacity decreased as the ϕ of nanoparticles increased. Yarmand et al.¹⁹⁹ studied the C_n capacity of carbon–graphene/EG nanofluid, revealing that the C_n capacity increased with higher temperatures and ϕ of the nanoparticle. According to a study by Shin et al.,²⁰⁰ the addition of carbon nanotubes at a mass fraction of 1% surges the C_n capacity of the eutectic salt $\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3$ by 19%. Research shows that both nanoparticle ϕ and temperature significantly affect C_n capacity.

A key drawback of thermal energy storage systems is the low C_n of the working fluid in use. It is essential for the fluid employed as a refrigerant to have a high C_n capacity,²⁰¹ especially for smaller-size HXs.²⁰² Therefore, enhancing the C_n of nanofluids is a persistent issue. One method to achieve this is by using nanoencapsulated phase change materials (NEPCMs) in the formulation of nanofluids. NEPCMs are a type of nanofluid where the nanoparticles consist of a core and a shell, with the core made of PCM capable of undergoing a phase change (solid–liquid) and absorbing or releasing energy based on latent heat (energy stored) during phase change. In another study, Ghalambaz et al.²⁰³ found that nanoencapsulated phase change material (NEPCM) particles enhanced HT performance in a cavity by increasing the C_n capacity. This was attributed to the higher latent heat storage at the core with PCM. Other researchers have also incorporated NEPCM particles in different systems, including eccentric annuli, mini-channel heat sinks, double pipe HX, and inclined porous cavities.^{201,202,204,205}

2.8. THP of the Thermal System with Nanofluids. The significance of the THP of a system is on the rise. As a result, alternative approaches to enhance THP in such fluid dynamics are being sought. These approaches involve strategies about the spatial configuration of pipes, commonly called passive techniques for enhancing HT and enhancements in fluid characteristics.

Using pipe bundles for fluid flow is common in industrial processes such as cooling/heating. The utilization of nanofluid is also growing steadily to boost HT in thermal systems. Substituting conventional working fluids with nanofluids is an efficient method for heightening the THP of various types of

HX. One such application is solar collectors, and in recent years numerous nanofluids have been employed to enhance THP in solar energy technologies to achieve this. The enhancement in HT and reduction in f should be considered.

The ratio of the enhancement rate indicating the surge in HT to f is known as THP. Equations 10 and 11 present the primary criteria for evaluating the THP of the thermal system.^{206–214} Models above a THP of 1 are considered advantageous, whereas models below this threshold are deemed unfavorable. The flow and thermal characteristics of nanofluids play a crucial role in evaluating and enhancing their performance. Thermal properties, including kp , μ , and ρ are influenced by multiple constraints such as Re , f , and pump efficiency.²¹⁵ The factors impacting THP are illustrated in Figure 11.

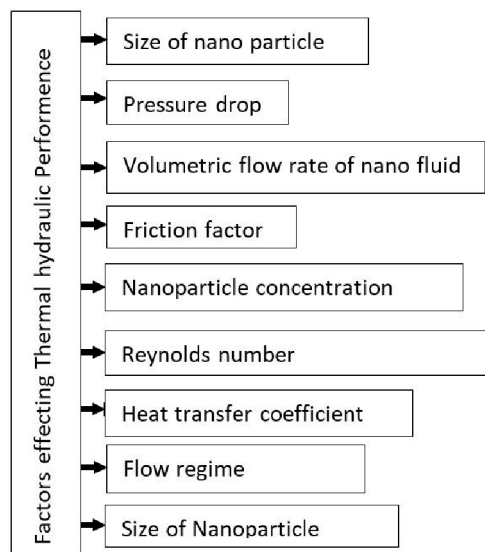


Figure 11. Factor effecting THP.

