

# Nanotechnology Revolutionizing Heat Transfer: A Review of Nanofluid Research and Applications

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Nanofluids are a mixture of nanosized particles dispersed in a fluid that has gathered significant interest due to their ability to enhance thermal conduction and heat transfer processes. This comprehensive review delves into formulation methodologies, thermal and physical characteristics, and the applications of nanosuspensions in heat transfer. Various techniques are used to prepare heat transfer nanofluids with uniform dispersion and stable suspension. Common methods include mechanical stirring, sonication, chemical synthesis, and surface modification. These methods are influenced by nanomaterials' dimension, structure, and surface properties, ultimately shaping nanofluids' thermophysical characteristics. Thermophysical properties like thermal conductivity, viscosity, and heat capacity are notably improved in nanofluids compared to base fluids. However, increasing nanoparticle concentration increases the fluid viscosity, requiring careful consideration for practical applications. Heat transfer nanofluids find applications across various industries, including thermal management systems, heat exchangers, electronics cooling, and renewable energy systems. They improve the performance and efficiency of heat transfer equipment, enhance thermal conductivity in electronics cooling, and optimize energy harvesting processes in solar collectors. In conclusion, heat transfer nanofluids present promising opportunities to improve thermal conductivity and heat transfer efficiency in diverse applications. Continued research and development in formulation methods, understanding of thermophysical properties, and exploring new applications are crucial for fully realizing the potential of heat transfer nanofluids in various engineering fields.

**Keywords:** Thermal conductivity; viscosity; stability; dispersion; nanofluid

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The global environment change has prompted a shift in energy utilization trends from fossil fuels towards sustainable sources, alongside a growing need for high-efficacy energy systems. The referred proposals aim to establish a sustainable energy usage approach [1]. The push for competent and compacted energy exchange devices is spurring investigation efforts to devise efficient heat transfer methods. Traditional working fluids are prevalent in engineering and domestic cooling and heating. The commonly utilized working heat transport fluids are water, ethylene glycol (EG), propylene glycol, ionic liquids, and thermal oils [2]. Amidst the growing demands and insufficient capabilities of existing conventional heat transfer fluids for improved heat transfer capabilities across industrial

sectors, a novel concept of nanofluids emerged in 1995. Compared to conventional liquids, the nanoparticle dispersion within nanofluids enhances fluid turbulence, diminishes thermal resistance, and delivers exceptional thermal efficiency. It has inspired considerable research interest in exploring nanofluid heat transfer performance across various uses, including thermal exchangers, automotive radiators, electronic chips, solar energy systems and more [3]. In recent years, nanofluids have gained popularity because of their distinctive thermophysical characteristics and promising applications in thermal transfer [4].

As a result of their outstanding heat and thermophysical capabilities in contrast to conventional fluids,

along with their significance in heat and mass transport behaviour, nanofluids now find diverse applications across various industries. Employing nanofluids leads to decreased energy consumption, enhances fluid heat efficiency, and ultimately contributes to downsizing equipment, a crucial aspect in emerging technologies [5]. Nanofluids exhibit significant property enhancements even at low nanoparticle concentrations [6]. Nanofluid technology presents exciting opportunities to enhance thermal performance, as demonstrated by a substantial increase in thermal conductivity observed in a nanofluid under specific conditions [7]. Achieving stable nanofluids is critical in enhancing their thermal performance [8]. Perfect nanofluids indicate higher thermal conduction, minimal viscosity, excellent steadiness, and cost-effectiveness [9]. The enhancement of heat transport associated with nanofluid thermophysical possessions relies heavily on nanoparticle dispersion stability within the fluid [10]. Numerous factors, including the characteristics of nanosized materials and base fluids, influence the stability of nanofluids [11]. Nanofluids are being explored as potential alternatives to traditional fossil fluids across a range of industries, spanning aerospace, aeronautics, energy generation, micro-electronics, treatment of water, medical technology, micro-fluidics, thermal administration, transfer of heat, and automobile systems. However, the widespread adoption of nanofluids in industrial settings faces a significant hurdle: ensuring their stability. This dispersion is impacted by various factors, including the preparation techniques, operating temperatures, and the utilization of surfactants. Achieving and maintaining nanoparticle dispersion is crucial for unlocking the full potential of nanofluids in diverse applications [12]. Furthermore, hybrid nano-enhanced fluids are reported to further enhance

heat transmission compared to single nanomaterials containing fluids [13]. A crucial aspect of research investigations is the formulation of nanofluids. Creating nano-enhanced fluids involves more than just blending nanoparticles and fluid; it requires specific physical and chemical processes to ensure homogeneity and prevent aggregation. Nanofluids are typically prepared using either a single or two-step method [14]. The synthesis, characterization, and employing of hybrid nano-enhanced fluids are still undergoing advancement. This area requires massive technical searching to explore a broad range of combinations of nanomaterials and base liquids that can yield optimal outcomes. Balancing thermo-physical things and leveraging the synergistic effects among the combined constituents holds the key to achieving optimum performance. Numerous permutations and combinations are yet to be explored, requiring the proper production and characterization techniques. Combining the finest-performing individual components with moderately performing counterparts in appropriate proportions could lead to exciting outcomes. The synergistic compatibility of thermo-physical properties in hybrid nanosuspensions represents a promising avenue for further research [15]. Figure 1 illustrates the typical preparation techniques employed to enhance the dispersion level of nanofluids.

As depicted in Figure 2, the selected technique and nanoparticle structure's anticipated significantly affect nanofluids' thermal conduction. Likewise, viscosity is determined by numerous factors, including dispersion quality, volume part, nanomaterial's size and structure, the temperature range in the application, nanoparticle composition, and the intrinsic properties of the base fluid [16].

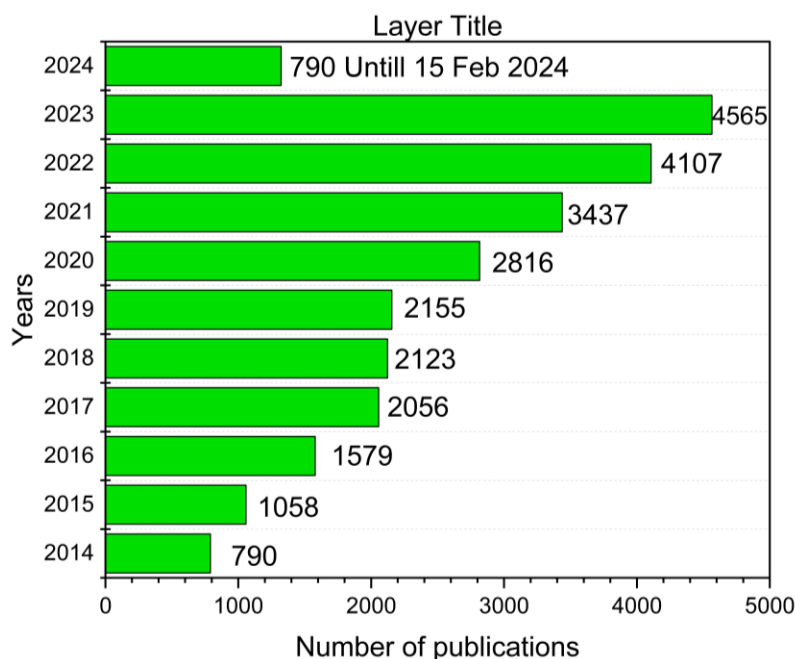
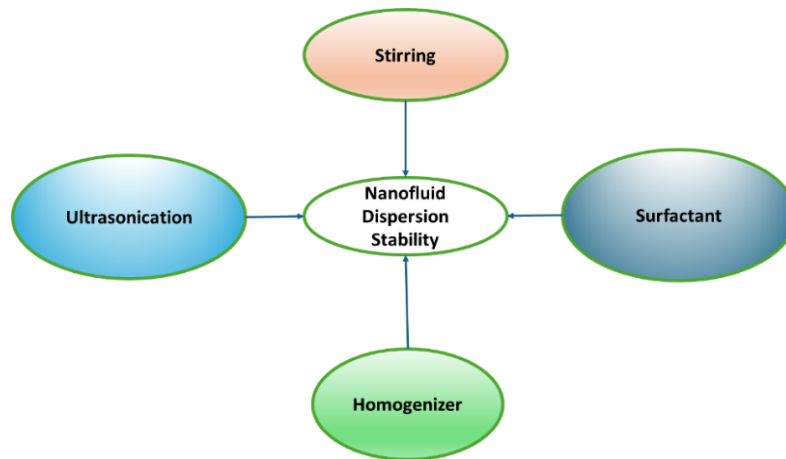


Figure 1. Publication status from 2014 – 15 Feb 2024 source: Elsevier database.



