Applied Chemical Engineering (2025) Volume 8 Issue 2 ISSN: 2578-2010 (O)
doi: 10.59429/ace.v8i2.5684

RESEARCH ARTICLE

Advances in the synthesis and applications of hybrid nanofluids: Supporting SDG 7.3 on energy efficiency

Vijay P Ate[1], Pramod B Lanjewar[2], Sagar D Shelare[3], Prateek D. Malwe[4], Choon Kit Chan[5], Subhav Singh[6 7] Deekshant Varshney[8 9]

[1] *Mechanical Engineering Department, Kavikulguru Institute of Technology and Science, Ramtek. Rashtrasant Tukadoji Maharaj Nagpur University Nagpur. 440033, India*

[2] *Mechanical Engineering Department, St Vincent Pallotti College of Engineering and Technology, Nagpur, Rashtrasant Tukadoji Maharaj Nagpur University Nagpur,440033, India*

[3] *Mechanical Engineering Department, Priyadarshani College of Engineering Nagpur, Rashtrasant Tukadoji Maharaj Nagpur University. Nagpur, 440033, India*

[4] *Mechanical Engineering Department, Dr. D. Y. Patil Institute of Technology, Pimpri, Pune,411018, India*

[5] *Faculty of Engineering and Quantity Surveying, INTI International University, Nilai, Negeri Sembilan 71800, Malaysia*

[6] *Centre for Research and Development, Chitkara University, Himachal Pradesh,174103, India.*

[7] *Division of research and development, Lovely Professional University, Phagwara, Punjab, 144411, India.*

[8] *Centre of Research Impact and Outcome, Chitkara University, Rajpura Punjab, 140417, India.*

[9] *Division of Research & innovation, Uttaranchal University, Dehradun, 248007,India.*

***Corresponding author:** Choon Kit Chan; choonkit.chan@newinti.edu.my

ARTICLE INFO

Received: 22 June 2025
Accepted: 8 July 2025
Available online: 22 July 2025

ABSTRACT

Nanofluids with advanced properties (also known as hybrid nanofluids), which form systems based on a combination of two or more nanoparticles (NPs dispersed in ordinary fluids), have been considered as a revolutionary solution to improve thermal efficiency in a wide range of industrial processes, and ultimately contribute to energy efficiency. These materials exhibit enhanced performance characteristics compared to traditional single-phase nanomaterials, owing to synergistic interactions between their components. Synthesis techniques such as sol-gel processing, hydrothermal methods, and chemical vapor deposition are extensively explored, each offering specific advantages in terms of particle dispersion, morphology control, and structural stability. The current critical review examines important synthesis techniques, delineating characteristics, and real-existing applications of the hybrid nanofluids and the ability of mixing them to increase the thermal conductivity and, subsequently, enhance energy conservation in heat exchangers and cooling devices. New trends confirm that the process of optimizing nanofluid arrangements can directly lead to Sustainable Development Goal (SDG) 7.3 by enhancing energy efficiency globally. At the same time, it critically evaluates the existing barriers such as stability, cost-effectiveness, and environmental friendliness as well as outline possible avenues of research that might raise the possibility of achievable industrial scalability and sustainability. Meanwhile, nanocomposites show promise in photocatalysis and solar energy applications due to their superior light absorption and charge transport

properties. Carbon-based hybrids exhibit outstanding electrical conductivity and are being developed for use in super capacitors, batteries, and electronic cooling systems. Biomedical applications, environmental sensors, and advanced fluid technologies (e.g., nanofluids) also benefit from these materials. Emphasis is placed on continued interdisciplinary research and innovation to unlock their full potential and expand their industrial applicability in the future. With strategic development, these materials promise transformative impacts across energy, medicine, electronics, and environmental sectors. To explore recent advancements in the synthesis techniques of hybrid nanofluids and analyze the thermophysical and chemical properties of hybrid nanofluids.
Keywords: Hybrid Nanofluids; thermal efficiency; energy conservation; SDG 7.3; sustainability, energy efficiency

1. Introduction

Various hybrid nanocomposites such as Al-Zn, MWCNT-HEG, TiO2-CNT, Au-CNT, Graphene-MWCNT, Cu-TiO2, Al2O3-Cu and MWCNT- Fe3O4, Ag-MWNT have been produced and their characteristics, applications assessed. HEG, TiO2-CNT, Au-CNT, Graphene-MWCNT, Cu-TiO2, Al2O3-Cu, MWCNT- Fe3O4, Ag-MWNT[1]. The implementation of heat exchangers makes it possible to transfer heat effectively between fluid streams essential parts of many industrial processes and thermal management systems. Heat exchangers are the industrial application of heat exchangers exists within different sectors for moving and recovering thermal energy and dissipating heat power generation and chemical processing to HVAC systems and automotive applications. Heat exchangers remain important for industrial operations because their operating capabilities allow maintaining ideal operating conditions while optimizing energy usage. Process efficiency along with energy optimization and usage improvement occur in multiple engineering applications through heat exchangers. The various uses of heat exchangers are illustrated in **Figure 1**.