Numerous research has delved into the effects of factors like μ , Re , Δp , m_f , and flow pattern on the thermal performance of nanofluids. μ plays a crucial role in determining the h_m of nanofluids. The properties of the fluid change significantly with increasing μ . Typically, the μ of a nanofluid is much higher than the base fluids, resulting in higher ν and pumping power at consistent Re . It is important to consider pumping power when comparing the practical efficiency of fluids. This is because the practical efficiency declines as the solid content in the fluid rises. Asirvatham et al.²¹⁶ examined the HT performance of HX with nanofluids as working fluid under countercurrent with various flow conditions from laminar to turbulent. Their outcome exhibited a rise in h_m by up to 28.7% and 69.3% upon adding silver nanoparticles by 0.3% and 0.9%, respectively. However, some research suggests that HT efficiency of nanofluids may decline with the addition of nanoparticles, regardless of ϕ of the nanoparticle.

$$\eta = \frac{(Nu_m/Nu_f)}{(f_m/f_t)^{1/3}} \quad (10)$$

$$\eta = \frac{(Nu_m/Nu_f)}{(f_m/f_t)^{1/3}} = \frac{h_m/h_f}{(\Delta P_m/\Delta P_f)^{1/3}} \times \frac{\lambda_f}{\lambda_m} \times \left(\frac{\rho_f}{\rho_m}\right)^{1/3} \times \left(\frac{\mu_m}{\mu_f}\right)^{2/3} \quad (11)$$

Table 7. Properties of Nanofluids with Water as a Base Liquid at 298 K

properties	base fluid (H ₂ O)	Al ₂ O ₃ + H ₂ O			CuO + H ₂ O			TiO ₂ + water		
		0.4	0.8	1	0.4	0.8	1	0.4	0.8	1
ρ	998.2	1010	1021	1027	1020	1042	1053	1011	1024	1030
C_p	4182	4128	4075	4050	4089	3999	3956	4123	4065	4037
K_p	0.6	0.606	0.61	0.617	0.606	0.61	0.616	0.605	0.611	0.614
μ	0.001	0.00098	0.00021	0.001	0.0009	0.001	0.001	0.0002	0.0002	0.0002

In a study by Mikkola et al.,²¹⁷ the effect of particle characteristics on nanofluid kp was examined. Various water polystyrene, SiO₂, and Al₂O₃ nanofluids were investigated with v_f ranging from 0.1 to 1.8 vol %. Heating experiments were conducted in a tube HX with Re ranging from 1000 to 11,000. The findings indicated that higher nanoparticle v_f led to decreased thermal conductivity. Aliabadi et al.,^{218,219} produced a nanofluid (Cu–water) with a weight fraction ranging from 0.1 to 0.4%, used in plate-fin HX and compared it with HX with VGs. They noticed that the combination of VG and nanofluids showed a TEF of 1.67. Their findings indicated that lower nanofluid ϕ led to superior results. Further experimentation on corrugated MHS (water-cooled) with different configurations of the fin (plate/plate-pin) employing Al₂O₃–water nanofluid with various weight fractions (0.1–0.3%) with Re between 100–900. Upon comparing different fin designs, a peak THP of 1.84 at 0.3 wt % was noted for sinusoidal plate-pin finned slotted MHS.

Sarafraz et al.²²⁰ explored the THP of a rectangular microchannel with Ga–CuO nanofluid. They examined the consequences of ϕ and nanofluid flow m_f on the system's h_m , Δp , and THP. They disclosed that Re substantially influenced the THP and the nanofluid ϕ ; additionally, they attained the highest THP in the laminar regime due to minimal Δp . Kaya et al.²²¹ found that while there is no improvement in THP at low frequency and intensity, a specific frequency exists that maximizes THP. By optimizing THP at high intensity and a specific frequency ($W_o = 10$), pulsating flow greatly enhanced HT, despite increasing f . The researchers noted that as the frequency exceeds the critical value ($W_o = 15$), the enhancement in THP diminishes due to reduced HT efficiency and higher f losses.

Sarafraz et al.²²² also explored the THP of Ga–Al₂O₃ nanofluid used in solar receiver-made copper rectangular microchannel. By varying the m_f of aluminum oxide in gallium to 5, 10, and 15 wt %, they observed that lower energy, f , and pumping power are required despite the small Re , leading to enhanced THP in the laminar regime. The study indicated that higher concentrations of Al₂O₃ increased the h_m and Δp compared to pure Ga. At the same time, they were using 15 wt % Al₂O₃ resulted in decreased THP due to heightened μ and aggregation of Al₂O₃ nanoparticles in Ga.

The type of thermal device used is a crucial factor impacting the THP of nanofluid systems.