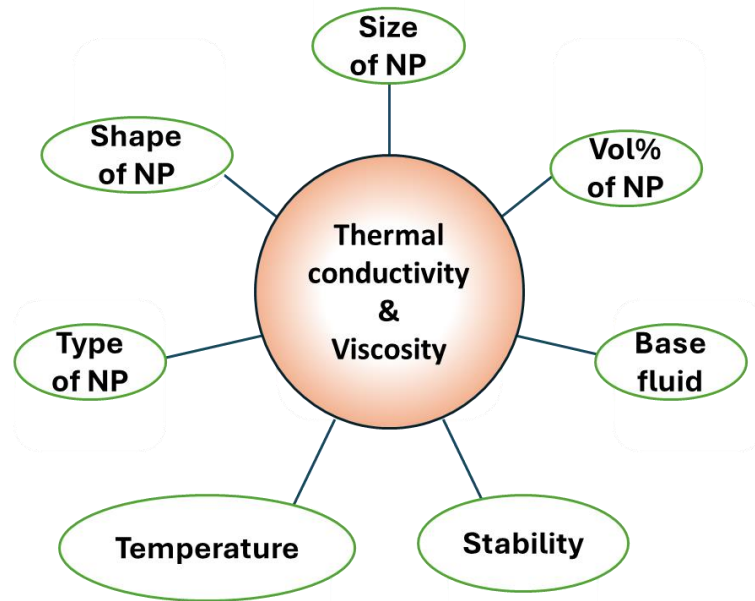
**Figure 2.** Preparation procedure of nanofluid.

Hence, variations in the dispersion parameters have a direct impact on the viscosity of nanofluids. Generally, Figure 3 illustrates the factors influencing nanofluid viscosity. While certain nanofluids exhibit Newtonian behaviour in viscosity experiments, others exhibit a non-Newtonian way of acting when volume part, heat, and particle dimension are altered. Certain research correlates viscosity levels with nanofluid rheologic quality. Therefore, alongside viscosity, two rheological parameters—shear stress and shear rate—are also considered [17]. The thermal conduction of nanofluid notably rises with a rise in the solid size fraction of nanomaterials. Additionally, there is an expansion in thermal conduction with rising temperatures. Mainly, the rate of rise is more definite at elevated temperatures. Consequently, the thermal effectiveness of this nano-enhanced fluid escalates at elevated temperature ranges [18].

Among the various techniques available for measuring nanofluid thermal conductivity, the transient hot-wire procedure is widely recognized for its effectiveness. The choice of base fluid, the class of nanoparticles, the particles' intensity, the particles' size and shape, and the nanofluid's temperature are all carefully considered while evaluating this attribute. Notably, the thermal conductivity of the carrier fluid, along with the particle intensity and size, emerges as critical parameters that significantly impact the overall thermal conductivity of the nanomaterial-enhanced liquid [19]. Thermal conductivity and viscosity are essential properties in studying hybrid nanofluids. Among the hybrid nanoparticles studied for thermal enhancement, notable blends include  $\text{Al}_2\text{O}_3\text{-CuO}$ ,  $\text{CuCu}_2\text{O}$ ,  $\text{Al}_2\text{O}_3\text{-SiO}_2$ ,  $\text{CuO-TiO}_2$ ,  $\text{Al}_2\text{O}_3\text{-Ag}$ ,  $\text{SiO}_2\text{-CNT}$ ,  $\text{Cu-Zn}$ ,  $\text{Al}_2\text{O}_3\text{-CNT}$ ,  $\text{GNP-Ag}$ ,  $\text{Ag-MgO}$  and  $\text{Ag-TiO}_2$  [20,21].

Nanofluids offer a reduction in pumping power for heat transfer by maintaining stable suspension of nanoparticles, thereby minimizing agglomeration and fluid flow resistance. Moreover, increasing the volume

fraction of nanofluid reduces the required pumping power while maintaining effective heat transfer. Furthermore, by modifying the nanoparticle volume percentage, nanofluid characteristics like surface wettability and thermal conductivity can be customized to suit particular applications. In boiling heat transfer, the degree of solid wetting plays a crucial role, benefiting from nanofluid stability and improved thermal conductivity resulting from Brownian motion. These consistent findings, as highlighted by various researchers, underscore the potential of nanofluids in enhancing heat transfer efficiency [22]. The thermal transfer properties of nanofluids are vital in energy conversion processes, providing significant advantages compared to traditional base fluids. With their superior thermal conductivity, nanofluids show potential for improving system performance. However, despite their benefits, the stability of nano-enhanced fluids remains a significant concern and a barrier to their widespread industrial use [3]. The effects of nanoparticle features need to be further investigated in order to fully understand how concentration, temperature, and flow rate affect the thermophysical properties of nanofluids. Generally, increasing the volume fraction of nanomaterial enhances nanofluid density, viscosity, and thermal conductivity, with studies indicating an optimal volume fraction for enhancing heat transfer. Challenges remain in ensuring stability across various applications, exploring hybrid nanofluids, understanding property variations under different conditions, and scaling up experimental findings for commercial use, especially in sectors like water desalination, power generation, and aerospace. Evaluating the environmental impact of nanofluids is also essential [23]. Nanofluids with ideal properties for advanced vehicles are currently unavailable, prompting a need for further research. Long-term stability issues persist, requiring additional theoretical and experimental work. Understanding the causes affecting thermal conductivity enhancement and determining the normalcy of observed enhancements are key areas requiring systematic investigation [24].



**Figure 3.** Factors influencing thermophysical properties of nanofluid.

While numerous review articles have discussed the progress in nanofluid research, most have focused on investigational and numerical research related to thermophysical possessions or convective heat transfer. This paper seeks to explore innovative methods for creating nanofluids, comprehend the mechanisms that maintain their stability, and identify emerging applications like electronics cooling systems, solar thermal collectors, automotive engine cooling, HVAC systems, biomedical devices, distillation, food processing, enhanced oil recovery process, spacecraft thermal management and desalination processes. Furthermore, it aims to analyze the heat transport matters of nanofluids thoroughly. The main objective is to uncover new approaches for preparing nanofluids, clarify the factors that ensure their stability, and pinpoint promising avenues for their utilization.

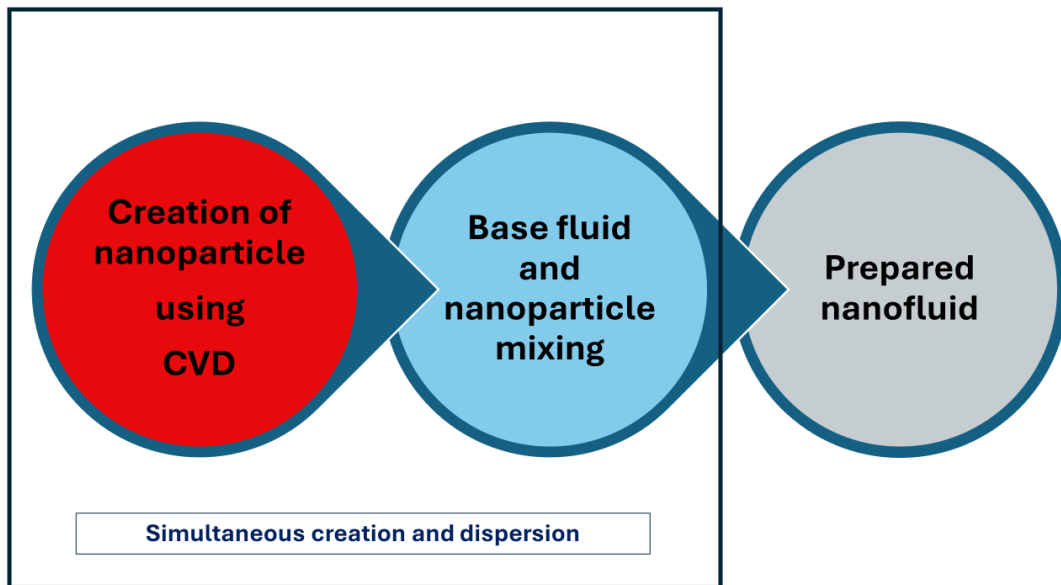
#### PREPARATION METHODS

##### One-Step Method.

In a one-step procedure shown in Figure 4, the formulation and diffusion of nanomaterials occur simultaneously for preparing nanosuspensions. This approach eliminates the need for transporting, storing, drying, and dispersing nanoparticles separately, thereby reducing the probability of nanoparticle accumulation and increasing nanofluid stability. Vapour deposition is among the one-step preparation methods utilized for nanofluid production [25]. This category may be subdivided into two groups: chemical vapour deposition (CVD) and physical vapour deposition (PVD), each containing multiple variants [26]. Chemical vapour deposition (CVD) is recognized as a dependable chemical technique for fabricating 2D nanosized

elements and thin layer films on a wide array of substrates. This technique involves the reaction or decomposition of precursor materials in vapour form on the substratum, with or without catalysts, within a vacuum chamber at elevated temperatures. CVD has several variations, low-pressure CVD, atmospheric pressure CVD, hot-wall CVD, cold-wall CVD, plasma-enhanced CVD, photo-assisted CVD, and laser-assisted CVD, among others. The CVD method is widely used in both research and industry. It has played a vital role in the synthesis of several carbon-based nanomaterials, including graphene, fullerenes, carbon nanotubes (CNTs), and carbon nanofibers (CNFs) [27].