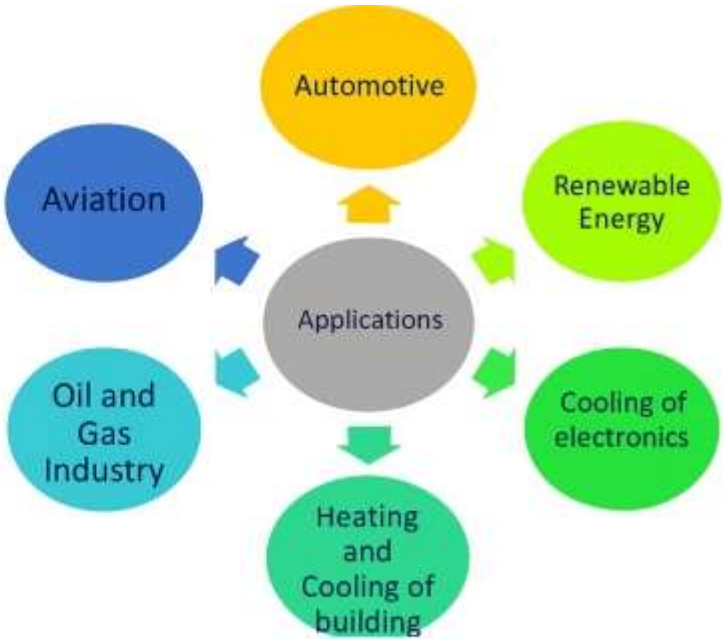

Figure 1. Applications of heat exchanger

The functioning of thermal management systems depends heavily on heat exchangers for temperature control. The devices maintain constant temperatures by extracting excess heat from electrical power systems and electronic devices and moving vehicles, automobiles. For example, heat exchangers are used in the electronics sector to cool electronic parts and avoid overheating, guaranteeing the dependability and durability of electronic systems. Similarly, heat exchangers such as oil coolers and radiators—are essential for keeping engine temperatures within ideal ranges in automobile applications, which improves vehicle dependability and performance[2].

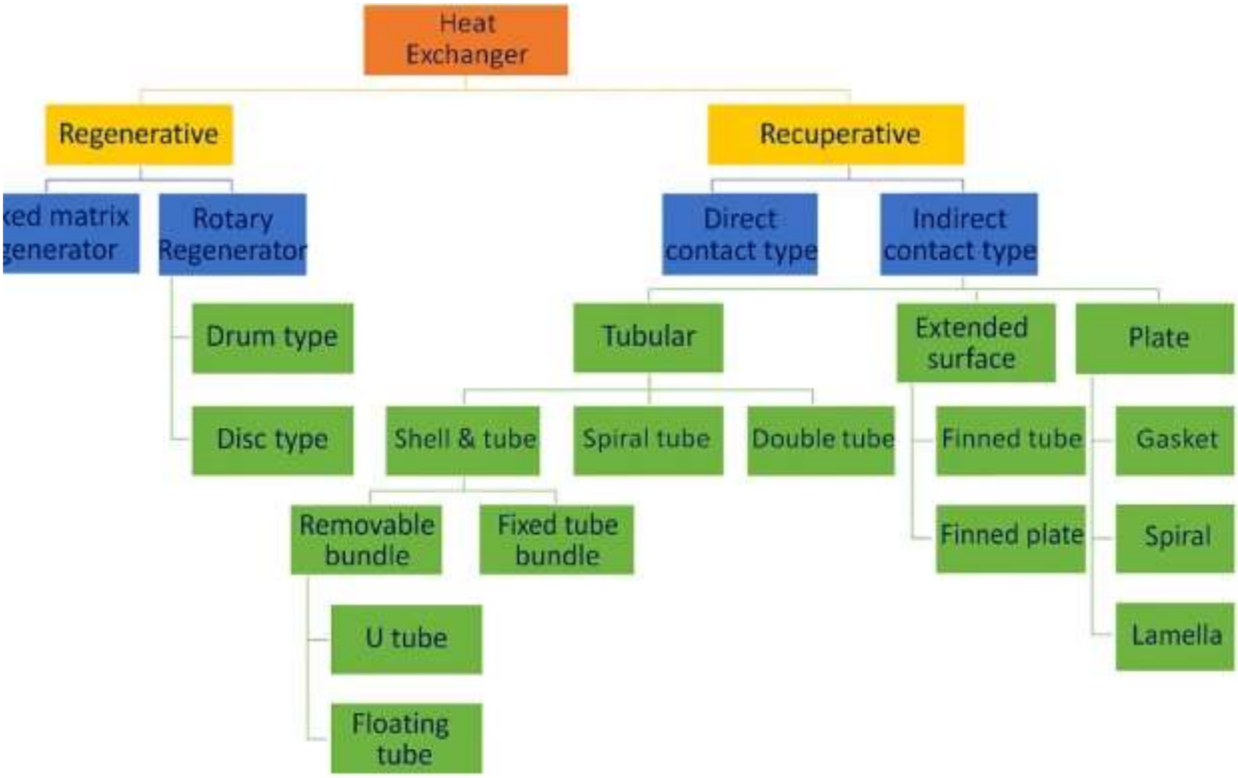

Figure 2. Classification of heat exchanger

The application, fluid characteristics, temperature ranges, and intended heat transfer rates all influence the design and functionality of heat exchangers. To meet a range of thermal processing requirements, heat exchangers come in shell-and-tube, plate-and-frame, finned- tube, and microchannel forms (**Figure 2**). Engineers can choose the best design depending on the needs of the application because each kind has unique benefits in terms of heat transfer efficiency, pressure drop, compactness, and ease of maintenance [3]

