

Nanofluids: Advanced Synthesis Methods, Innovative Applications, and Future Directions

Pinki Kumari^{1,*}, Mahendra Prajapati²

Abstract

Nanofluids, a novel mixture of nanoparticles and base fluids, is an innovative blend that has appeared as a transformative advancement in heat transfer and thermal management technologies. This study is going to discuss advanced synthesis methods, properties, and extensive applications of nanofluids in various fields, such as biomedical engineering, electronics cooling, solar energy, and machining. Optimization techniques such as nanoparticle selection, concentration control, and computational fluid dynamics modelling are also highlighted to enhance the stability and thermal efficiency of nanofluids. The study further presents comparative analyses and case studies, which point out significant improvements in thermal performance and energy efficiency through nanofluids. The findings suggest the critical role of nanofluids in providing solutions to global challenges such as sustainable energy solutions, efficient water desalination, and advanced medical diagnostics. Heat transfer is fundamentally about moving energy in the form of heat from one system to another. The discipline looks at the amount of energy that is stored or transferred in the form of heat and at the different ways that the energy is moved through the systems.

Keywords: Nanofluids, heat transfer, thermal conductivity, optimization, advanced applications, biomedical engineering.

INTRODUCTION

The demand for tiny, lightweight gadgets with enhanced capabilities is undoubtedly increasing as the industrial sector grows. The efficient production, conversion, and consumption of energy must be prioritized to achieve sustainable growth. Nearly all energy-consuming or energy-generating devices utilized in a variety of commercial and industrial sectors depend on heat transfer technologies [1]. The manipulation of materials at the nanoscale, where particles are one billionth of a meter or 10^{-9} m, is made easier by nanotechnology. For example, materials with relatively high heat conductivity, such as titanium oxide and alumina, can be manufactured into tiny nanoparticles. To transport heat, these nanoparticles are incorporated into base fluids to create a stable colloidal solution. They can improve the heat transfer

*Author for Correspondence

Pinki Kumari
E-mail: nishant.mgi@gmail.com

¹M.Tech. Scholar, Department of Electronics and Communication Engineering, Millennium Institute of Technology and Science, Bhopal, Madhya Pradesh, India

²Assistant Professor, Department of Electronics and Communication Engineering, Millennium Institute of Technology and Science, Bhopal, Madhya Pradesh, India

Received Date: December 20, 2024

Accepted Date: January 02, 2025

Published Date: January 07, 2025

Citation: Pinki Kumari, Mahendra Prajapati. Nanofluids: Advanced Synthesis Methods, Innovative Applications, and Future Directions. Journal of Nuclear Engineering & Technology. 2025; 15(1): 1–11p.

properties of base fluids with low thermal conductivity. One of the most recent developments in nanotechnology is this novel mixture, referred to as nanofluid. Interestingly, nanofluid adds unique heat transfer properties that help save energy in a manner like reducing the size of heat transfer equipment [2]. The ever-increasing cooling requirements of contemporary gadgets are addressed by two main strategies. One focuses on engineering advancements, such as miniaturized cryogenic systems and methods of increasing surface area, such as fins, micro-channels, and integrated spot cooling. The alternative approach aims to improve the cooling fluids' current capacity to transfer heat. This latter strategy has enormous potential since it can

maximize the effectiveness of existing technologies for smaller, more potent devices while leveraging them. Though they have pushed the envelope, conventional techniques such as redesigning cooling devices with fins, micro channels, and tiny cooling systems are now approaching their limits [3].

The heat transfer behaviours of nanofluid flows across various CHX types have been the subject of numerous investigations to date. Single tube heat exchangers (HXs) (micro/mini channel), shell and tube HXs, micro heat sinks (MCHS), and plate heat exchangers (PHXs) are the subjects of the most frequent experimental and numerical studies in this field [4]. When base fluid and nanoparticles are combined, a nanofluid is created. Choi was the one who first proposed the idea of nanofluid. The term “nano”, which comes from Latin, refers to 10^{-9} nm units. The geometrical shape, size, and stability of the nanoparticle, as well as the type of base fluid, temperature, and thickness, all affect the conduction of heat in nanofluids. Water, organic liquids (C_2H_2 , refrigerants, etc.), oils, bio-fluids (blood, synovial fluid, etc.), and other liquids can all be considered basic fluids. Metals such as gold, copper, metal oxides like Al_2O_3 , SiO_2 , TiO_2 , oxide ceramics like Al_2O_3 , CuO , metal nitrides, metal carbides, and carbon in different forms like carbon nanotubes, graphite, and diamond are among the materials that must be chemically stable to be used for nanoparticles [5]. Solid nanoparticles are added to base fluids to create nanofluids, which are top tier working fluids for heat transmission. Overall thermal performance can be significantly improved by homogenized combinations of low-volume-fraction nanoparticles and common fluids as ethylene glycol, glycerine, oil, and water. Nanofluids are currently the subject of a growing amount of research because of their potential for use in a wide range of engineering applications. Furthermore, the heating and cooling processes that are frequently observed in solar cells, solar stills, and other thermal energy storage techniques as well as thermal conductivity are where nanofluids are most frequently employed [6].