Physical vapour deposition encompasses various vacuum deposition techniques for producing thin films and coatings. It involves transitioning material from a condensed phase to a vapour phase and back to a thin film condensed phase. Popular methods include sputtering and evaporation. The procedure consists of sputtering/evaporating dissimilar components to create a vapour phase, supersaturation in a passive atmosphere to stimulate condensation of metallic nanomaterial, and finally, association of the nanocomposite through heat treatment beneath static conditions [28]. Laser ablation involves directing a pulsed laser onto a target surface, causing rapid heating and material removal. In pulsed laser ablation in liquid (PLAL), the laser beam is directed onto a graphite target submerged in deionized water, generating nanoparticles through vaporization or phase change. The experimental setup includes a laser source, optics for beam focusing, and a turntable for uniform ablation. Variations in laser frequency and power are being explored to understand their effects on the formation of nanoparticles [29]. This approach offers advantages,



**Figure 4.** One-step preparation method.

including high purity, excellent dispersion, and long-term suspension stability, with nanofluids remaining stable for days or weeks. However, residual reactants in the nanofluids are costlier and impractical for widespread use. Alternative vapour-phase production methods for nanosized materials, like sputtering, electro-winning evaporation, and reactive hydrogen-melt metal reaction, may offer more practical and cost-effective alternatives [30].

### Two-Step Method

This represents the most cost-effective methodology for broad-level nanofluid preparation. In the two-step technique illustrated in Figure 5, nanomaterials are synthesized by applying various procedures and then diffusing into carrier fluid to make the anticipated nano-enhanced fluid. This formulation method is both low-cost and scalable. However, the main drawback lies in the tendency for nanoparticle aggregation because of their high surface space and properties, necessitating surface-active agent usage for stabilization. Despite this challenge, the two-step method remains the researchers' desired commercial approach for nanofluid preparation [31-32]. In the two-step method, ultrasonic vibrators are commonly employed to blend base liquids and nanoparticles, offering superior results in specific nanofluid processing scenarios. Agglomeration poses a significant challenge in nanofluid creation, making the two-step method particularly advantageous. It enables industrial-scale production and is considered the most effective nanofluid processing method.

Furthermore, utilizing oxide nanoparticles instead of metal ones has been suggested as a more

suitable option for this method [33]. Over time, sedimentation of nanoparticles occurs, leading to a deterioration in the steadiness of nano-enhanced fluids. The two-step methodology is favoured for broad-scale processing because of its ease of implementation and relatively low cost [34]. In the literature, three distinct approaches have been reported for the formulation of hybrid nanofluids using the two-step approach: sequentially diffusing nanoparticles into the base liquid, preparing unitary nanofluids and then mixing them, and synthesizing nanocomposites before dispersing them into the base fluid. However, certain studies have employed these techniques with modifications aimed at achieving better dispersion of nanoparticles [35].

### THERMOPHYSICAL PROPERTIES AND CHARACTERIZATION OF NANOFLUID

Nanosuspensions exhibit enhanced thermophysical attributes like thermal conduction, specific heat, viscosity, and density compared to base fluids. A researcher highlighted that nanoparticle concentration, shape, size, material, base fluid, and temperature significantly influence these properties. Despite their potential applications in various fields, poor stability due to particle aggregation and sedimentation poses a challenge. It has discussed the approaches for nanofluid steadiness from formulation to practical use, emphasizing the importance of stability under different operating conditions. An investigation explored nanofluids' potential as heat transmission fluids in solar collectors, considering features like particle dimension, pH, stability methods, and measurement techniques affecting thermal properties [36]. Characterizing nanofluids involves various techniques to determine their properties and behaviours. Some

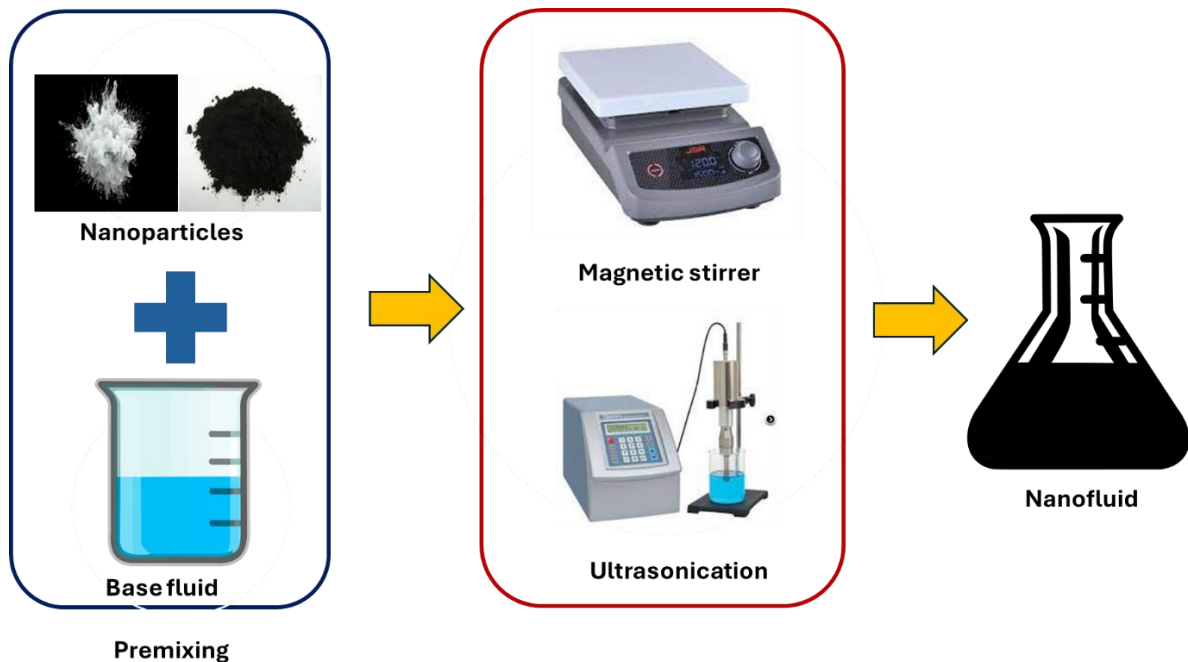


Figure 5. Two-step preparation method.

standard characterization techniques for nanofluids are SEM, TEM, XRD, FT-IR, DLS, TGA, and zeta potential analysis. SEM and TEM examine morphology and microstructure, with TEM offering higher resolution. XRD identifies crystal structure, FT-IR analyzes surface chemistry, DLS estimates nanoparticle size, TGA studies thermal stability, and zeta potential assesses dispersion stability. Collectively, these techniques provide insights into nanofluid properties, aiding in several applications, including heat transfer enhancement, besides material science [37].

### Thermal Conductivity

The heat conduction of nano-enhanced fluids is of great interest because of its capability to boost heat transmission in many applications. Nanofluids, consisting of nanomaterials dispersed in a base liquid, expose notable improvements in thermal conductivity contrasted to standard fluids like water or oil. This enhancement is recognized as the addition of nano-sized particles with inherently high heat conductivities, facilitating enhanced heat transfer within the liquid. Optimizing the nanofluid's thermal conductivity remains crucial for enhancing efficiency in industries spanning thermal management systems to solar energy harvesting, where experimental investigations are vital to understanding their behaviour under different conditions [38–40]. In the experiment, zirconium oxide ( $ZrO_2$ ) and silicon carbide (SiC) nanomaterials were mixed in distilled water (DW). Results indicated that higher concentrations and temperatures led to improved thermal conductivity, with the highest conductivity observed at 60°C and a 0.1% solid volume fraction. Specifically,  $ZrO_2$ /DW and SiC/DW nanofluids enhanced thermal conductivity by 20.455% and 30.303%, respectively, at a 0.1% volume fraction

[41]. In this study, a water-based magnetic fluid was filled with multi-walled carbon nanotubes (MCNTs), silver (Ag) nanoparticles, and copper (Cu) nanoparticles to boost thermal conductivity. The hybrid magnetized fluids containing these nanoparticles exhibited notable improvements in thermal conductivity.