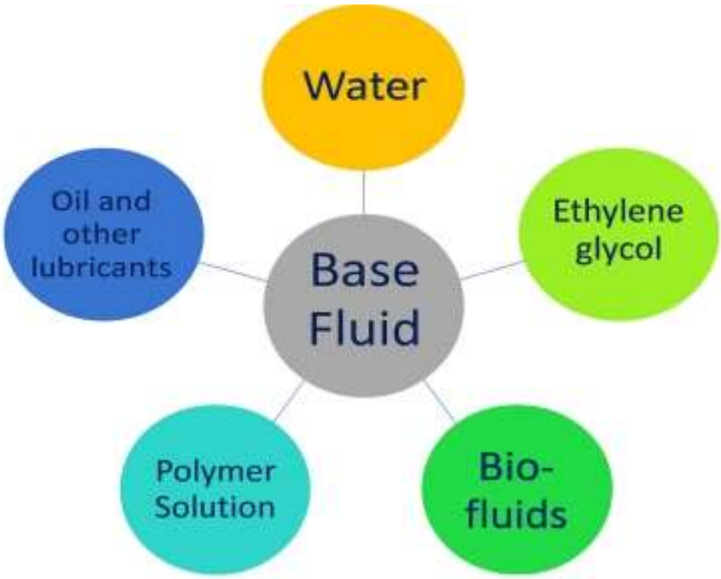

Figure 3. Base fluid for nanoparticles

Nanofluids are colloidal suspensions in which nanoparticles usually in the size range of 1–100 nm are dispersed in a base fluid like water, oil or ethylene glycol (**Figure 3**). The nanoparticles could be carbon based (CNTs, graphene), non metallic (oxides, carbides) or metallic (copper, aluminum) as opposed to the base fluid alone the thermal and rheological characteristics of the base fluid are altered by nanosized particles and produce a fluid with better heat transfer characteristics [4].

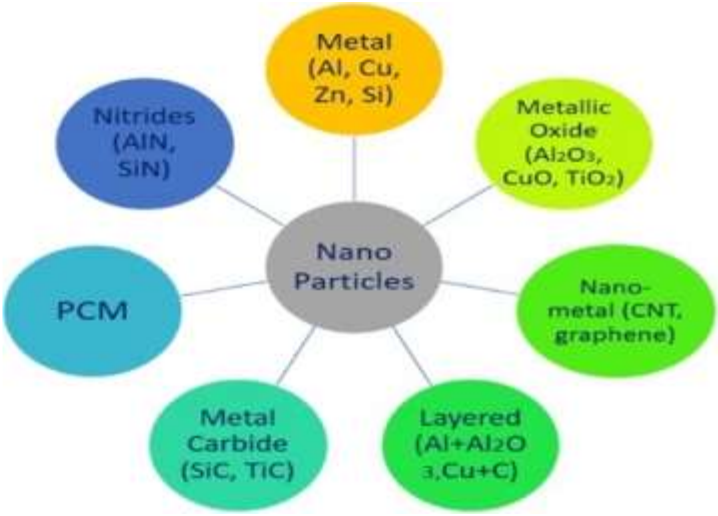

Figure 4. Nanoparticles

The thermal conductivity of the nanofluid is enhanced in general by the nanoparticles, which have a higher thermal conductivity than that of the base fluid. This increased thermal conductivity enhances the rate of heat transfer through the fluid in heat exchangers by improving the rate of heat transport within the fluid. The nanoparticles affect the convective heat transfer characteristics and fluid dynamics of the heat exchanger. This is because nanoparticles cause turbulence by disturbing the boundary layer close to the heat transfer surface to enhance the convective heat transfer coefficients. The fluid and the heat exchanger surface transfer heat more quickly as a result. Because of their high surface-to-volume ratio, nanoparticles offer a vast area for heat transfer across surfaces. The increased surface area of the nanoparticles with the surrounding fluid allows for more efficient thermal exchange, which enhances heat exchanger performance. The thermal properties of nanofluids, such as viscosity and specific heat capacity, can be tailored by altering the type, size, and concentration of nanoparticles. Heat exchanger systems operational features and heat transfer performance can be optimized because to this tenability. When exposed to temperature gradients and fluid flow, nanoparticles display thermophoresis and Brownian motion phenomena, respectively. Heat transmission and fluid mixing in heat exchangers are improved by these events, which cause particle migration towards hotter areas and promote particle dispersion within the fluid[5].