In their study, Bahiraei et al.²²³ examined how a green graphene nanoplatelet nanofluid performed thermally and hydraulically within a rotating twisted tape tube. They explored the influence of rotational speed, y , and nanoparticle m_f on the system and found that nanoplatelets had little effect on convective HT at higher rotational speeds. Increasing the rotational speed and m_f improved the h_m and pumping power, while increasing the y had the opposite effect.

Ajeel et al.²²⁴ examined the THP of silica nanofluid in corrugated channels, such as semicircle-corrugated and

trapezoidal-corrugated channels, along with a straight channel. Their findings indicated enhanced performance in nanofluids compared to base fluids, with HT and Δp increasing with SiO₂ V_f . The use of a corrugated channel improved HT rates, Δp , and thermal performance significantly compared to straight channels.

Qi and colleagues²²⁵ studied HT and f characteristics of nanofluids in circular and elliptical tubes (horizontal), examining mass concentration effects. They discovered that TiO₂–water nanofluid with 0.5 m_f increased Nu compared to water in both tube geometries.

Ajeel et al.²²⁶ delved into the effects of V_f of nanofluid and HX geometric parameters on the TPF of curved-corrugated channels with CuO/MgO–water (nanofluid) as the working fluid. They found that increasing V_f , BR, and decreasing PR improved the THP, with optimal results observed at specific PR. The THP of a radiator using hybrid nanofluids was investigated by Sahoo and team,²²⁷ highlighting the significant impact of particle shape on the system's performance, with the radiator system's performance index declining with higher coolant flow rates and V_f of hybrid nanofluids.

Recent research has focused on the impact of magnetic fields on the THP of magnetic nanofluids. Fan et al.²²⁸ studied the THP of Fe₃O₄–water–arabic gum nanofluids used in a novel HX system with a corrugated tube and perforated turbulator. They found that high nanoparticle m_f , magnetic flux density, bilateral staggered magnetic fields, and perforated turbulators can significantly enhance THP. Mei et al.²²⁹ investigated the effects of paralleled magnetic fields on Fe₃O₄–water nanofluids in a circular tube, noting that the Nu correlated with nanoparticle m_f and had an inverse relationship with magnetic induction intensity. At the same time, the f increased with both nanoparticle m_f and magnetic field strength. A few thermophysical properties are represented in Table 7.

3. APPLICATIONS

Since the inception of nanofluids in 1995, scholars from various disciplines and countries have rigorously investigated their characteristics and possible uses. This collaborative endeavor has not only propelled the field of nanofluids forward but has also yielded remarkable results. These novel cooling technologies, unlike conventional coolants, demonstrate intriguing heat transfer characteristics, with a specific emphasis on convective heat transfer and thermal conductivity. Figure 12 shows a few fascinating uses of nanofluids.

3.1. HX. HX are devices that transfer heat between fluids of different types, with a current emphasis on using nanofluids in various HX. One such HX is HP, an effective tool for moving substantial amounts of heat through phase change or vapor diffusion. HP is considered one of the most effective passive HT technologies on the market and boasts high k_t . The steam condenses due to wall temperature difference, releasing latent heat and enabling the fluid to revert to the evaporator area through gravity (thermosiphons) or a capillary wick structure.

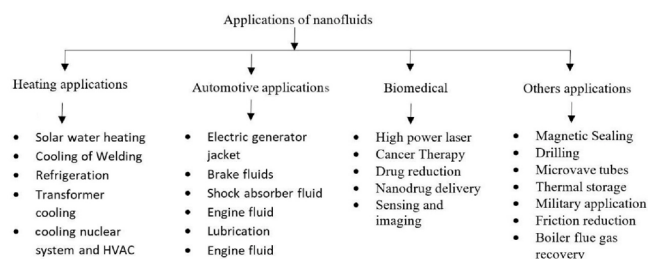


Figure 12. Few applications of nanofluids.

The performance of HP is affected by various factors, including thermal resistance. Vapor bubbles between liquid and solid phases cause thermal resistance in the HP. The large size of bubble cores hinders heat transfer between solid surfaces and liquid. Nanoparticles in the working fluid interact with vapor bubbles, resulting in smaller nucleation and improved HT between solid surfaces and liquid in the HP, reducing thermal resistance. Aydin et al.²³⁰ discovered that utilizing nanofluid (bauxite-water) decreased the f of HP by 24.3% and augmented thermal efficiency by nearly 20.9% when equated with working fluid without nanoparticles.