Figure 1 shows the wide applications of nanofluids, and their importance in various industries and scientific fields. At the centre, the idea of “Nanofluids applications” is surrounded by several application areas, each in a different blocks. These are their applications in solar collectors and heat pipes for efficient

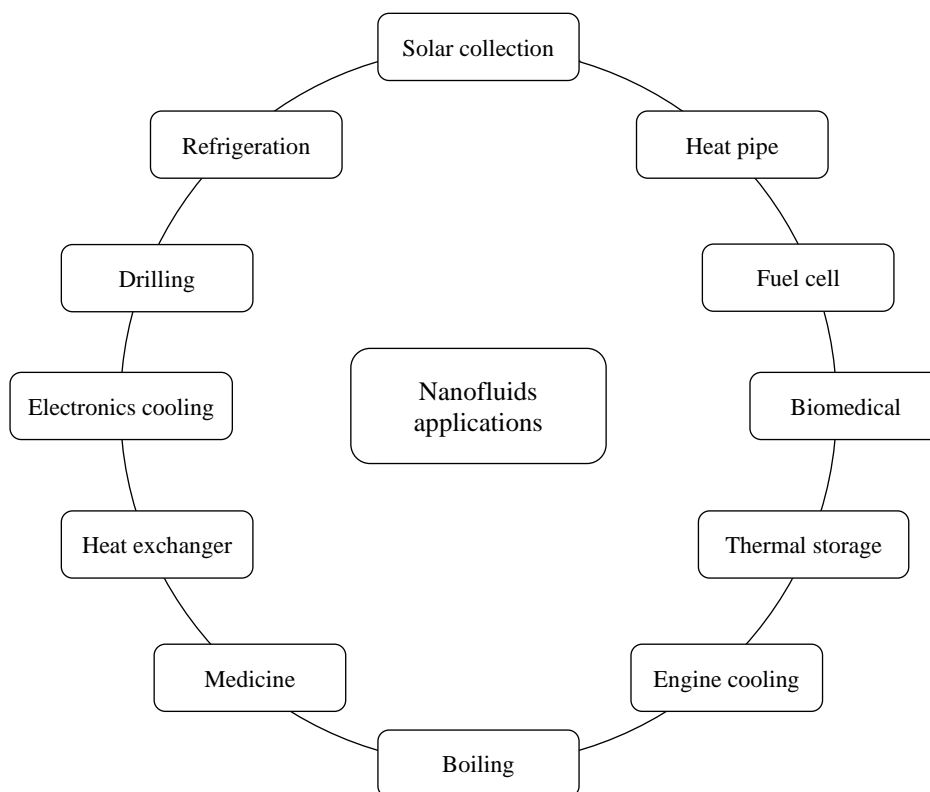


Figure 1. Versatile applications of nanofluids across industries.

energy management, fuel cells for enhanced electrochemical performance, and biomedical applications for drug delivery and therapeutic processes. Nanofluids have a critical role in the refrigeration and electronics cooling systems, giving the excellent heat transfer abilities. Further applications include using nanofluids in thermal storage systems, car engine cooling systems, and heat exchanger to enhance thermal performance. It has a further application in the boiling process, in medical applications as innovative treatment and used in drilling for improving the lubrication properties along with its thermal properties. This diagram captures the enormous versatility and potential of nanofluids across different sectors very effectively.

PROPERTIES AND CHARACTERIZATION OF NANOFLUIDS

The development of better thermo-hydraulic features for heat transfer devices requires both numerical and experimental research on the transport properties of nanofluids, including density, viscosity, thermal conductivity, coefficient of expansion, and specific heat capacity. This section covers the primary factors that clearly affect how thermophysical properties change, along with how to measure them. Schematic illustration of the primary methods for determining NFs' thermal conductivity is shown in Figure 2. To understand the vital importance and impact of density, specific heat capacity, and coefficient of expansion of nanofluid on engineering thermal devices' heat transfer performance, a thorough mathematical framework is developed. Because it is crucial to include thermophysical properties in order to obtain working fluids with higher heat transfer rate proficiencies, researchers had to carefully examine temperature, volumetric flow rate, heat flux, and other critical parameters that could increase their influence on thermal performances. The ratio of heat flux to a local temperature gradient is known as thermal conductivity [7].

This image depicts the chronological development of methods used to measure thermal conductivity, spanning from 1931 to 2018. It begins with the Transient Hot-Wire Method (1931), followed by advancements like the Steady-State Parallel Plate, Laser Flash, 3ω Method, Transient Plane Source, Coaxial cylinders, Temperature oscillation, and Sub- μ l thermal conductivity.