Figure 5 illustrates the patterns and expansion in research efforts across several geographic regions based on a regional study of publications on nanofluids from 2010 to 2022. A range of academic sources provided the data for this analysis, with a focus on peer-reviewed publications on the subject of nanofluids published between 2010 and 2022. This analysis considers the following regions: North America, Europe, Asia, and Other Regions (which includes Africa, South America, and Oceania). The annual publication counts were combined for tracing both discipline-based geography and historical trends combined annually. The review article conducts a comprehensive analysis of nanofluid usage in heat exchangers. The research investigates heat exchangers while explaining how their improved heat transfer functions operate. The evaluation of experimental and computational research and real-world observations form the core of this article which investigates heat exchanger performance improvement through nanofluids applications in a range of industries. The analysis provides current research insights into nanofluid heat exchanger technology. The article analyzes nanofluid-based heat exchanger technology through identifying main limitations while indicating research directions for potential breakthroughs future lines of inquiry and possible breakthroughs

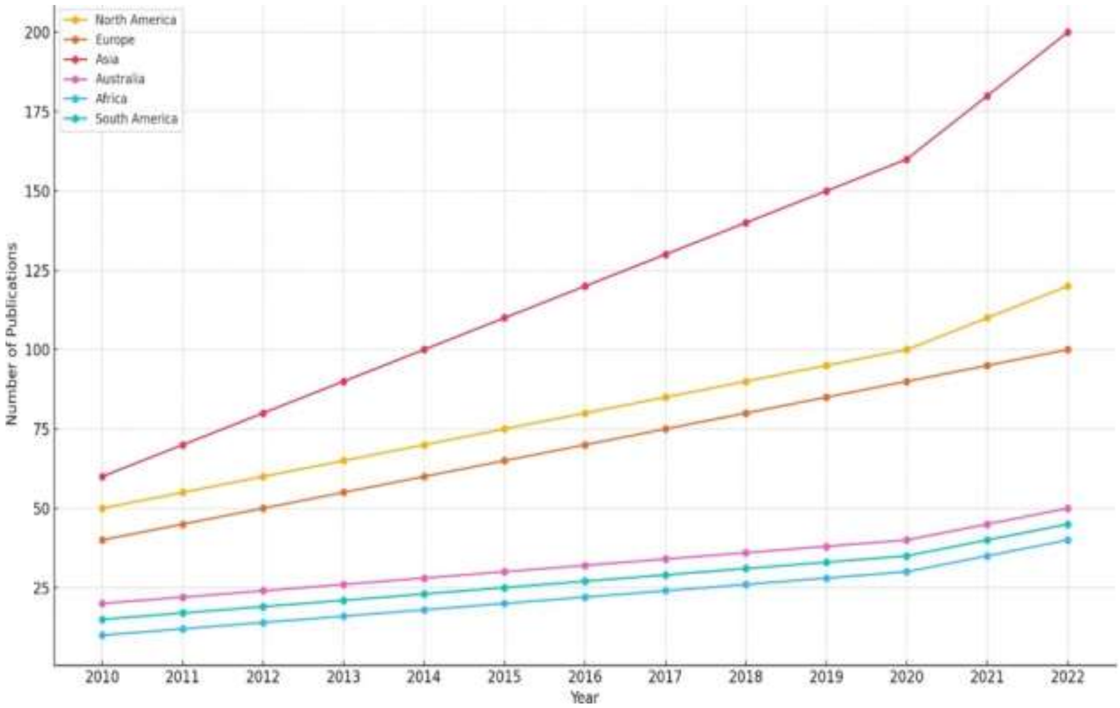

Figure 5. Publications on Nanofluids by region (2010-2022)[5]

1.1. Methods of nanofluids preparation

The synthesis of nanofluids happens through dispersing nanoparticles into base fluids which form colloidal suspensions. A range of techniques exists to develop nanofluids by optimizing nanoparticle distribution as well as controlling particle sizes and maintaining their stability. The methods used to prepare nanofluids are explained in this section through analysis of ten relevant research articles.

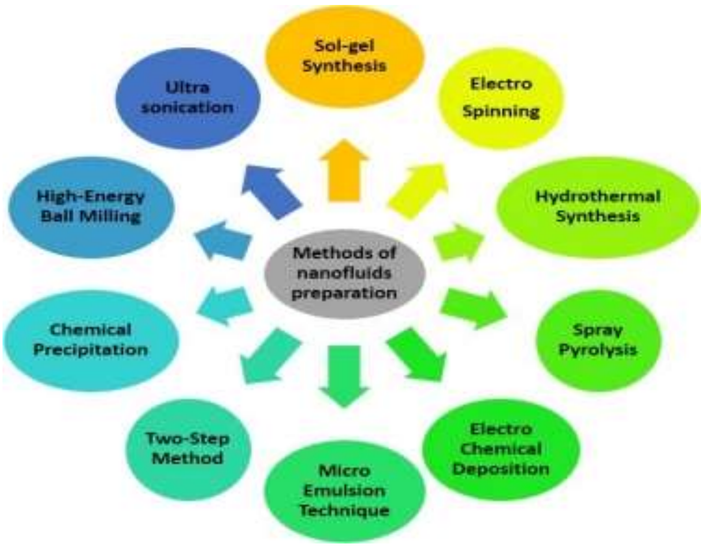

Figure 6. Methods of nanofluids preparation[6]

The information comes from ten academic research documents about this field. R. Bhatia and his colleagues published this research[6]. The sol-gel method serves as a method to produce metal oxide nanoparticles .The authors showed how dispersing TiO2 and Al2O3 nanoparticles in water or ethylene glycol solution through this method. Hydrolysis of metal oxides and subsequent condensation enables the production of nanoparticles with defined size and shape.