Jose and Hotta²³¹ numerical transient investigation of wickless heat pipes. A thermosyphon's thermal behavior was examined using CuO and Al₂O₃ with ϕ of 1 and 5 wt % with DI water as the base fluid. The findings reveal that a 5% concentration of CuO nanoparticles yields a maximum reduction in thermal resistance of 4.31% at 50 W. In contrast, the same concentration of alumina nanoparticles results in a more significant reduction of 6.66% under the same heat load, with the highest convective heat transfer coefficient for the heat pipe's evaporator (437.91 W/m²K) achieved using Al₂O₃ nanofluid with a 1% nanoparticle concentration at 50 W. Further, Naruka et al.²³² studied the performance of Al₂O₃-DI water in HP for a prolonged time of 6–12 months with ϕ of 0.1–0.8 vol % of NP tested under varying heat loads of 10–60

W. Results indicate that DI-Al₂O₃ is more stable for prolonged use at a higher heat load of 60W. Khanlari²³³ examined Al₂O₃-SiO₂/deionized water hybrid nanofluid and how it affects the U tubular HX with different flow orientations. He found that the hybrid nanofluid provided significant enhancements in U.

Variyenli et al.²³⁴ prepared nanofluid using fly ash particles as the working fluid in plate HX, achieving a maximum enhancement in h_m with a nanoparticle weight concentration of 2 wt %. Said et al.²³⁵ used CuO/water as the HT fluid in an STHX, demonstrating an increase in the HT and h_m . In a plate HX study, Khanlari et al.²³⁶ found that kaolin/deionized water nanofluid outperformed TiO₂/deionized water nanofluid in terms of thermal performance. They observed significant enhancements in HT rate with both nanofluids.

A few applications of nanofluids in dual-tube HX are illustrated in Table 8. The initial temperature (T_{in}) of nanofluids significantly impacts their HT properties. Zheng et al.²³⁷ observed that nanofluids containing 0.25 vol % and 0.5 vol % Al₂O₃ in water had 8.27% and 4.84% higher Nu when the inlet temperature was 40 °C compared to 50 °C. For nanofluids with 0.15 vol % Al₂O₃ in water, Nu was 17.7% and 10.2% higher at 65 and 55 °C than at 45 °C. In the case of 0.05% Al₂O₃ in water nanofluids, there were increases of 18.2% and 13.6% in Nu . The impact of inlet temperature on the k_p and μ of Al₂O₃ in water nanofluids was similar to that of the m_p . The rise in μ had a more detrimental effect on HT than the increase in k_i in the study by Zheng et al.,²³⁷ However, Raei et al.²³⁸ found that the surge in μ had a lesser adverse impact on HT than the rise in thermal conductivity. Additionally, the particle sizes of Al₂O₃ nanoparticles used by Zheng et al.²³⁷ and Raei et al.²³⁸ were 50 and 20 nm, respectively. Smaller nanoparticles were more susceptible to temperature changes, with increased Brownian motion at higher temperatures. Combining Al₂O₃ nanofluids with TiO₂ nanoparticles at a 1:1 mass ratio resulted in Al₂O₃+TiO₂ in water nanofluids (Singh and Sarkar).²³⁹ When the inlet temperature was 50 °C,