The MF+MCNTs nanofluid exhibited the most significant enhancement at 10.93%. Several theoretical models were assessed to predict thermal conductivity, with the Evans model showing excellent predictive accuracy, deviating within 5%. This study offers valuable insights into enhancing the thermal conduction of magnetic fluids and presents a more precise theoretical approach for calculating it in hybrid magnetic fluids [42]. The study utilized  $Al_2O_3$  nanoparticles, CuO nanoparticles, and a Sodium dodecylbenzene sulfonate surfactant to produce hybrid nanofluids. A significant enrichment in heat conduction of the hybridized nanomaterial-enhanced fluid was observed, showing a 14.6% increase compared to  $Al_2O_3$  Nanofluid at 1.0 vol.% concentration, both at 60°C and 30°C. These findings highlight the potential of hybrid nanofluids for applications requiring improved thermal properties, including solar energy systems [43]. Utilizing  $Al_2O_3$  and MWCNT nanoparticles in a Water and Ethylene Glycol (EG) mixture (80:20 volume%) with CTAB surfactant increased thermal conductivity with higher volume concentration and temperature. The peak thermal conductivity recorded was 0.5416 W/mK, representing an 8.47% enhancement over the base fluid, observed at  $T = 50^\circ C$  [44].

### Density

The nanofluid's density remains a critical yet under-explored physical property that has significant

implications for its fluid behaviour. While previous studies have commonly employed classical mixture density models, there remains a dearth of in-depth investigation into this crucial aspect. Understanding and accurately characterizing nanofluid density are paramount for unlocking their full potential in various applications, prompting the need for more comprehensive research efforts in this domain [45]. Density assessments were carried out on nanofluids comprising  $\text{Al}_2\text{O}_3$ ,  $\text{Sb}_2\text{O}_5\text{:SnO}_2$ , and ZnO nanomaterials suspended in a 60% EG and 40% water-based liquid. Comparison with established data demonstrated outstanding alignment for the base liquid. Over a heat range of  $0^\circ\text{C}$  to  $50^\circ\text{C}$ , the density estimation exhibited satisfactory correspondence with theoretical predictions for  $\text{Al}_2\text{O}_3$  and  $\text{Sb}_2\text{O}_5\text{:SnO}_2$  nanofluids. However, deviations from expected values were more pronounced in the case of ZnO nanofluid, particularly as the intensity of particles by volume increased [46]. The density of nanofluids generally rises with higher concentrations of nanoparticles, indicating a direct relationship between density and nanoparticle concentration. Temperature variations tend to have minimal impact on nanofluid density. Notably, using mixture formulas exhibits satisfactory accuracy in predicting nanofluid density, underscoring its utility in practical applications [47]. Nanosized particles, including aluminium oxide ( $\text{Al}_2\text{O}_3$ ), zinc oxide (ZnO), copper oxide (CuO), titanium oxide ( $\text{TiO}_2$ ), and silicon dioxide ( $\text{SiO}_2$ ), along with carbon nanotubes (CNTs) dissolved in deionized water (DI), were utilized. The base fluid comprised a 60:40 propylene glycol and water (PG/W) mixture by volume. Density tests were conducted on the base fluid within a  $0$ – $90^\circ\text{C}$  temperature range. Density measurements were subsequently performed on various nanosuspensions with nanomaterials volumetric strengths ranging from 0 to 6% and nanoparticle dimensions varying between 10 and 76 nm. These measurements were taken across  $0$  to  $90^\circ\text{C}$  [48].

### Viscosity

Viscosity plays a crucial role in understanding nanofluids, prompting extensive research efforts over recent decades. Factors affecting viscosity encompass nanoparticle concentration, size, type, nanofluid temperature, base fluid surfactant, and stability. Nevertheless, establishing a universal trend for the effect of particle dimension on viscosity enhancement remains elusive. Notably, there is a tendency for the lowest increase in viscosity with higher nanoparticle concentrations [49]. Research has also been focusing on analyzing nanofluids' dynamic viscosity, particularly those containing MWCNT (MKN-MWCNT-RG1020) nanoparticles dispersed in distilled water. Experimental tests were performed across a heat range of  $38$  to  $78^\circ\text{C}$ . The MWCNT nanoparticles utilized had inner and outer diameters falling within  $5$ – $10$  nm and  $10$ – $20$  nm, respectively, with an overall size range of  $10$ – $30$   $\mu\text{m}$ . The nanofluid consisted of a volume strength of 0.05%

MWCNT nanoparticles. The study proposed novel correlations to predict dynamic viscosity, employing experimental data and polynomial regression techniques. The resulting correlation demonstrated high accuracy, evidenced by an  $R^2$ -value of 0.99 and an RMSE of  $1.18\text{E-}06$  mPa s [50]. The study explores the impact of nanoparticle intensity, dimension, and heat on the viscosity of nanosuspensions, utilizing CuO nanoparticles with mean dimensions of 15 nm, 45 nm, and 75 nm. Viscosity estimations cover volume strength ranging from 1% to 4% across temperatures from 293 K to 353 K. Results indicate a highest 23% improvement of effective viscosity with nanoparticle addition. In comparison, temperature elevation from 293 K to 353 K leads to an 80% decrease in viscosity. Furthermore, increasing particle size increases the maximum viscosity by 0.5% [51].

### Specific Heat

An in-depth comprehension of the heat capacity of nanosuspensions holds paramount importance in evaluating their thermal characteristics and efficacy in energy-related applications. This discourse aims to intricately examine the specific heat in nanofluids, encompassing measurement methodologies and theoretical frameworks employed therein. The discussion will elucidate how nanoparticle concentration, temperature variations, and nanoparticle properties influence specific heat, navigating through the realms of consensus and discordance within extant literature. The overarching objective is to comprehensively understand heat capacity in nanofluids and its multi-faceted significance across diverse domains [52–53]. A study of the heat capacity of  $\text{Al}_2\text{O}_3$ -ZnO nanomaterials dispersed in water revealed that the maximum reduction in heat capacity was 30.12% [54]. In another research, the study explored the heat capacity, an essential factor in energy transfer for working fluids, in relation to nano-additives and temperature. It was discovered that the heat capacity could be effectively increased by 26.23% compared to the original base liquid.

Through experimental methods, a mechanistic analysis indicated that the increase in heat capacity was attributed to the formation of hydrogen bonds between the deep eutectic solvent (DES) and nanoparticles [55]. The study explored how different solvents in molten salt nanofluids affect heat capacity (HC), investigating  $\text{SiO}_2$  and graphite nanoparticles dispersed in  $\text{NaNO}_3$ ,  $\text{KNO}_3$ , and  $\text{NaNO}_3$ - $\text{KNO}_3$  mixtures. Using differential scanning calorimetry, the SHC was measured, revealing up to a 17.2% increase in the SHC of  $\text{NaNO}_3$ - $\text{SiO}_2$  nanofluids in the liquid phase. Conversely, SHC enhancements varied between  $-1.2\%$  and  $8.2\%$  for binary salt- $\text{SiO}_2$  nanofluids and were  $<7.8\%$  for binary salt-graphite nanofluids. The electrical double layer (EDL) analysis also suggested that  $\text{SiO}_2$  nanomaterials had more potent attractive forces in ionic mixtures than graphite, influencing the SHC enhancement mechanism in molten salt nanofluids [56].

## Summary

The heat conductivity of nanosuspensions, increased by nano additives, is crucial for diverse applications. ZrO<sub>2</sub>/DW and SiC/DW nanomaterial added fluid exhibited significant enhancements of 20.455% and 30.303% at 0.1% tiny volume. Similarly, the MF+MCNTs nanosuspension showed the highest enrichment at 10.93%, while hybrid nanofluids demonstrated a 14.6% increase compared to base fluids. Additionally, utilizing Al<sub>2</sub>O<sub>3</sub> and MWCNT nanoparticles led to an 8.47% enhancement compared to the base liquid at 50 °C. Viscosity in nanofluids, influenced by factors like nanoparticle concentration and temperature, is a subject of extensive research. Varying effects of nanoparticle size on viscosity enhancement, with a tendency for lower increases at higher concentrations. MWCNT nanofluids in distilled water revealed high accuracy in predicting dynamic viscosity alongside a value of R<sup>2</sup> of 0.99 and RMSE of 1.18E-06 mPa s. Nanofluids, with dispersed nanoparticles, exhibit enhanced thermal properties compared to conventional fluids, as outlined in Table 1.

Another study examining CuO nanoparticle nanofluids demonstrated a maximum 23% viscosity increase with nanoparticle addition, an 80% decrease with temperature elevation and a maximum 0.5% increase with larger particle sizes. The heat capacity of nanosuspension is vital for their thermal behaviour, influenced by factors like nanoparticle concentration

and temperature. Both increases and decreases in specific heat capacity due to nano-additives and solvent composition. For instance, while Al<sub>2</sub>O<sub>3</sub>-ZnO nanofluids exhibited a 30.12% decrease in specific heat, deep eutectic solvent (DES) interactions with nanoparticles led to a 26.23% increase. Nanofluids with molten salt exhibited varied specific heat capacity enhancements influenced by nanoparticle type and solvent composition, with SiO<sub>2</sub> nanoparticles showing more vital attractive forces in ionic solutions. The density of nanofluids, crucial for understanding fluid behaviour, exhibits a direct correlation with nanoparticle concentration, with minimal impact from temperature variations. Nanofluids containing Al<sub>2</sub>O<sub>3</sub>, Sb<sub>2</sub>O<sub>5</sub>:SnO<sub>2</sub>, plus ZnO nanoparticles in a 60:40 EG/water base fluid showed good agreement with theory for Al<sub>2</sub>O<sub>3</sub> and Sb<sub>2</sub>O<sub>5</sub>:SnO<sub>2</sub> nanofluids, but higher deviations for ZnO nanofluid increased with particle volume concentration.