R. Maniraman et al.[7] produced copper oxide nanofluids via chemical precipitation. The process of creating nanoparticles through metal salts addition to base fluids results in their dispersion. The researchers performed their study by using this precipitating agent while closely controlling its operational environment

Research by T. Xing et al.[8] developed stable suspensions of carbon-based nanoparticles including grapheme and carbon nanotubes. The research group successfully dispersed carbon nanotubes along with other liquids using high-energy ball milling. This mechanical milling method process helps nanoparticles integrate better into base fluids and achieves complete mixing distribution.

V. Fuskele et al.[9] developed a method to mix SiO2 and CuO nanoparticles with base fluids using ultrasonication. Nanoparticles agglomerates become separated when ultrasonic vibrations create cavitation bubbles. Vibrations, improving colloidal stability.

B. Sharma et al.[10] presented a dual-step method for nanofluid stability creation which merges surface modification with ultrasonication processes. The first step of nanoparticle dispersion occurs through base fluid compatibility enhancement procedures undergo surface functionalization. The next step involves ultrasonication for generating uniform nanoparticle distribution.

A research team led by M M Husein et al.[11] developed nanofluid stability through metal nanoparticle (such as gold and silver) dispersion methods within water. The microemulsion technique enables the production of silver nanoparticles dispersed in water. The method leads to homogenous nanoparticle dispersion. The microemulsion technique enables surfactants together with co-surfactants to produce nanoscale emulsions for nanoparticle dispersion. Numerous studies exploit the microemulsion technique to establish stable nanofluids incorporating metal nanoparticles including silver and gold.

CTJ Low et al.[12]Water-based nanoparticle dispersion occurs through the microemulsion method. The method produces uniform nanoparticle distribution across the solution through its operation. Surfactants and co-surfactants create nanoscale emulsions to achieve the consistent dispersion of nanoparticles.

The research by Badwai et al.[13] demonstrated the method to disperse oxide nanoparticles including ZnO and Fe2O3. The spray pyrolysis method allows researchers to distribute solvents. The technique allows the spraying of precursor solutions into a hot furnace which produces nanoparticle distribution throughout the carrier fluid. The hot furnace enables chemical reactions between materials which produce nanoparticles before distributing them throughout the carrier fluid. Stable nanofluids containing metal oxide nanoparticles (ZnO and MgO) were produced by S. Wang et al.[14] A Hydrothermal synthesis enabled the dispersal of nanoparticles in water solutions. The procedure both generates and scatters nanoparticles through this mechanism. The authors employed high temperatures and high pressures in their research to treat precursor solutions. Electro spinning allowed Z. Zhang et al.[15] to create nanofibers containing metal nanoparticles through their research. (e.g., silver, copper). The method starts by using electrostatic spinning to create solutions which contain polymers. A dispersion process occurs when nanoparticles receive base fluid for creating nanofluids.

2. Synthesis of hybrid nanoparticles

Hybrid nanoparticles integrate multiple materials at the nanoscale, enhancing individual properties and creating new functionalities. This section provides an overview of the synthesis methods for various hybrid nanocomposites, including Al-Zn, MWCNT-HEG, TiO2-CNT, Au-CNT, Graphene-MWCNT, Cu-TiO2, Al2O3-Cu, MWCNT-Fe3O4, Ag-MWCNT, and Silica-MWCNT.

Table 1. Comparison of synthesis methods, key parameters, advantages, limitations, and applications of various Hybrid Nanocomposites

Hybrid Nano composite	Synthesis Methods	Key Parameters	Advantages	Limitations	Applications	Ref.
Al-Zn	Mechanical Alloying	High-energyball milling	Enhanced mechanicalproperties, corrosionresistance	High energy consumption, possible contamination	Structural materials, automotive parts	[16]
	Sol-Gel Method	Hydrolysis, condensation, calcination	High surface area,uniform particle distribution	Time-consuming, sensitive to process conditions	Coatings,sensors	[17]
	Co-precipitation	Mixing aqueous solutions, precipitation	Uniform dispersion of Znwithin Al matrix	Control over particle size canbe challenging	Catalysts, electronics	[18]
MWCNT- HEG	Hydrothermal Method	Hydrothermal treatment	Robust hybridstructure, high mechanicalstrength	Requires high temperature and pressure	Composites, electronic devices	[19]
	Chemical Vapor Deposition (CVD)	Gaseous carbon precursor deposition	Enhanced electrical properties, uniform hybrid Structures	High cost, complex setup	Nanoelectronics, sensors	[20]
	Electrostatic Self-Assembly	pH and ionic strength adjustment	Stable nanocomposite Formation	Limited to specific material combinations	Biomedical applications, energy storage	[21]
TiO2-CNT	Sol-Gel Method	Titanium alkoxide, acidic medium	Enhanced photocatalytic Properties	Sensitive tosynthesis conditions	Photocatalysis,environmental cleanup	[22]
	Hydrothermal Synthesis	Titaniumprecursor solution, hydrothermal	Growth of TiO2nanoparticles onCNT surface	High temperatureand pressure required	Water treatment, solarcells	[23]
	Chemical Vapor Deposition (CVD)	High-temperature gasdecomposition	Uniform TiO2 coating on CNTs	Expensive equipment, complex process	Photocatalysis,sensors	[24]