Table 8. Thermal Performance in a Plate HX with Nanofluids as the Working Fluid

authors	nanofluids	MHTE (%)	remarks
Zheng et al. ²⁴²	Al ₂ O ₃ -water	19.8	0.05 wt% Fe ₃ O ₄ -water showed the optimal HT performance; empirical formulas of four nanofluids were summarized
	SiC-water	17.2	
	CuO-water	13.8	
	Fe ₃ O ₄ -water	21.9	
Kumar et al. ²⁴³	TiO ₂ -water	9.09	MWCNT nanofluid showed the optimal HT performance; the optimum spacing of plate HX was 5 mm
	Al ₂ O ₃ -water	16.81	
	ZnO-water	19.28	
	CeO ₂ -water	23.41	
	Cu + Al ₂ O ₃ -water	37.11	
	GnP-water	45.45	
	MWCNT-water	52.86	
Wang et al. ²⁴⁴	GnP-EGW	4	The correlations of hm and f of the nanofluids in MPHE were summarized
Tiwari et al. ²⁴⁵	CeO ₂ -water	35.9	0.75 vol% CeO ₂ -water nanofluids had an optimal performance index up to 16%
	Al ₂ O ₃ -water	26.3	
	TiO ₂ -water	24.1	
	SiO ₂ -water	13.9	
Bhattad and Sarkar ²⁴⁶	Al ₂ O ₃ -water	17.1	performance of hybrid nanofluids was higher than that of single-nanoparticle nanofluids
	Al ₂ O ₃ + MWCNTs (4:1)-water	25.36	the increase in Δp was negligible

the Nu of $Al_2O_3+TiO_2$ in water nanofluids was 38.5% higher than at 70 °C.²³⁹ This observed difference was attributed to changes in the fluid's ρ , μ , and thermal diffusivity with temperature. Investigation of TiO_2 nanofluids revealed that the h_m of 0.2% TiO_2 in water was highest at 15 °C.²⁴⁰ The h_m of TiO_2 nanofluids decreased as temperature increased. Furthermore, CNT nanofluids exhibited higher Nu at 70 °C compared to 50 °C due to improved thermal properties and enhanced Brownian motion and thermal diffusion abilities at higher temperatures. In another study, the h_m of 0.3 wt % MgO in ethylene glycol (EG) nanofluids was 9% higher at 60 °C than at 25 °C.²³⁰ Arya et al.²⁴¹ noted changes in thermal conductivity, C_p , and μ of MgO in EG nanofluids between 25 and 100 °C. Thermal conductivity increased with temperature while viscosity decreased, explaining the improved HT performance at higher temperatures. A higher inlet temperature enhanced the HT performance of fluids containing MgO and CNTs, while TiO_2 nanofluids performed better at lower inlet temperatures. Further research is needed to investigate the impact of thermal conductivity and viscosity on fluid behavior.

4. ENVIRONMENTAL IMPACT OF NANOFLUIDS

Microscopic liquid suspensions containing tiny particles in the main fluid are known as nanofluids. Consequently, the overall environmental influence of nanofluids is a blend of the environmental impression of the main fluid and the nanoparticles. H_2O is widely favored as the main fluid due to its nontoxic, nonflammable, safe, and easy-to-use properties. The nature of the nanoparticles, their physical, chemical, toxic, and ecological effects, plays a crucial role in determining the environmental footprint of nanofluids. Additionally, the v_f nanoparticles influences the environmental consequence of nanofluids.²⁴⁷ Effective management of the environmental effects of nanofluids relies heavily on the optimal design of the nanofluid. Utilizing natural substances like silica, alumina, and iron oxides outcomes in considerably lower environmental influences compared to the synthetic manufacturing of such particles. This approach helps minimize energy and material requirements for production. Furthermore, employing natural nanoparticles, typically nontoxic variants, can further mitigate potential toxicity concerns during the application and disposal of nanofluids. Similarly, reducing the concentration of nanoparticles can mitigate potential environmental harm. The manner in which nanofluids are prepared significantly influences their environmental impact. For instance, Barberio and colleagues²⁴⁸ assessed the environmental impact of alumina nanofluids created using either a one-step or two-step method. Their findings, based on a combined life cycle assessment and risk assessment, indicated that the one-step method had nearly three times the environmental impact compared to the two-step approach. The use of nanofluids to improve HT processes offers environmental advantages by enhancing energy efficiency, thereby reducing energy consumption, heat losses, and heat dissipation. Nanofluids contribute to environmental and economic savings by lowering greenhouse gas emissions. Nanofluids can increase CO_2 absorption, which helps reduce the environmental impact of carbon emissions that contribute to climate change and air pollution. Various studies have demonstrated the positive environmental impact of nanofluids, such as reducing CO_2 emissions from solar water heaters by using CeO_2 /water nanofluids or copper nanoparticles. These examples highlight

the potential of nanofluids in reducing environmental harm and promoting sustainability.^{249–251}

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This study discusses the latest advancements in the development, stability, heat properties, and effectiveness of nanofluids in thermal systems. Upon reviewing the literature, several key findings were made regarding the recent progress of nanofluid technology.