Nanoscale particles, including Al<sub>2</sub>O<sub>3</sub>, ZnO, CuO, TiO<sub>2</sub>, SiO<sub>2</sub>, and CNTs mixed in Propylene Glycol/Water, showed density across nanoparticle concentrations and sizes, with measurements taken ranging from 0 to 90 °C of temperature. Nanofluids exhibit enhanced thermophysical properties compared to conventional fluids but face challenges like poor stability. Nanoparticle characteristics, concentration, and temperature influence viscosity, heat capacity, and density, impacting their performance in diverse applications.

**Table 1.** Thermophysical properties of nanofluid.

Nanoparticle	Concentration	Base fluid	Thermal conductivity increment%	Viscosity	Density	Specific heat	Key findings	Ref.
Al <sub>2</sub> O <sub>3</sub>	0.02,0.05,0.08, 0.11	Water	2.3%	-	-	-	The new comparative interferometric method was used.	[57]
CuO, MgO, Fe <sub>2</sub> O <sub>3</sub>	0.05%, 0.1%, and 0.2%	Water and EG	288% 272% 234%	-	-	-	Thermal conductivity declines with a temperature rise.	[58]
Mn <sub>3</sub> O <sub>4</sub>	0.25 %, 0.5 %, 0.75 %, 1.00 % and 1.25 % vol.	EG	1.25% vol. 18.8% at 60°C.	89.4% at 20°C	-	-	Magnetic field application further enhances thermal conductivity and viscosity.	[59]
ZrO <sub>2</sub> (20 nm) And SiC (45-60 nm)	0.025, 0.05, 0.075, 0.1	DI Water	25.75% at 0.1% 60 deg	-	-	-	Hybrid formulation.	[60]
SiC-MgO (20, 55, and 90 nm)		EG	Increased	-	-	-	Thermal conduction decreased with increasing nanoparticle size.	[61]
CuO/MgO	m 0.25 to 1.5 %	Water	12.5 % at 55°C.	-	-	-	The addition of MgO nanomaterials resulted in a marginal improvement in thermal conductivity.	[62]
SiC, ZnO	0.2% to 1.0%	EG	15.91%	-	-	-	Both at the greatest temperature and volume percentage of the feasible tiniest nanoparticles.	[63]



Graphene Oxide Silver	0.050, 0.075, 0.1 %	Water	11%. Increased in 0.1 wt%	13% Increased	0.4%.	-	Long-term stability lasting for months.	[64]
SiO <sub>2</sub>		Mineral oil	8.55%	10.64%	-	-	Dielectric nanofluids significantly improve thermal properties.	[65]
Al <sub>2</sub> O <sub>3</sub> MgO Graphene Oxide (GO)	1.0%	Water	1% 1%	3% 2%	4% 4%	2% 3%	Improve their thermo- physical properties.	[66]
MXene	0.1to0.5 wt%	Water EG	30.6% 27.3%				No significant increase in viscosity.	[67]
SWCNT, MWCNT, SWCNT, MWCNT	0.05 to 1%. 0.05 to 1%.	EG Water	-	Increased Increased	- -	- -	Displayed pseudo- or viscoplastic behaviour.	[68]
rGO-Al <sub>2</sub> O <sub>3</sub>	0.01–0.1%	DI water	Increased	Increased	-	-	Increased when the temperature and concentration increase, the nanofluids exhibited non-Newtonian behaviour.	[69]
CuO/PANI	0.01% to 0.5%	Palm oil	31.34%	Increased	-	-	Palm oil displayed flow characteristics resembling those of a Newtonian fluid.	[70]
Al <sub>2</sub> O <sub>3</sub> TiO <sub>2</sub>		Water-EG (EG) mixer (60:40)	8.3% at 80°C(PEG) 3.6% at 80°C (PVP)	37.2% at 30°C. 28.9% to viscosity increment at 30°C.	-	-	Showed Newtonian behavior. Adding surfactants enhanced the viscosity alongside polyethene glycol (PEG), showing the maximum.	[71]

## APPLICATIONS OF NANOFLUID

Nanofluids, comprised of nanoparticles in a base liquid, are gaining attention for their wide-ranging applications. They enhance heat transfer in thermal management systems, boosting efficiency in heat exchangers and cooling systems. Additionally, nanofluids hold promise in renewable energy for improving solar thermal collectors and photovoltaic panels and in biomedicine for targeted drug delivery and medical imaging, showcasing their potential across various sectors. The ensuing elucidations aim to impart comprehensive knowledge to the audience regarding the significant attributes of diverse nanomaterial-dispersed nanofluids employed across different applications.

### Automobile Cooling System

The radiator is at the core of the automotive nanofluid cooling setup, as shown in Figure 6. As per the reviewer's evaluation, the adoption of CuO–EG/water (50:50) nanofluids resulted in an increase in temperature transfer coefficients. This enhancement subsequently lowered engine and coolant temperatures, consequently promoting engine power output and pump efficiency improvements. Notably, in Al<sub>2</sub>O<sub>3</sub>–water nanosuspensions, the heat transfer coefficient reached its peak at a 1 vol.% nanoparticle concentration, leading to significant enhancements in coolant heat transfer

rate (14.79%), heat transfer coefficient (14.72%), and Nusselt number (9.51%). Additionally, nanofluids comprising Al<sub>2</sub>O<sub>3</sub> in many base liquids like water, ethylene glycol, and EG/water mixtures demonstrated highest heat transfer coefficient enhancements of 6.52% with a 5.0 vol.% nanoparticle intensity compared to water. In the case of nanodiamond–engine oil nanofluids, engine performance was notably improved, with increases in both engine energy and turning force to 1.15% and 1.18%, correspondingly. Fuel utilization decreased by approximately 1.27% compared to conventional engine oil.

Furthermore, TiO<sub>2</sub>–water and SiO<sub>2</sub>–water nanofluids substantially enhanced heat transfer rates, reaching 20% and 32%, respectively [72]. CuO/SiO<sub>2</sub> nanoparticles are uniformly dispersed within an ethylene glycol-based coolant to create a hybrid nanofluid for studying its impact on thermophysical qualities in automobile engines. The study encompasses simulations across a spectrum of volume strengths from 0.1% to 0.5%. Results specify a notable improvement attributed to the utilization of nanoparticles possessing superior thermal conductivity. Specifically, the enhancement in thermal conductivity is observed to surpass that of water/ethylene glycol coolant by 6.5% [73]. An analytical investigation used a hybrid nanofluid of water, Al<sub>2</sub>O<sub>3</sub>, and CuO nanoparticles combined with ethylene glycol (EG) within a radiator system to enhance heat exchange

rates. The concentrations of EG,  $\text{Al}_2\text{O}_3$  nanoparticles, and CuO nanoparticles in the base fluid were 30%, 0.1%, and 0.1%, respectively. Results from the study indicate a noticeable improvement in heat transfer rates attributed to incorporating hybrid nanoparticles compared to the base liquid [74]. Experimental evaluation of  $\text{TiO}_2$  nanofluids in an automobile radiator coolant, blended with 40% EG and 60% aqua, reveals enhanced forced convective heat transfer coefficients compared to the base fluid. Testing across Reynolds numbers of 4000 to 15,000 indicates that increasing fluid circulation rates positively impact heat transfer performance, with negligible influence from liquid inlet temperatures. Notably, low strengths of  $\text{TiO}_2$  nanomaterial 0.1% to 0.5% exhibit up to a 37% enrichment in heat transfer rates over the carrier fluid, showcasing the potential for improved automotive cooling systems [75].

A study investigates the formulation and evaluation of stable graphene nanoplatelet nanofluids in silicone oil base liquid, focusing on thermal conductivity and viscosity trends across temperatures  $30^\circ\text{C}$  to  $55^\circ\text{C}$ . Three ultrasonication durations (1h, 2h, 3h) are examined to assess their impact on nanofluid properties. Many particle strengths (0.05%, 0.1%, 0.15%) are tested with sodium lauryl sulfate

as a surfactant for enhanced particle stability [76]. An experimental investigation on a novel hybrid nanofluid for vehicle radiators containing GnP and MWCNT in a 1:1 ratio dissolved in radiator coolant oil was studied. Volume concentrations range from 0.05% to 0.5%, with significant enhancement in thermal conductivity (59% increase at 0.5% volume strength), leading to improved convective heat transfer coefficients was reported. The OHTC is maximally enhanced ( $\sim 124\%$ ) at 0.5% volume concentration and 5 m/s air velocity assessed to base liquid, albeit with a 23.72% rise in pressure drop. This suggests a potential for the GnP-MWCNT/coolant oil HyNf as a coolant oil alternative [77].