Hybrid Nano composite	Synthesis Methods	Key Parameters	Advantages	Limitations	Applications	Ref.
Au-CNT	Chemical Reduction	HAuCl4, reducing agents	Formation of goldnanoparticles on CNT surface	Control over particle size can be challenging	Catalysis, biosensors	[25]
	Electrochemical Deposition	Gold ions, potential application	Catalytic properties enhancement	Requires precise control of electrochemical parameters	Electrochemicalsensors, fuel cells	[26]
	Microwave-Assisted Synthesis	Microwave irradiation	Rapid, uniform heating for hybrid Formation	Requires specialized equipment	Medical diagnostics, electronics	[27]
Graphene-MWCNT	Solution Blending	Dispersion in solvent, reduction	High surface area,mechanical Strength	Requires effective dispersion techniques	Supercapacitors,conductive films	[28]
	In-situ Polymerization	Monomer polymerization	Integrated carbonnanomaterials	Complex synthesis process	Structural composites, electronics	[29]
	Layer-by-Layer Assembly	Sequential deposition	Enhanced electrical andmechanical Properties	Time-consuming, requires multiple steps	Energy storage devices, sensors	[30]
Cu-TiO2	Sol-Gel Method	Copper andtitanium precursors, surfactants	Enhanced photocatalytic andantimicrobial Properties	Sensitive tosynthesis conditions	Antimicrobial coatings, water treatment	[31]
	Impregnation Method	Impregnationwith copper salts	Cu nanoparticleson TiO2 surface	Control over particle size and distribution can be difficult	Catalysts,sensors	[32]
	Electrochemical Deposition	Electrochemical reduction of copper ions	Excellent catalyticproperties	Requires precise control of depositionparameters	Electrochemicalsensors, fuel cells	[33]
Al2O3-Cu	Mechanical Milling	Al2O3 and copper powders	Enhanced thermaland mechanical properties	High energy consumption, possible	Thermal management, structuralmaterials	[34]

Hybrid Nano composite	Synthesis Methods	Key Parameters	Advantages	Limitations	Applications	Ref.
				contamination		
	Sol-Gel Method	Co-hydrolysis, condensation, calcination	Uniform composite Structure	Time-consuming, sensitive to process conditions	Catalysts, thermal barrier coatings	[35]
	Thermal Spray Technique	High- temperature plasma	Composite coating withimproved properties	Requires specialized equipment, high energy consumption	Wear-resistant coatings, thermal barriers	[36]
MWCNT-Fe3O4	Co-precipitation Method	Iron salts, base precipitation	Magnetic applications, biomedical fields	Control over particle size and distribution can be difficult	Drug delivery,magnetic separation	[37]
	Hydrothermal Synthesis	Iron salts, hydrothermal treatment	Growth of Fe3O4on CNT surface	High temperatureand pressure required	Magnetic sensors, environmental remediation	[37]
	Sol-Gel Method	Hydrolysis,gelation, calcination	Stable MWCNT-Fe3O4 Nanocomposites	Time-consuming, sensitive to process conditions	MRI contrast agents, magnetic datastorage	[38]
Ag- MWCNT	Chemical Reduction	Silver ions, reducing agents	Antimicrobialproperties,	Control over particle size canbe challenging	Antimicrobialcoatings,	[39]
	Microwave-Assisted Synthesis	Microwave irradiation	Rapid, uniform synthesis of Ag-MWCNT Composites	Requires specialized equipment	Medical diagnostics,electronics	[40]
Silica- MWCNT	Sol-Gel Method	TEOS hydrolysis, condensation	Enhanced mechanical strength, thermal Stability	Time-consuming, sensitive to process conditions	Composites, thermal insulation	[41]
	Chemical Vapor Deposition (CVD)	Silica precursors, hightemperature	Formation of silica layer onCNT surface	Expensive equipment, complex process	Protectivecoatings, electronic materials	[42]

Hybrid Nano composite	**Synthesis Methods**	**Key Parameters**	**Advantages**	**Limitations**	**Applications**	**Ref.**
	Electrostatic Self-Assembly	pH and ionic strength adjustment	Stable hybrid nanocomposites	Limited to specific material combinations	Biomedical applications,sensors	[43]

Table 1. (*Continued*)

2.1. Synthesis of Al-Zn based hybrid nanocomposite

Hybrid Al-Zn nanocomposites leverage aluminum weight reduction properties and zinc corrosion resistance advantage. Mechanical alloying stands as a common method to generate Al-Zn nanocomposites through which zinc particles distribute uniformly throughout the aluminum matrix. The high-energy ball milling process creates a fine dispersion of zinc particles that rest in the Al matrix. The method enhances the mechanical qualities and corrosion protection features of this material composite[44]. The sol-gel procedure enables the production of a gel through the hydrolysis and condensation of zinc nitrate and aluminum alkoxide. The reaction combines zinc nitrate with aluminum alkoxide under condensation conditions. A nanocomposite with a large surface area and homogeneous zinc particle dispersion emerges through drying and subsequent calcination of the material[45]. In order to create the co-precipitation method reunites aqueous salts of zinc and aluminum through a combined reaction that produces Al-Zn hydroxides with a precipitating agent, like NaOH. The hybrid nanocomposite material is made through calcining these materials hydroxides[46].