Researchers have noted that incorporating nanoparticles into base fluids can enhance thermal characteristics such as h_m , k_p , μ , and ρ , impacting parameters like f , Re , Nu , and pump efficiency. Nanofluids are utilized in different applications based on their properties, and optimal conditions of temperature, ϕ , and particle size exist for improved THP. Using nanofluids with greater heat capacity than the base fluid enhances thermal system efficiency. Thus, nanoparticles that enhance heat capacity and k_p of the base fluid should be utilized for enhanced HT.

Stability is a crucial factor for nanofluids, with pH variation playing a significant role in enhancing the stability and k_p of nanofluids. Higher pumping power is required to counteract the effects of nanoparticle size and shape on Δp , stability analysis, rheological properties, and HT augmentation.

Thermohydraulic properties play a crucial role in assessing and augmenting the performance of nanofluids, with factors like solid particle ϕ , Re , Δp , m_f regime, magnetic field, f , and type of thermal device affecting the improvement of THP.

Additionally, thermodynamic performance is vital in designing HT systems, with entropy generation and exergy efficiency being essential factors reliant on the type of nanoparticle, thermal application, type of flow regime, and ϕ . Increasing thermal efficiency reduces pressure, lowers system energy consumption, and minimizes exergy destruction. Analysis of entropy generation is necessary to determine beneficial models for thermal systems.

Replacing conventional working fluids with nanofluids offers advantages in HT performance, though it may lead to increased Δp , pumping power, and consequently high energy consumption, incurring additional costs. Limited studies exist on the thermo-economic performance of nanofluids, necessitating further research to analyze and optimize the cost performance of nanofluids for enhanced thermal applications.

The enhanced k_t and reduced viscosity of nanofluids make them promising for high-temperature applications, allowing for HT area expansion and potential size and weight reduction in thermal systems. Nanofluids could have diverse applications in space exploration, aircraft engineering, and defense technology industries.

The form of additives profoundly influences the properties of nanofluids. Investigating innovative approaches to synthesizing nanofluids for precise control over microscopic structures opens up intriguing avenues for research.

The stability of suspensions holds paramount importance in both theoretical investigations and practical implementations. This encompasses enduring stability throughout extended durations and thermal cycles, necessitating heightened scrutiny.

The thermal performance of nanofluids at elevated temperatures remains relatively uncharted territory, presenting promising prospects for applications in high-temperature settings such as solar energy absorption and storage. However,

the rise in temperatures could trigger surfactant deterioration and heightened foam generation, demanding thorough consideration.

Nanofluid research can be enriched and broadened by delving into innovative nanomaterials.

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Notes

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NOMENCLATURE

f	Friction factor
h_m	Convective heat transfer coefficient ($\text{W m}^2 \text{K}^{-1}$)
HT	Heat transfer
K_p	Thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$
Δp	Pressure drop in HX, (Pa)
Re	Reynolds number
PEC	Performance evaluation criteria
CBP	Conical baffle plate
TEF	Thermal enhancement factor
MHS	Miniature heat sinks

MNCNT	Multiwalled CNT
STHX	Shell and tube heat exchanger
TPF	Thermal performance factor
THP	Thermal hydraulic performance
U	Overall heat transfer coefficient
FED	Flow energy dissipation
HX	Heat exchanger
CNT	Carbon nanotube
C_n	Specific heat
DBP	Deflector baffle plate
Nu	Nusselt number
PR	Pitch ratio
DPHE	Double pipe HX
Pr	Prandtl number
PI	Perforation index
DR	Depth of wing cut ratios
TT	Typical twisted tape
VG	Vortex generator
HP	Heat pipes
nm	Nanometer

GREEK LETTERS

ρ	Density (kg m^{-3})
μ	Coefficient of dynamic viscosity ($\text{kg m}^{-1} \text{s}^{-1}$)
β	Perforation ratio
ϕ	Concentration
α	Inclination angle
v	Average velocity (m s^{-1})
v_f	Volume fraction
m_f	Mass fraction

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