### Refrigeration and Air Conditioning System

Nano-enhanced liquids play a crucial role in enhancing heat transfer for various applications due to their exceptional properties. Achieving long-term stability is vital for their effectiveness. The research found that  $\text{Al}_2\text{O}_3$ /water nanofluids can significantly boost cooling system performance, as shown in Figure 7, with potential COP enhancements of up to 20.8%. Additionally, incorporating  $\text{Al}_2\text{O}_3$  nanoparticles into refrigerants like R-134a and R-600a can substantially improve COP, aiding in efficient heat exchange [78].

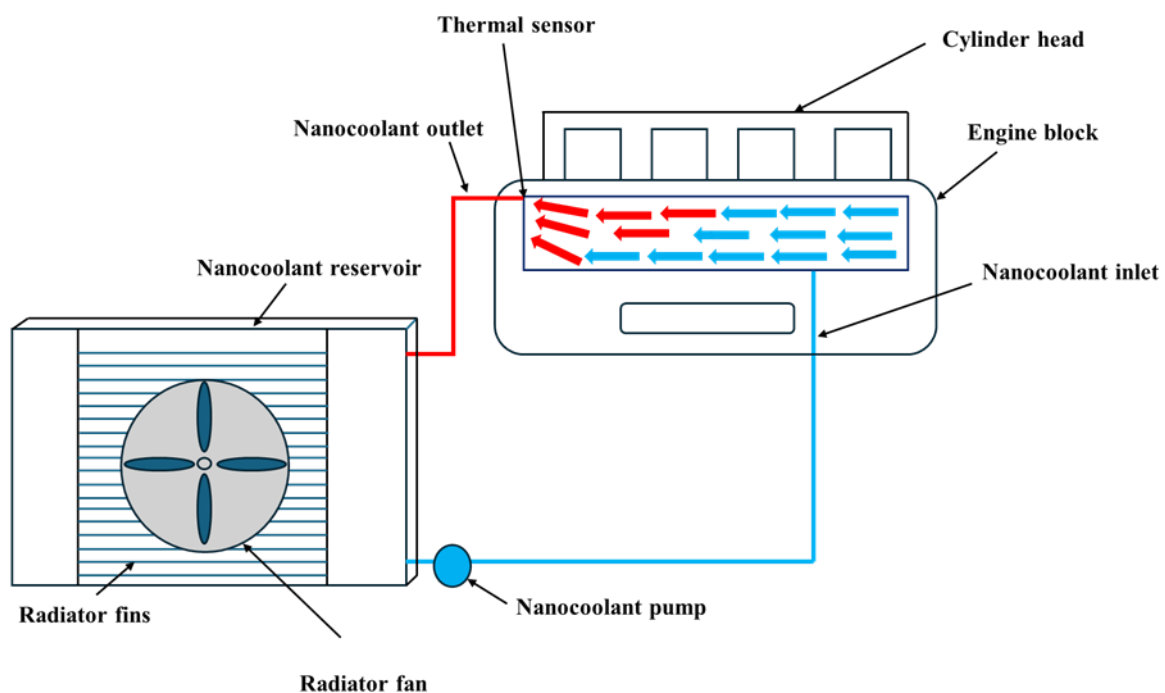


Figure 6. Nanofluid engine cooling system.

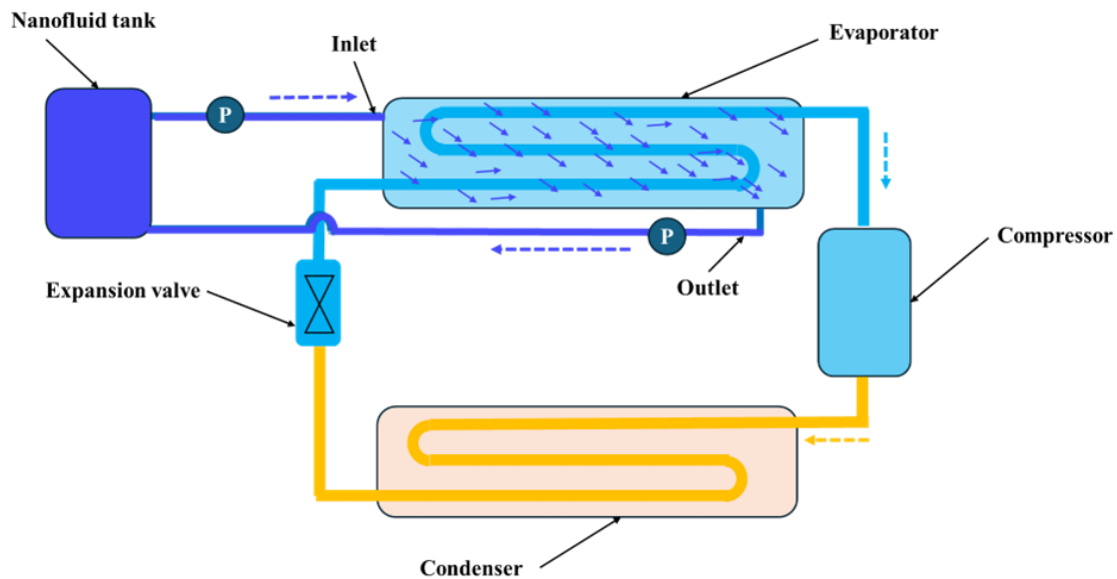


Figure 7. Nanofluid refrigeration and air conditioning system.

Due to concerns over R134a's high Global Warming Potential and its incompatibility with natural oil, there's a pressing need for long-term refrigerant alternatives that adhere to international standards. These alternatives should prioritize energy efficiency, enhanced heat transfer, greater refrigeration capacity, increased condenser heat rejection rates, and higher Coefficient of Performance (COP). They should also boast minimal Global Warming Potential (GWP) and zero Ozone Depletion Potential (ODP). Research suggests that mixed refrigeration systems or blends, along with various types of nanofluids, can be promising solutions to improve and optimize refrigeration system performance [79]. From the review, in CuO-water nanofluid at 0.24% concentration, turbulence heat transfer improved by 25%, accompanied by a 20% increase in pressure drop. Al<sub>2</sub>O<sub>3</sub>-water and TiO<sub>2</sub>-water nanofluids exhibited minor improvements (<3%) in natural convection. MWCNT-water Nanofluid at 0.25% concentration significantly enhanced 30–40% in forced convection [80].

The study employed an insulated tank with a helical coil filled with 0.19 vol.% TiO<sub>2</sub> water-based nanofluid PCM and a water/alcohol coolant. Compared to water alone, the nanofluid enhanced ice formation by 11.1% and accelerated charging by 10.6%. Additionally, the nanofluid system exhibited a 17.18% increase in maximum energy storage rate, attributed to improved natural convection between the ice layer and PCM due to TiO<sub>2</sub> nanoparticles [81].

### Electronic Cooling System

In hydrothermal synthesis, graphene-silver alloyed quantum dots were created using citric acid and silver nitrate. These alloyed quantum dots formed a stable nanofluid suspension, exhibiting a zeta potential of

-49 mV under neutral pH conditions. Employing this nanofluid as a coolant in a virtual electronic system resulted in a notable 46% improvement in thermal conductivity. Consequently, the core temperature of the electronic system experienced a significant decrease of 16% [82]. This study explored the thermal properties and impact of nonliquids on the cooling performance of computer microchip electronic liquid cooling systems, aiming for improved thermal efficiency compared to conventional liquids similar to water and ethylene glycol. Three types of nanoparticles (alumina, silica, and titania) were examined in a water/EG mixture as the base liquid. Utilizing these nano-enhanced fluids notably decreased the operating temperature of the processor compared to that of pure base liquid. The variety of nanomaterials indicates the possibility of other nanoparticles offering even better thermal performance, potentially resulting in a more beneficial impact on the cooling approach. It is anticipated that integrating carbon nanotubes into the base fluid could further enhance heat transfer performance [83]. The study utilized Ag, SiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub> nanoparticles dispersed in water to explore their impact on heat transmission in microchannel heat sinks of different shapes (MCHSs). Findings proved that adding a 6% volume portion of Al<sub>2</sub>O<sub>3</sub> nanomaterials to the rectangular MCHS (MC-R) at Reynolds number 500 enhanced the average heat transfer coefficient by 12.3% and reduced entire thermal resistance by 8%, associated with pure water. The omega-shaped configuration (MC-O) with Al<sub>2</sub>O<sub>3</sub> nanoparticles exhibited superior convective heat transfer, the maximum Nusselt number, and a minor maximum heat decline temperature. Additionally, the entire entropy generation decreased with the improvement of the Reynolds number, with MC-O demonstrating the least entropy generation, suggesting optimal flow and heat transfer efficiency [84]. An assessment was