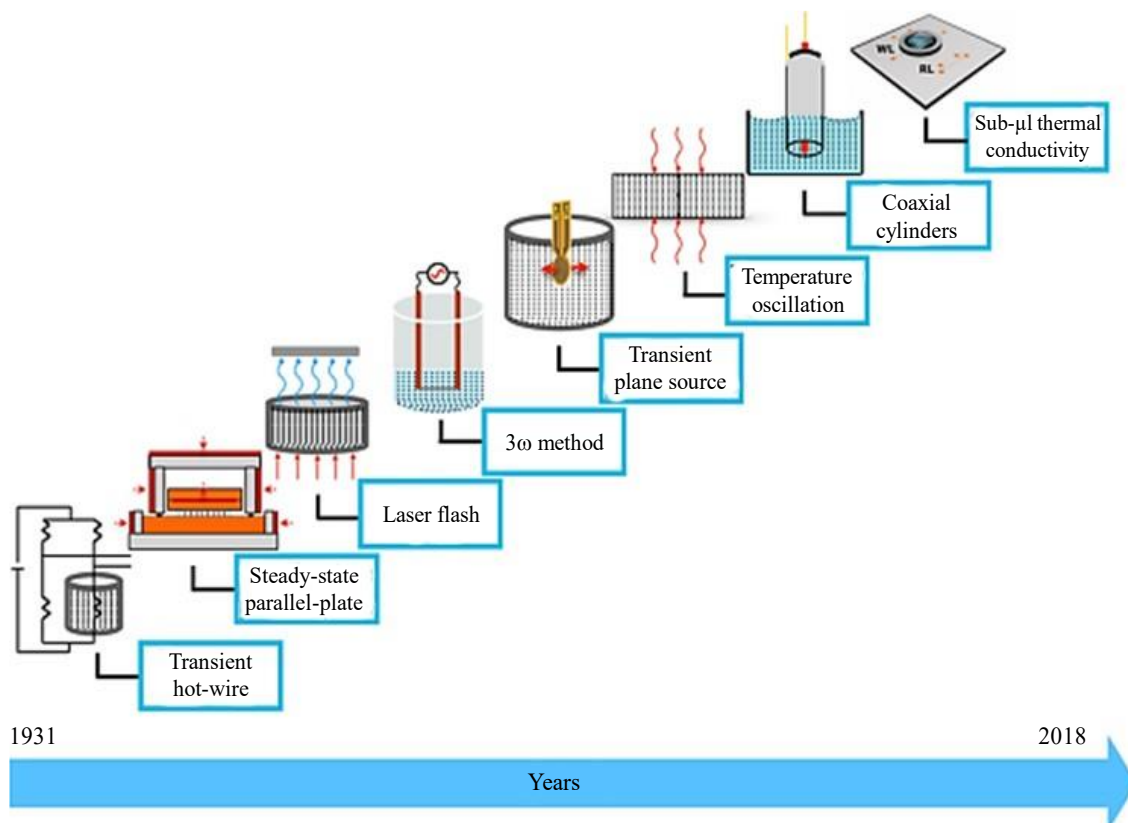


Figure 2. Schematic illustration of the primary methods for determining NFs' thermal conductivity [8].

Temperature Oscillation, Coaxial Cylinders, and culminates in the Sub- μ Thermal Conductivity technique (2018). The progression highlights innovations in experimental approaches to improve precision and applicability across diverse materials and scales. The timeline visually emphasizes the evolution of technology in thermal measurement techniques [8].

The key variables that govern their heat shifting properties are thermal conductivity, specific heat, effective density, dynamic viscosity coefficient, and capacity. Furthermore, the operating temperature, volume fraction, particle size, and other factors all affect the thermal characteristics of nanofluids. Assessing the temperature-dependent properties of nanofluids is essential for estimating the heat transport coefficient. When compared to micro-level particles, the nanoparticles dispersed in the base fluid exhibit long-lasting stability, higher thermal conductivity, and less pressure drop [9]. One essential thermo-physical characteristic is thermal conductivity, and a thermal system with high thermal conductivity will be more efficient. Numerous fluids, such as EG and water, are employed as heat carriers in a variety of heat transfer applications, such as power plant heat exchangers, building cooling systems, automobile air conditioning systems, and cooling systems in practically all processing facilities. Studies have indicated that nanofluids with smaller improvements in thermal conductivity correlate with base fluids with better thermal conductivity [10].

CUTTING-EDGE APPLICATIONS OF NANOFLUIDS

Nanofluids in Milling

The machining technique known as milling involves removing the material layer from the work piece's surface in the form of grooves using a multi-point cutting tool. The metal surface is sliced by feeding the work item against the spinning multipoint cutter. This application allows the tool to save many cutters with identical data as well as a single cutter. A milling machine can operate in a variety of ways. Among their basic varieties are keyways, grooves, slots, gear milling, helical milling, cam milling, thread milling, angular milling, gang milling, form milling, profile milling, end milling, saw milling, plain milling, face milling, side milling, straddle milling, angular milling, and gang milling. Various studies have employed distinct nanofluids in the milling process and discovered varying enhancements to the milling process as a whole. In addition to enhancing temperature balance and surface quality, these nanofluids prolong tool life by preventing wear and tear. The entire efficiency of the milling machining operation is increased by the altered thermophysical characteristics of nanofluids, which typically include thermal diffusivity, thermal conductivity, heat transfer coefficients, etc. [11]. Three categories of cutting fluids are distinguished by a traditional classification: gases, water-soluble fluids, and neat cutting oil. The most prevalent are water-soluble fluids, which can be made into nanofluids by adding nanoparticles. Nanofluid, as opposed to conventional cutting fluid, is a colloidal mixture of metallic and non-metallic particles smaller than 100 nm. This new class of cutting fluids can be created by combining metallic, non-metallic, or carbon nanoparticles with regular cutting fluid. The resulting fluid exhibits higher stability, superior thermal conductivity, rheological characteristics, and no pressure drop in comparison to the isolated fluid. Compared to traditional cutting fluids, nanofluids have a higher degree of heat extraction capacity (thermal conductivity) [12].

Nanofluids in Heat Transmission

The heat transmission performance of standard heat pipes, such as GNP, CuO, Al₂O₃, Cu, ZnO/TiO₂, and Ag, can be significantly enhanced by adding nanoparticles to the base fluid. Three factors allow for the conclusion of the heat transfer enhancement process. The improvement of nanofluids' effective thermal conductivity is the primary cause. The second reason is that nanofluids increase capillary force in heat pipes by decreasing the solid-liquid contact angle. The development of a thin, porous layer on heat pipe surfaces, which raises capillary force and solid-liquid wettability, is the third explanation. Additionally, there is a concentration of nanoparticles that is ideal for balancing the capillary force and flow drag force. Particle types determined the ideal concentration of nanofluid in a heat pipe, and as nanofluid concentration increases, the heat pipe's thermal resistance decreases. The thermal performance of LHPs is influenced by capillary pressure and gravity. Compared to an LHP charged

with pure water, the one charged with nanofluids had a lower thermal resistance. Compared to DI water, Ag-H₂O nanofluids have increased the heat transmission performance and heat pipe start up. The most promising working fluids are anticipated to be Ag-H₂O nanofluids with a high thermal conductivity and low viscosity.