2.2. Synthesis of MWCNT-HEG hybrid nanocomposite

The synthesis of MWCNT-HEG hybrids happens because hydrothermally exfoliated grapheme (HEG) maintains a high surface area while MWCNTs deliver mechanical strength. The structural combination of MWCNTs and HEG hybrid nanocomposite depends on their mechanical strength properties. Graphene oxide (GO) and aqueous solution containing MWCNTs undergoes hydrothermal treatment that produces exfoliated GO from this mixture. The hydrothermal process transforms graphene oxide into graphene while integrating it with MWCNTs to produce a robust hybrid structure[47]. By depositing carbon from a gaseous precursor onto MWCNT and HEG-containing substrates enables the CVD technique. The process leads to hybrid structures which show better characteristics[48]. By modifying the PH and ionic strength of MWCNT and HEG solutions, electrostatic self-assembly facilitates electrostatic interactions and the production of stable nanocomposite[49].

2.3. Synthesis of TiO2-CNT hybrid nanocomposite

The combination of titanium dioxide (TiO2) photocatalysis properties with carbon nanotube (CNT) conductivity allows production of TiO2-CNT hybrid nanocomposites and electrical conductivity of carbon nanotubes (CNTs). The Sol-Gel method serves to combine titanium alkoxide and CNTs in a solution with acidic properties. The sol-gel method enables the formation of a TiO2 matrix structure that surrounds CNTs improves their photocatalytic capabilities. [50]. Scientists promote the development of TiO2 nanoparticles on the surface. Carbon nanotubes (CNTs) receive titania coatings through hydrothermal treatment after titanium precursors mix with them[51]. High temperature processing enables CVD to decompose gasses containing titanium. The CVD method generates a uniform hybrid structure which coats CNTs with a thin layer of TiO2[52].

2.4. Synthesis of Au-CNT hybrid nanocomposite

Au-CNT hybrids connect carbon nanotubes electrical conductance with their ability to act as catalysts of gold nanoparticles. Nanoparticles of gold salts HAuCl4 become reduced through the use of reducing agents including sodium citrate and NaBH4. The reduction process of gold salts using CNTs in chemical reduction methods results in gold nanoparticles formation on the CNT surface[53]. The CNTs operate as electrodes inside an electrolytic solution containing gold ions in electrochemical processes. Deposition when a potential is applied, gold is deposited onto the CNTs, creating Au-CNT hybrids[54]. Microwave-Assisted Synthesis involves the reduction of gold precursors in the presence of CNTs under microwave irradiation, providing rapid and uniform heating to facilitate hybrid nanocomposite[55]

2.5. Synthesis of Graphene-MWCNT hybrid nanocomposite

The mechanical strength and electrical conductivity of MWCNTs are combined with the large surface area of graphene to create graphene-MWCNT hybrids. Solution blending creates a hybrid structure with improved characteristics by dispersing graphene oxide (GO) and MWCNTs in a solvent and then reducing them chemically or thermally[56]. Polymerization in-situ the carbon nanomaterials are integrated into a composite matrix by mixing graphene and MWCNTs with monomers that polymerize in-situ[57]. Graphene and MWCNT layers are sequentially deposited via covalent or electrostatic interactions in a process known as layer-by-layer assembly[58].

2.6. Synthesis of Cu-TiO2 hybrid nanocomposite

Cu-TiO2 hybrids are renowned for their improved antibacterial and photocatalytic capabilities. Using the Sol-gel method Cu-doped TiO2 nanocomposites are created by hydrolyzing and condensing copper and titanium precursors in the presence of surfactants, then calcining the mixture[59]. The impregnation method involves impregnating TiO2 nanoparticles with copper salts, which are subsequently reduced to produce Cu nanoparticles on the surface of the TiO2[60]. Copper ions are electrochemically reduced onto TiO2 substrates in electrochemical deposition, creating a Cu-TiO2 hybrid with superior catalytic capabilities[61].

2.7. Synthesis of Al2O3-Cu hybrid nanocomposite

Al2O3-Cu hybrids combine the thermal conductivity of copper with the mechanical strength of alumina. In Mechanical Milling, Al2O3 and copper powders are mechanically milled, resulting in fine dispersion of copper within the alumina matrix, enhancing thermal and mechanical properties[62]. In Sol-Gel method, Aluminum and copper precursors are co- hydrolyzed and condensed to form a gel, which is then calcined to produce Al2O3-Cu nanocomposites[63]. In thermal spray technique copper and alumina powders are fed into a high-temperature plasma, where they melt and form a composite coating upon cooling[64].