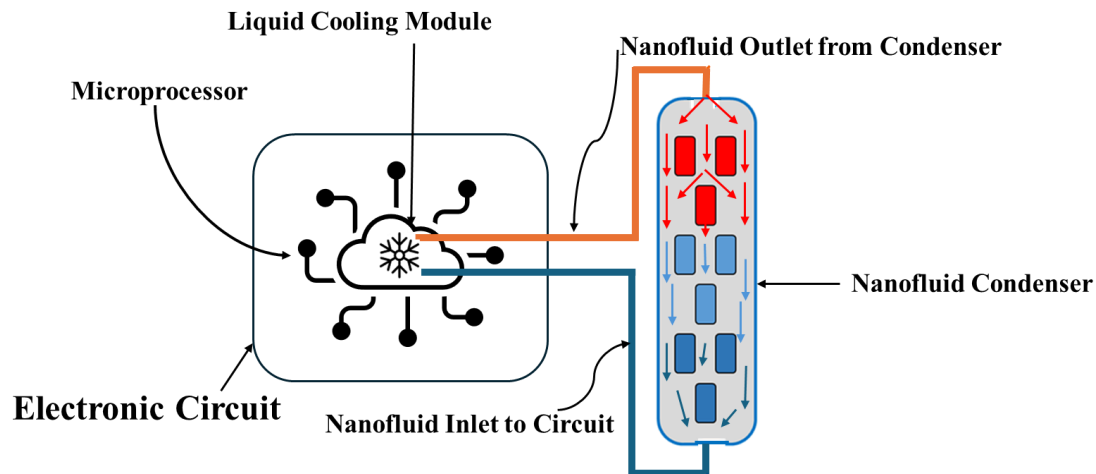


Figure 8. Electronic processor cooling system using nanofluid.

carried out to determine the efficacy of nanofluids as CPU coolants, utilizing a mixture of  $\text{Al}_2\text{O}_3$  nanoparticles and SDS surfactant in water at a volume fraction of 0.5%. These nanosuspensions were prepared utilizing an ultrasonic cleaner. Testing parameters included evaluating heat transfer execution and pump power utilization. Results indicated that nanofluids with higher concentrations displayed enhanced convection coefficient values and were more effective in lowering the temperature of the water block. However, it was observed that they required greater pumping power [85]. The typical nanofluid electronic cooling system is illustrated in Figure 8.

### Photovoltaic Systems

The typical nanofluid used in photovoltaic system cooling is illustrated in Figure 9. Nanofluids show promise as spectral beam splitters (SBSs) in photovoltaic power systems due to their effective regulation of spectral absorption. However, challenges, including high cost and instability, hinder their practical application. To address this, we propose a hybrid nano coolant enhanced fluid SBS comprising carbon quantum dots (CQDs) and antimony tin oxide (ATO) nanomaterials, offering excellent stability and cost-effectiveness. This hybrid nanofluid SBS effectively regulates light absorption due to the corresponding optical properties of CQDs and ATO nanoparticles. Assessment through PV/T conversion modelling and indoor testing demonstrates superior filtering performance, with a high merit function value of 1.815, surpassing pure CQD nanofluids and other reported SBSs [86]. The study utilized Oleic acid (OA) to modify  $\text{Al}_2\text{O}_3$  nanoparticles, creating OA-modified  $\text{Al}_2\text{O}_3$  nanofluids (OA- $\text{Al}_2\text{O}_3$ - $\text{H}_2\text{O}/\text{C}_2\text{H}_6\text{O}$ ). These nanofluids exhibited excellent stability for over 48 hours, with a surface temperature remaining constant at  $40^\circ\text{C}$ . Testing the electrical efficiency of solar cells under high energy current density revealed that the OA- $\text{Al}_2\text{O}_3$ - $\text{H}_2\text{O}/\text{C}_2\text{H}_6\text{O}$  nanofluid consistently achieved an

electrical efficiency above 27%, reaching a peak of 29.37%. This efficiency was 1.3% higher than utilizing water as the employed fluid [87]. The study evaluated four configurations across flow rates (0.4–0.8 litres/minute) for photovoltaic (PV) and photovoltaic-thermal (PVT) systems. TRNSYS simulation compared phase change materials (PCM) and non-PCM integrated PVT systems, revealing increased pressure drop and reduced friction factor with higher flow rates. The non-PCM integrated PVT system showed notable temperature reductions and increased electrical power output, achieving a remarkable energy-saving efficiency of 75.67% at 0.4 litres per minute, with total efficiencies of 81.9%, 84.5%, and 85.05% for PVT, PCM-integrated PVT, and non-PCM integrated PVT systems, respectively [88]. Paraffin wax and graphene nano-particles in an experimental investigation, embedding graphene increased thermal conductivity by up to 75.09%, maintaining melting enthalpy. The nanocomposite exhibited stability up to  $210^\circ\text{C}$ , with improved thermal stability due to nano-particle addition. Enhanced optical absorbance and reduced transmittance were observed, improving solar energy absorption potential. Additionally, the nano-composite demonstrated durability after 500 thermal cycles and significantly enhanced the efficiency of the integrated photovoltaic thermal system [89].

### HVAC Systems

Experimental measurements were conducted on a ratio of 40:60 vol.% of MWCNTs/EG–water nano-enhanced fluid with varying solid volume fractions (0.025% to 1.0%) and temperatures ( $25^\circ\text{C}$  to  $50^\circ\text{C}$ ). Results revealed that the thermal conductivity ratio increases with higher solid volume fractions and temperatures, with a more pronounced effect at greater MWCNT concentrations. The maximum enhancement, reaching 34.7%, was observed at 1.0% solid volume part and  $50^\circ\text{C}$  temperature. These findings underscore

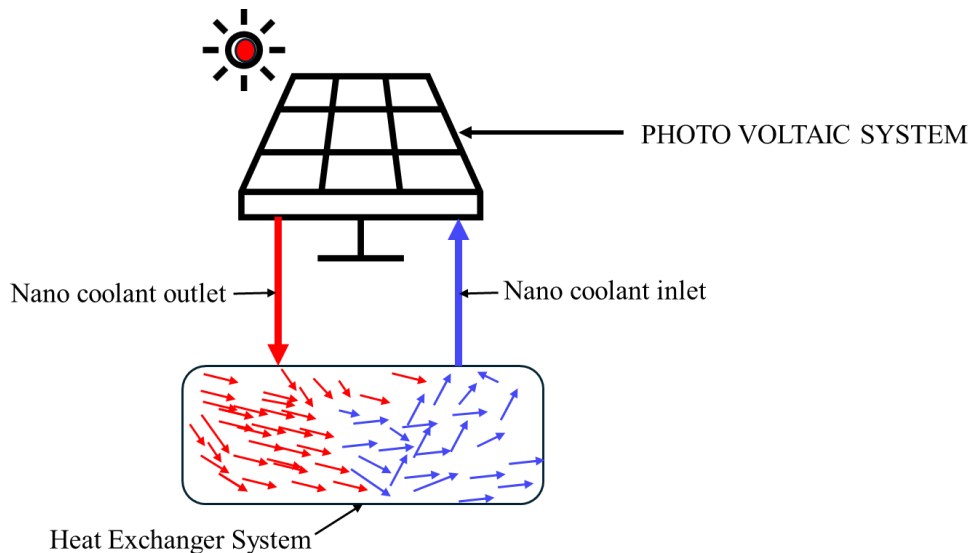


Figure 9. Nanofluid used photovoltaic system cooling.

the significant influence of both solid volume fraction and temperature on nanofluid thermal conductivity [90]. An investigational study was undertaken to evaluate the dynamic viscosity of a water-based nanofluid containing magnetite to assess its suitability for heating and cooling applications. Viscosity measurements were conducted over a 20–55 °C temperature, encompassing different samples with solid volume parts ranging from 0.1% to 3%. The results unveiled a discernible decline in viscosity with rising temperatures.

Furthermore, viscosity exhibited an upward trend with cumulative solid volume parts, underscoring the combined impact of temperature and solid volume portion on the viscosity of the nanosuspension [91]. Three different formulations of SiO<sub>2</sub>, TiO<sub>2</sub>, and CNT nano-sized particles were mixed with water using ultrasonic methods to produce nanofluids. Total

dissolved solids (TDS) were measured to assess deposit formation. The SiO<sub>2</sub> nanofluid exhibited lower energy consumption and achieved efficient temperature levels, indicating its potential suitability for heating applications in HVAC systems [92]. Nanofluid used the HVAC cooling system shown in Figure 10 below,

The study utilizes a methanol-silver nanofluid-filled thermosyphon heat exchanger and evaluates its efficiency and energy-saving potential compared to pure methanol. Investigational findings reveal energy savings ranging from 8.8% to 31.5% for the cool-off and 18% to 100% for reheating the supply air stream in an air conditioning system when employing the methanol-silver nanofluid. A 31.5% for cooling and 18% to 100% for rewarming the supply airflow in a climate control (a/c) system when using the methanol-silver nanofluid was obtained [93].