The heat transfer properties of a CuO nanofluid-filled heat pipe with microgrooves: The findings showed that, in comparison to pure water, the evaporator section's heat transfer coefficients could be improved by roughly 46% and the critical heat flow could be boosted at a maximum rate of 30% [13].

Nanofluids in Biomedical

To improve disease diagnosis and treatment, various types of nanoparticles (NPs) have been developed in the biomedical field. They can enter the bloodstream and interact with cells because of their small size. Their outstanding surface-to-volume ratio, high charge carrier mobility, biocompatibility, and physicochemical stability have also been proven. NPs can change their size, shape, charge, and surface functional groups to target particular cells or release the loaded material in a controlled way. This is possible when the NPs contain biomarkers or drugs. Compared to the macroparticles, the NPs have a greater surface-area rate. In order to have a wider area of contact with the cells, they thus enable the addition of greater amounts of drugs, targeting agents, or biomarkers. Exogenous stimuli, alternating magnetic fields, near-infrared light, and endogenous stimuli like pH or enzymes can all control the drug's release. Some NPs can be used as a monitoring or diagnostic tool, and some have shown antibacterial or anticancer properties when used alone. These features have led to research into using NPs to treat severe conditions such as cancer, heart disease, and neurological diseases [14].

For many crucial applications, the biomedical sector mostly depends on nanoparticles and nanofluids. According to studies, NP suspension fluids are crucial in a number of medical sector domains, including drug distribution, disease diagnostics, antibacterial instances, cooling biomedical components, cryopreservation, sterilisation procedures, and micro pumping systems for hormones and drugs. However, it is important to carefully consider NFs' characteristics, uniform suspension, size, shape, biocompatibility, and crystallinity in order to use them safely. Applications of nanofluids for diagnostics have been studied in the fields of molecular biology and biomedicine. Numerous innovative management techniques are being created as a result of research into the diagnosis and treatment of COVID-19, which is caused by the SARS-CoV-2 virus. Numerous researches have looked into using nanotechnology to speed up the time-consuming process of traditional nucleic acid extraction for COVID-19 diagnosis [15].

Nanofluids in Electronics

Heat transmission gets more complicated when electrical gadgets like cameras and cell phones get smaller. It is necessary to increase heat transfer capacities while ideally reducing the cooling system's size. The cooling system becomes more and more crucial as the heat-flux produced by computer processors rises. Applications and benefits of nanofluids in various fields are shown in Figure 3. Heat production from computer components is the main issue when utilizing computers. Therefore, several methods are available to drain heat from the CPU, graphics card, processor, and other components in order to operate in a secure environment. Maintaining the CPU and graphics card within acceptable operating temperature ranges is crucial for improving their performance. Electronics can be cooled using a variety of methods, including as heat pipes, thermoelectric cooling, air coolers, liquid coolers, and vapour compression refrigeration systems (VCRS). In addition, within the constraints of size, nanofluids can offer the necessary capabilities [16].

OPTIMIZATION TECHNIQUES IN NANOFLUIDS

Nanofluids are engineered fluids consisting of nanoparticles, such as Al₂O₃, ZnO, or graphene oxide, suspended in base liquids such as water, ethylene glycol, or oils. Nanofluids have been widely applied to thermal management systems because of their excellent thermal conductivity and heat transfer characteristics, particularly for high-level applications in radiators, heat exchangers, and electronics

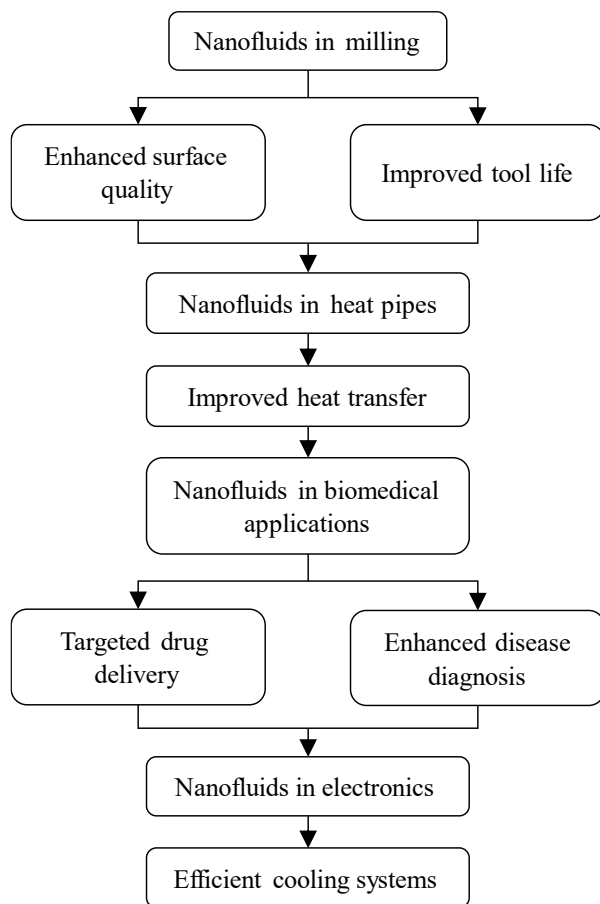


Figure 3. Applications and benefits of nanofluids in various fields.

cooling. But the actual application potential depends upon the optimization of these fluids in terms of stability, thermal efficiency, and operation. Among the various techniques of optimization, one important aspect is the selection and concentration of nanoparticles. The type of nanoparticles determines the thermal performance; the concentration must be controlled such that it maximizes heat transfer without sedimentation or too much viscosity. Modification of the surface of the nanoparticles with functional groups like hydroxyl or carboxyl improves the compatibility of the nanoparticles with the base fluid, hence improving dispersion and stability. The choice of base fluid is also critical, as it must be compatible with nanoparticles [17]. Surfactants and additives are typically used to ensure uniform suspension and avoid particle aggregation.

Another important tool used for nanofluid optimization is the tool of computational fluid dynamics, which models the fluid using computers. CFD simulations can evaluate and analyse heat transfer behaviour over a wide range of flow rates, temperatures, and nanoparticle distributions, in real-world scenarios that closely mimic the actual conditions. Experimental validations are then conducted to ascertain that the predictions made through these simulations are accurate. Parameters such as temperature gradients, heat transfer rates, and flow characteristics are examined to improve the nanofluid formulation. Beyond performance enhancements, optimization also addresses practical concerns like viscosity management and sustainability. High nanoparticle concentrations can increase viscosity, requiring more pumping power, so, balancing thermal efficiency with manageable viscosity is crucial. Hybrid nanofluids, combining different nanoparticles, offer a solution by enhancing thermal conductivity without compromising fluid flow [18]. In addition, eco-friendly and economical nanoparticles guarantee that optimized nanofluids will remain sustainable and economically feasible for large-scale applications in automotive radiators, industrial heat exchangers, electronics cooling, and solar energy systems. Through these optimization techniques, nanofluids have become a cornerstone of modern thermal management.

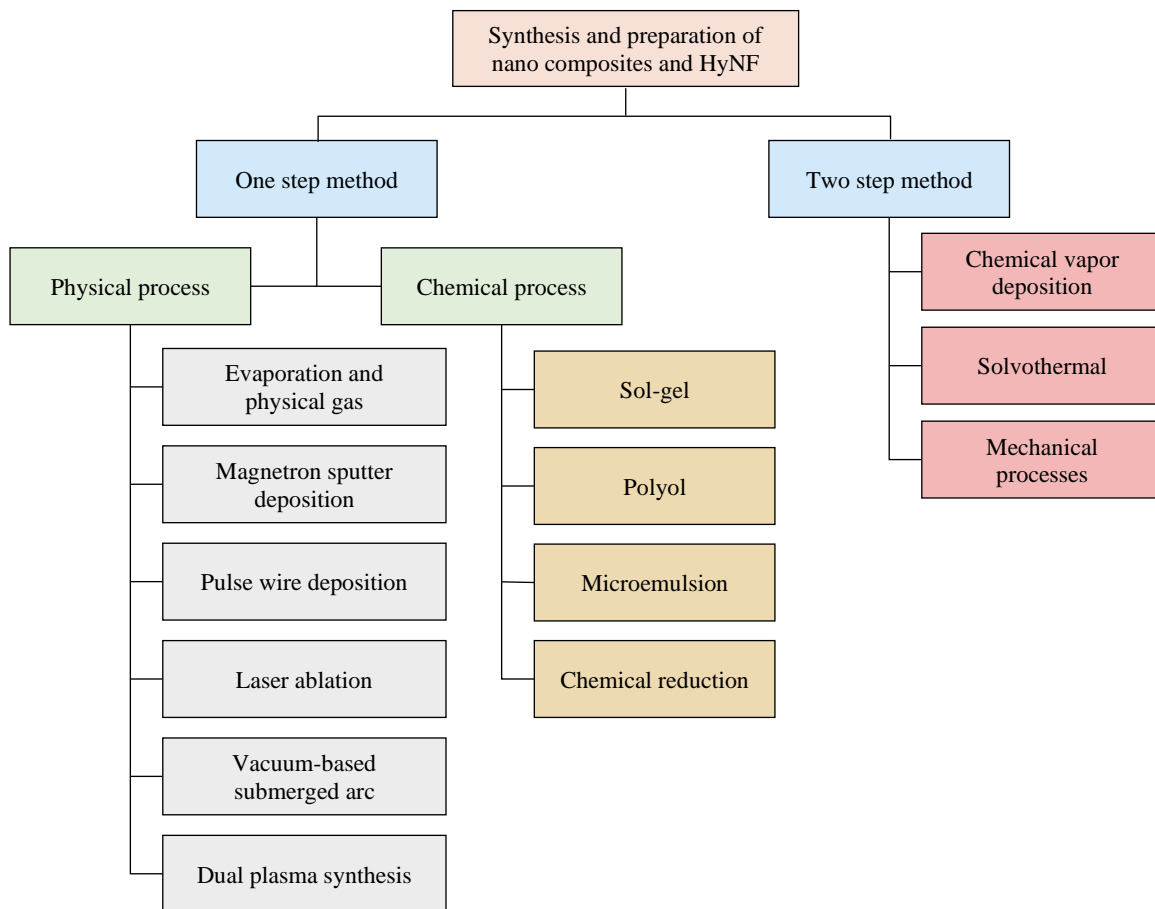


Figure 4. Techniques for synthesis and preparation employed in the one- and two-step methods [20].

While viscosity augmentation is considered a detrimental side effect on the heat transfer coefficient, thermal conductivity enhancement is considered a beneficial consequence. As viscosity increases, molecules' and nanoparticles' random motion decreases. The heat transfer coefficient would decrease as a result of less mass and energy being transferred between layers. To increase the heat transfer coefficient, nanoparticles' influence on the thermal and physical properties of base liquids must be optimized [19].