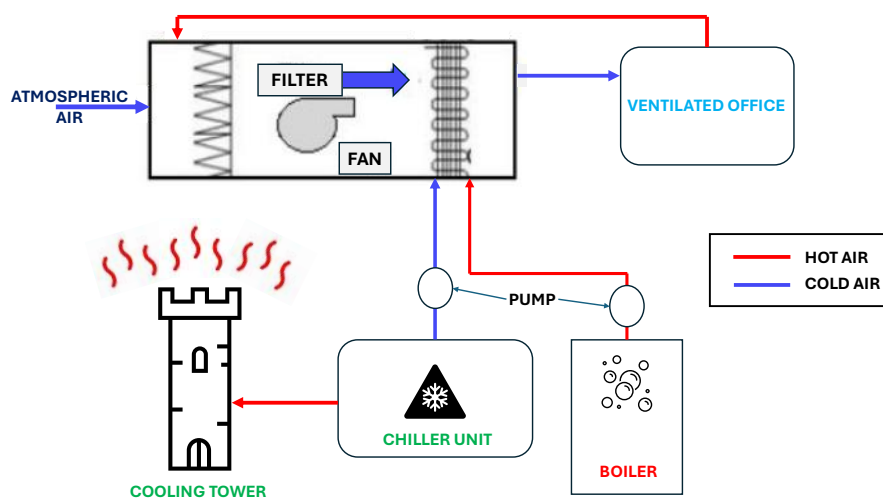
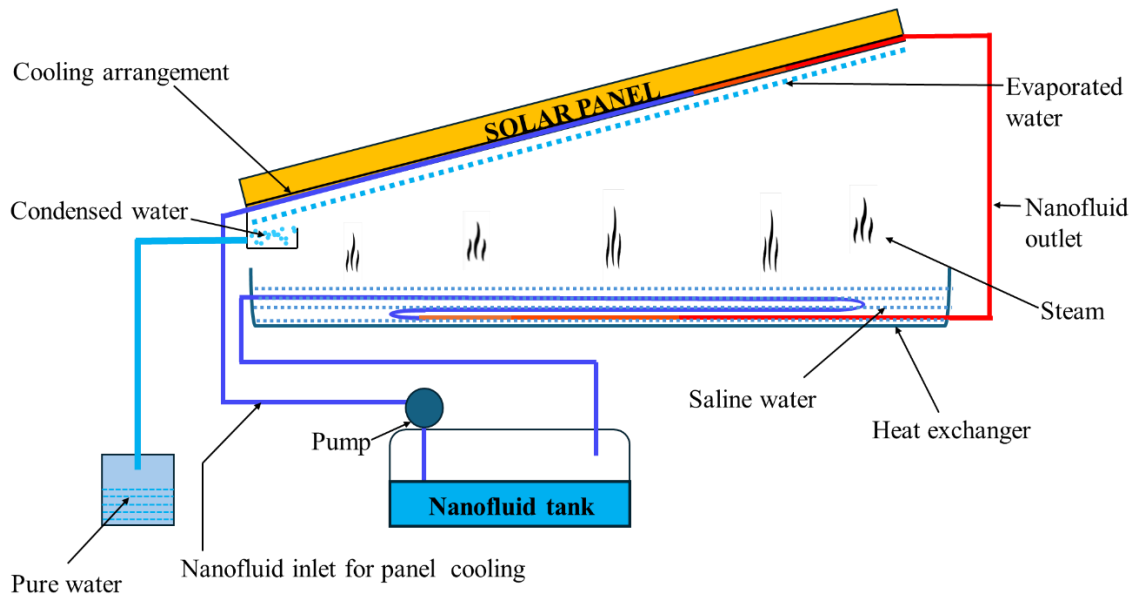


Figure 10. Nanofluid HVAC system.



**Figure 11.** Nanofluid heat exchanger in desalination system.

## Desalination

A study investigates the incorporation of  $\text{Fe}_2\text{O}_3$  nanoparticles into saltwater to enhance evaporation and heat transfer coefficient (HTC) in multi-stage flashing (MSF) desalination. The physical abilities of the saline water (SW) nano-enhanced fluid were assessed, incorporating steadiness, thermal conductivity (TC), evaporation volume and rate, boiling temperature (BT) and time, and local HTC in stagnant conditions. Stable SW nanofluids showed reduced BT and accelerated boiling, leading to a 2% decrease in steam usage. Evaporation volume increased by 15% under atmospheric pressure and 25% under vacuum. Notably, local HTC saw a significant improvement (up to 134%) under stagnant conditions with  $\text{Fe}_2\text{O}_3$  NPs of 20 nm size and a volume portion ( $\phi$ ) of 0.05%, suggesting potential for enhancing water output in MSF processes [94]. Exploring a desalination system employing a focal point concentrator as the heat source entailed integrating photovoltaic thermal (PV) panels and Humidification Dehumidification Desalination (HDD) systems. The investigation assessed the influence of applying nanosuspensions as the solar operating fluid on desalination performance. Various oil-based nanofluids were examined, including  $\text{Al}_2\text{O}_3/\text{oil}$ ,  $\text{Cu}/\text{oil}$ ,  $\text{CuO}/\text{oil}$ ,  $\text{TiO}_2/\text{oil}$ , and  $\text{MWCNT}/\text{oil}$ , with  $\text{Cu}/\text{oil}$  demonstrating the highest thermal performance. Results indicated increased cavity heat gain and thermal efficiency with rising nanofluid intensity. However, exergy efficiency decreased, particularly with  $\text{Cu}/\text{oil}$  nanofluid, suggesting its potential for maximizing freshwater production with a minimized desalination system output ratio [95]. Figure 11 below shows a typical nanofluid heat exchanger in a desalination system,

A comparative study of active water/active vapour and passive water/active vapour demonstrates slightly superior results, improving yield, energy efficiency, and exergy efficiency by 31%, 30%, and 12.56%, respectively. Incorporating  $\text{CuO}$  in fluid at a concentration of 1 wt% notably elevated performance metrics, exhibiting enhancements of 42.8% in yield, 46% in energy efficiency, and 54.85% in exergy efficiency. Subsequent integration of ultrasonic foggers further magnified these advancements, resulting in an impressive augmentation of 59.1%, 65.5%, and 63.8% in yield, energy efficiency, and exergy efficiency, respectively. These enhancements also contribute to  $\text{CO}_2$  reduction and yield freshwater of satisfactory quality at a reasonable expense [96]. The study aimed to boost the performance of a hemispherical solar still (HSS) through sequential modifications. These included using corrugated copper with black cotton fabric, replacing paraffin wax with sheep fat, employing graphite nanofluid, and introducing a nano-based sheep fat with graphite nanoparticles. Each modification significantly increased daily yield, with the final case showing the highest improvement, achieving thermal and exergy efficiencies of 61.7% and 5.8%, respectively. This optimized design led to a 33.90% reduction in freshwater price, a 6.27-ton  $\text{CO}_2/\text{year}$  reduction in emissions and considerable cost reduction [97]. The research shows a novel approach employing tungsten carbide nanofluids to enhance solar evaporation efficiency, targeting desalination and wastewater treatment. The device minimizes heat loss, ensures nanofluid stability, and prevents nanoparticle contamination. Findings indicate that a 0.3 wt% concentration of tungsten carbide nanofluid can absorb 99% of solar energy within a 1 cm depth, achieving a photothermal conversion efficiency of 97.7%.

The machine shows great promise for real-world applications, boasting an evaporation rate of 1.235 kg/m<sup>2</sup>.h and a solar evaporation efficiency of 74.9% under 1-sun irradiation. Furthermore, its desalination capabilities are impressive, with high ion rejection rates (>99.99%) for seawater and significant reductions in heavy metal ion content compared to WHO drinking-water standards [98].

## CONCLUSIONS AND RECOMMENDATIONS

This assessment provides a comprehensive overview of nanofluids, delving into crucial aspects with preparation methods, stability, thermal conductivity, viscosity, and applications. Through thorough analysis of existing research, several key insights have emerged.

- The preparation of nanofluids involves intricate processes that significantly impact their stability and overall performance.
- Stability poses a major challenge in the practical use of nanofluids. Understanding the underlying mechanisms governing stability is vital for overcoming this obstacle and ensuring sustained performance in industrial settings.
- The remarkable enhancement in thermal conductivity offered by nanofluids compared to base fluids holds great promise for enhancing energy conversion processes. This property creates new opportunities for improving system efficiency and performance.
- Viscosity, another critical parameter, is influenced by nanoparticle concentration and size distribution. Striking a balance between viscosity enhancements and flow properties is crucial for optimizing nanofluid performance across various applications.
- Nanofluids find diverse applications across multiple industries, including thermal management systems, heat exchangers, electronics cooling, and solar energy harvesting. As research progresses, nanofluids are poised to revolutionize energy conversion technologies and contribute to more efficient and sustainable systems.

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