The two primary methods for creating nanoparticles are the one-step and two-step methods, as illustrated in Figure 4. The one-step approach entails the simultaneous production of the nanoparticles and their dispersion into the base fluid. Either a physical or chemical procedure can be used in the one-step method to synthesize the nanofluid. Laser ablation, vacuum-based submerged arc, dual plasma synthesis, magnetron sputter deposition, evaporation and physical phase gas condensation, and pulse wire evaporation are all included in the physical method. In addition, the chemical process uses chemical reduction, sol-gel, polyol, and microemulsion procedures. The one-step method is frequently used to create metal nanoparticles with high thermal conductivity in order to prevent oxidation; however, this technology is not appropriate for large-scale manufacturing. In contrast, mass production is best served by the two-step process. Nanoparticles are created in the first stage of the two-step process, and in the following steps, they are suspended in the base fluid. Numerous procedures, including chemical vapour deposition, the solvothermal method, and mechanical processes (such as grinding, milling, and sintering), can be used to manufacture the nanocomposites in the two-step method. A magnetic stirrer and an ultrasonicator can then be used to carry out the dispersion [20].

It has been shown that the convective heat transmission and thermal properties of both mono and hybrid NFs are significantly influenced by their stability. Instability is seen by the mono and hybrid NPs floating in the base fluid, sedimenting, and aggregating. Unreliable outcomes are inevitable when

the resulting mono and hybrid NFs are used in a variety of applications. This highlights how important it is for both mono and hybrid NFs to have good and desired stability. However, the stability of mono and hybrid NFs is greatly affected by preparation factors such as stirring duration, rate, temperature, sonication time, power, frequency, amplitude, and dispersion percentage (if a surfactant is used). The sonication factors (time, power, mode, frequency, and amplitude) are associated with the sonication energy required to create homogenized and stable mono and hybrid NFs. Nanofluids (NFs), composed of metallic or hybrid nanoparticles (MNPs) floating in base fluids, form an electrical double layer (EDL) around the nanoparticle surfaces due to surface charges. This effect affects the stability of NFs in addition to making them electrically conductive. For NFs to retain their optical performance and thermophysical characteristics (such as heat conductivity and viscosity), stability is essential. Stability is greatly impacted by variables such as particle size, surface charge, ion concentration, and nanoparticle volume percentage. In order to prevent sedimentation and agglomeration, which might impair performance, stable nanofluids provide homogeneous dispersion of nanoparticles.

Ultrasonication for Stability Improvement

Ultrasonication is a widely adopted technique to enhance the stability of nanofluids by ensuring homogeneous dispersion of nanoparticles in the base fluid. It works by mechanically agitating and breaking up clusters of nanoparticles, preventing sedimentation. Studies have shown that the optimal sonication time is a critical factor, with reported durations ranging from 12 min to as long as 60 h, depending on the system and desired properties. Proper optimization of sonication parameters is essential, as excessive or insufficient sonication can adversely affect properties like thermal conductivity, viscosity, and particle size distribution.

Surfactant Addition for Enhanced Dispersion

Surfactants are another commonly used method for improving NF stability. These complex chemical compounds reduce interfacial tension between nanoparticles and the base fluid, promoting better dispersion. Surfactants create electrostatic repulsion among nanoparticles, which prevents aggregation. Examples of surfactants used include acetyl trimethyl ammonium bromide (CTAB), sodium dodecyl sulphate (SDS), and oleic acid (OA). However, surfactants have limitations, particularly at elevated temperatures (above 60°C), where weakened bonds between the nanoparticles and surfactants can lead to reduced stability and sedimentation.

pH Control to Improve Stability

Adjusting the pH of the nanofluid is another effective technique to enhance stability. Altering the pH away from the isoelectric point (IEP) increases the electrostatic repulsion between nanoparticles, reducing the risk of aggregation and sedimentation. The zeta potential (ZP), which measures the electrostatic repulsion between particles, is a critical metric for assessing stability. A high ZP value (greater than 60 mV) indicates excellent stability, while lower values suggest weaker repulsion and greater instability. Researchers have demonstrated that combining pH adjustments with surfactants can further enhance stability [21].

COMPARATIVE ANALYSIS OF NANOFLUID PERFORMANCE

The increasing global scarcity of water emphasizes the implementation of renewable energy sources such as a solar-powered desalination system, also known as a solar still. These are environmentally friendly but suffer from efficiency issues. This review examines studies from the past decade on enhancing solar still performance using mono and hybrid nanofluids. It highlights key factors such as nanoparticle size, shape, preparation methods, stability, and their overall impact on efficiency. Design improvements, such as glass cooling, external condensers, and reflectors, are also discussed. The maximum yield enhancement of 285.1% was realized with Cu₂O nanofluid at 1.97% concentration with design improvements [22]. The exergy efficiency, environmental effects, and water quality are further discussed in the review to provide recommendations for the optimization of solar stills to overcome water scarcity problems.

Population growth is exerting increasing pressure on global water supplies, making renewable solutions like solar desalination imperative. Solar stills are known for their reliability and eco-friendliness but face efficiency challenges. This study investigates the role of nanofluids in improving the performance of solar stills by optimizing their optical, thermal, and physical properties to enhance heat transfer between absorber plates and saline water. It focuses on research over the past decade, indicating how metal oxide-based nanofluids, such as Cu_2O at 1.95% concentration, have improved yield by 279.6% compared to conventional stills. The author discussed key factors, such as the nanofluid particle size, shape, and stability, besides preparation methods and their effect on solar still performance. The research introduces sustainable environmental controls for solar stills to reduce pollution and purify water [23]. Such findings emphasize nanofluids in advancing the technology of solar desalination and helping in solving global challenges of water scarcity.

Double-tube heat exchangers (DTHX) are commonly utilized in industrial, sanitary, and food applications. With the improvement of thermal performance becoming an area of interest, using CuO nanofluid with superior thermophysical properties has been studied for replacement of conventional fluids in DTHXs. This study deals with both parallel and counterflow configurations and includes equations and correlations for evaluating parameters. The preparation, thermophysical properties, and factors influencing performance of nanofluids are also considered. The results show that CuO nanofluid improves heat transfer significantly in DTHXs and, even though pressure drop increases with friction, it is further enhanced by methods such as twisted tapes [24]. Comparing this oxide-based nanofluid with other oxides, CuO has a better performance, and the size of DTHX can be smaller and power consumption reduced.

Nanofluids greatly improve the thermal performance of flat plate solar collectors (FPSC) compared to conventional fluids, enhancing thermophysical properties for better heat transfer. However, the stability of nanofluids becomes a critical issue in determining long-term performance and even the success of solar projects, which are projected to be 20–30 years in duration. Author discusses the stability of thermal efficiency in solar water-nanofluid heaters, including nanoparticle characteristics, surfactant use, preparation methods, and fouling effects on nanofluid lifespan. Nanofluids enhance thermal efficiency between 5 and 35%, with some cases reaching up to 85%. Stability indicators like Z-potential give information about the particle dispersion and usage time. These improvements are achieved using surfactants, optimized preparation, and specific nanoparticle content of 0.2–0.3% volume [25]. Fouling is still a big issue in nanofluids; it reduces the thermal conductivity more than 11%. Instability over time increases viscosity, friction, pressure drop, and pumping power requirement that ultimately affects the performance. Stability in FPSC applications only accounts for 2.5% of the lifetime of the system, thus calling for further improvement. More effective nanoparticle dispersion and optimized stability parameters, such as Z-potential, as well as thermal stability above 90°C , are crucial in sustaining the feasibility of nanofluids in long-term solar heating projects. This can pave the way for more reliable and efficient solar energy solutions.

The scarcity of potable water in the world has led researchers to seek alternative solutions, since there is plenty of saline seawater with dissolved solid content of 35,000–45,000 ppm. The use of solar stills, which are devices that use solar energy to desalinate saline water [26], has been a sustainable solution but suffers from low productivity. Water-based nanofluids have emerged as a promising method to enhance the performance of solar stills. This review investigates the effects of nanofluid type, nanoparticle concentration, and fluid depth on solar still productivity based on recent state-of-the-art literature. It also reviews different augmentation techniques that help enhance nanofluid performance inside the solar still. Hybrid nanofluids are reviewed for far surpassing the benefits of mono-nanofluids and their applications in solar stills critically reviewed [26]. Key findings, presented in extensive tables, emphasize the advantages of nanofluids in enhancing desalination efficiency. The conclusion synthesizes these outcomes, while the scope for future research highlights areas requiring further optimization to establish solar still technology as a sustainable solution for potable water production. Table 1 summarizes studies on nanofluid applications in solar stills and heat transfer systems.

Table 1. Summary of studies on nanofluids applications in solar stills and heat transfer systems.

Reference	Study focus	Key findings	Outcomes
[22]	Enhancing solar still performance using Cu ₂ O nanofluids	Nanoparticle size, shape, concentration (1.97%), design improvements (glass cooling, reflectors, condensers)	Yield enhancement of 285.1% achieved with Cu ₂ O nanofluids at 1.97% concentration and design modifications.
[23]	Role of nanofluids in solar still optimization	Nanoparticle optical, thermal, and physical properties; stability; Cu ₂ O concentration (1.95%)	Yield improvement of 279.6% compared to conventional stills; sustainable environmental controls introduced for reduced pollution and better water quality.
[24]	CuO nanofluids in double-tube heat exchangers (DTHX)	Preparation methods, thermophysical properties, pressure drop, friction enhancement via twisted tapes	Significant heat transfer improvement with CuO nanofluids; potential for smaller heat exchanger size and reduced power consumption despite increased pressure drop.
[25]	Nanofluids in flat plate solar collectors (FPSC)	Stability (Z-potential, fouling effects), nanoparticle content (0.2–0.3%), surfactant use, preparation	Thermal efficiency improvement of 5–35%; issues with fouling and long-term stability noted; recommendations for optimizing dispersion and stability parameters.

CONCLUSION

The study concludes that nanofluids represent a cutting-edge solution for enhancing thermal management and energy efficiency across diverse applications. Their unique properties, such as high thermal conductivity, stability, and compatibility with base fluids, make them ideal for modern engineering challenges. Applications in biomedical fields, electronics cooling, solar energy systems, and machining demonstrate the versatility and transformative potential of nanofluids. However, challenges such as long-term stability, viscosity management, and large-scale feasibility must be addressed through optimized nanoparticle formulations, advanced modelling techniques, and eco-friendly practices. Future research should focus on hybrid nanofluids and innovative synthesis methods to expand their utility and address pressing global issues such as water scarcity and sustainable energy needs. Nanofluids are poised to be a cornerstone in advancing technology and achieving sustainable development goals.

REFERENCES

- Babar H, Wu H, Zhang W, Shah TR, McCluskey D, Zhou C. The promise of nanofluids: A bibliometric journey through advanced heat transfer fluids in heat exchanger tubes. *Adv Coll Interface Sci.* 2024; 325: 103112.
- Rahman MA, Hasnain SM, Pandey S, Tapalova A, Akyzbekov N, Zairov R. Review on nanofluids: preparation, properties, stability, and thermal performance augmentation in heat transfer applications. *ACS omega.* 2024; 9(30): 32328–32349.
- Mohite DD, Goyal A, Singh AS, Ansari MI, Patil KA, Yadav PD, Londhe PV, et al. Improvement of thermal performance through nanofluids in industrial applications: A review on technical aspects. *Mater Today: Proc.* 2024.
- Ajeeb W, Murshed SS. Nanofluids in compact heat exchangers for thermal applications: A State-of-the-art review. *Therm Sci Eng Prog.* 2022; 30: 101276.
- Suneetha S, Subbarayudu K, Reddy PBA. Hybrid nanofluids development and benefits: A comprehensive review. *J Therm Eng.* 2022; 8(3): 445–455.
- Muzaidi NAS, Fikri MA, Wong KNSWS, Sofi AZM, Mamat R, Adenam NM, Adli HK, et al. Heat absorption properties of CuO/TiO₂/SiO₂ trihybrid nanofluids and its potential future direction towards solar thermal applications. *Arab J Chem.* 2021; 14(4): 103059.
- Awais M, Bhuiyan AA, Salehin S, Ehsan MM, Khan B, Rahman MH. Synthesis, heat transport mechanisms and thermophysical properties of nanofluids: A critical overview. *Int J Thermofluids.* 2021; 10: 100086.

8. Souza RR, Faustino V, Gonçalves IM, Moita AS, Bañobre-López M, Lima R. A review of the advances and challenges in measuring the thermal conductivity of nanofluids. *Nanomaterials*. 2022; 12(15): 2526.
9. Stalin PMJ, Arjunan TV, Matheswaran MM, Kumar PM, Sadanandam N. Investigations on thermal properties of CeO₂/water nanofluids for heat transfer applications. *Mater Today: Proc*. 2021; 47: 6815–6820.
10. Scott TO, Ewim DR, Eloka-Eboka AC. Hybrid nanofluids flow and heat transfer in cavities: A technological review. *Int J Low-Carbon Technol*. 2022; 17: 1104–1123.
11. Amin AR, Ali A, Ali HM. Application of nanofluids for machining processes: a comprehensive review. *Nanomaterials*. 2022; 12(23): 4214.
12. Nobrega G, de Souza RR, Gonçalves IM, Moita AS, Ribeiro JE, Lima RA. Recent developments on the thermal properties, stability and applications of nanofluids in machining, solar energy and biomedicine. *Appl Sci*. 2022; 12(3): 1115.
13. Wang X, Luo L, Xiang J, Zheng S, Shittu S, Wang Z, Zhao X. A comprehensive review on the application of nanofluid in heat pipe based on the machine learning: Theory, application and prediction. *Renew Sustain Energy Rev*. 2021; 150: 111434.
14. Mukherjee S, Paria S. Preparation and stability of nanofluids—a review. *IOSR J Mech Civ Eng*. 2013;9(2):63–9. DOI: 10.9790/1684-0926369.
15. Kalsi S, Kumar S, Kumar A, Alam T, Dobrotă D. Thermophysical properties of nanofluids and their potential applications in heat transfer enhancement: a review. *Arab J Chem*. 2023; 16(11): 105272.
16. Dey D, Sahu DS. A review on the application of the nanofluids. *Heat Transfer*. 2021; 50(2): 1113–1155.
17. Dalke PA, Karanjkar AV, Deshmukh GP. A Review: Nanofluids in Machining for Performance and Sustainability. In *J Phys: Conf Ser*. 2024 May; 2763(1): 012012. IOP Publishing. DOI 10.1088/1742–6596/2763/1/012012
18. Rashid FL, Aljibori HS, Mohammed HI, Ameen A, Ahmad S, Hamida MBB, Al-Rubaye AH. Recent advances and developments of the application of hybrid nanofluids in parabolic solar collector energy systems and guidelines for future prospects. *J Eng Res*. 2024. <https://doi.org/10.1016/j.jer.2024.04.023>
19. Wohld J, Beck J, Inman K, Palmer M, Cummings M, Fulmer R, Vafaei S. Hybrid nanofluid thermal conductivity and optimization: original approach and background. *Nanomaterials*. 2022; 12(16): 2847.
20. Muneeshwaran M, Srinivasan G, Muthukumar P, Wang CC. Role of hybrid-nanofluid in heat transfer enhancement—A review. *Int Commun Heat Mass Transf*. 2021; 125: 105341.
21. Yasmin H, Giwa SO, Noor S, Aybar HŞ. Influence of preparation characteristics on stability, properties, and performance of mono-and hybrid nanofluids: Current and future perspective. *Machines*. 2023; 11(1): 112.
22. Gunay T, Gumus C, Sahin AZ. The impact of using nanofluid on the performance of solar stills: A comprehensive review. *Process Saf Environ Prot*. 2024; 189: 1464–1516. <https://doi.org/10.1016/j.psep.2024.06.104>
23. Suresh C, Chithambaram V, Muthucumaraswamy R, Praveenkumar S, Saleh SM, Rao MC, Shanmugan S. Transformative nanofluid solutions: Elevating solar still performance for enhanced output. *Ain Shams Eng J*. 2024; 15(12): 103088. <https://doi.org/10.1016/j.asej.2024.103088>
24. Kadhim SA, Hammoodi KA, Askar AH, Rashid FL, Wahhab HAA. Feasibility review of using copper oxide nanofluid to improve heat transfer in the double-tube heat exchanger. *Results Eng*. 2024; 24: 103227. <https://doi.org/10.1016/j.rineng.2024.103227>
25. García-Rincón MA, Flores-Prieto JJ. Nanofluids stability in flat-plate solar collectors: A review. *Sol Energy Mater Sol Cells*. 2024; 271: 112832. <https://doi.org/10.1016/j.solmat.2024.112832>
26. Modi KV, Patel PR, Patel SK. Applicability of mono-nanofluid and hybrid-nanofluid as a technique to improve the performance of solar still: A critical review. *J Clean Prod*. 2023; 387: 135875. <https://doi.org/10.1016/j.jclepro.2023.135875>