2.8. Synthesis of MWCNT-Fe3O4 hybrid nanocomposite

MWCNT-Fe3O4 hybrids are widely used in magnetic applications and biomedical fields. In co precipitation method, Fe3O4 nanoparticles are synthesized in the presence of MWCNTs by precipitating iron salts with a base like NaOH, followed by magnetic separation and drying to form the hybrid nanocomposite[65]. In hydrothermal synthesis, a mixture of iron salts and MWCNTs is subjected to hydrothermal treatment, promoting the growth of Fe3O4 nanoparticles on the CNT surface[66]. In Sol Gel method, iron precursors are hydrolyzed in the presence of MWCNTs, followed by gelation and calcination to produce MWCNT-Fe3O4 nanocomposites[67].

2.9. Synthesis of Ag-MWCNT hybrid nanocomposite

Ag-MWCNT hybrids exhibit excellent antimicrobial and electrical properties. In chemical reduction, silver ions are reduced in the presence of MWCNTs using reducing agents like sodium borohydride, forming silver nanoparticles on the CNT surface[68]. In electrochemical deposition MWCNTs are used as electrodes in a silver ion-containing electrolyte, where applying a potential leads to the deposition of silver nanoparticles onto the MWCNTs[69]. Microwave-Assisted Synthesis involves the rapid reduction of silver ions in the presence of MWCNTs under microwave irradiation, facilitating uniform formation of Ag-MWCNT nanocomposites[70].

2.10. Synthesis of Silica-MWCNT hybrid nanocomposite

Silica-MWCNT hybrids combine the mechanical strength of CNTs with the thermal stability of silica. In Sol-Gel method, tetraethyl orthosilicate (TEOS) is hydrolyzed and condensed in the presence of MWCNTs to form a silica matrix around the CNTs, enhancing mechanical strength and thermal stability[71]. A silica layer forms on the surface of the CNT as a result of the high-temperature breakdown of silica precursors in the presence of MWCNTs in CVD[72]. By varying the pH and ionic strength of their solutions, silica nanoparticles are built onto MWCNTs via electrostatic interactions in electrostatic self-assembly[73].

3. Hybrid nanofluids in heat exchangers

The implementation of hybrid nanofluids stands as a feasible way to boost heat exchanger efficiency. A base fluid contains two or more kinds of nanoparticles distributed as nanofluids. Using the synthesis and characterization of hybrid nanofluids are analyzed based on two published research studies. The research evaluates hybrid nanofluid applications in heat exchanger systems.

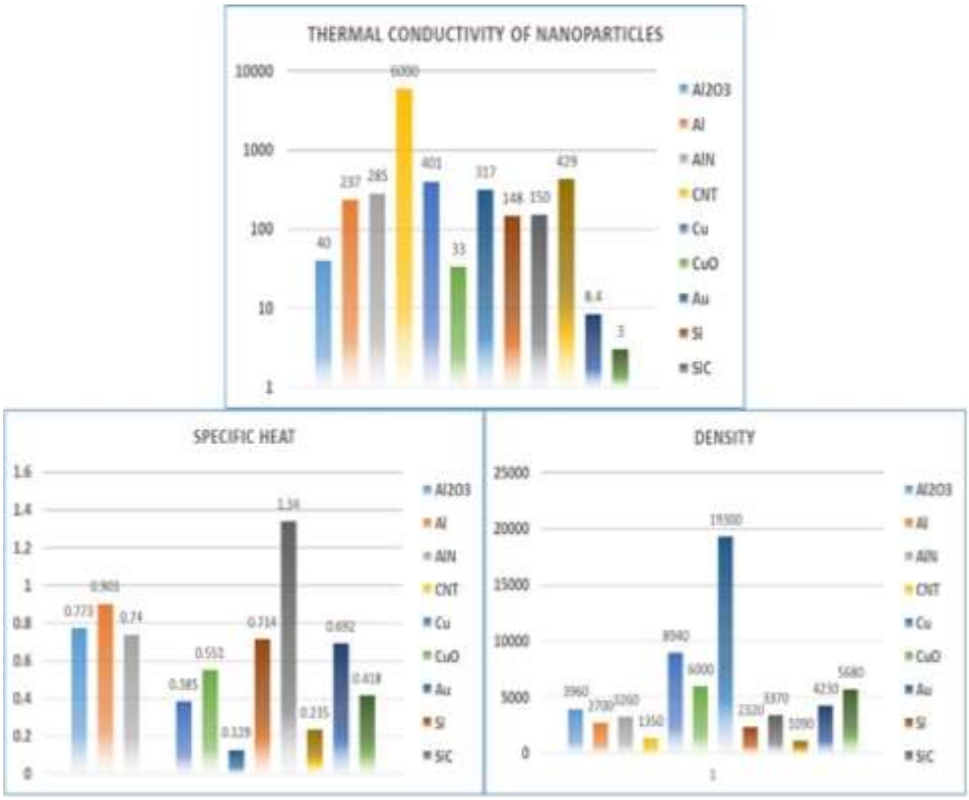

Figure 7. Thermal conductivity, specific heat and density of nanoparticles[77]

3.1. Synthesis methods

3.1.1. Combination of different nanoparticles

Urmi et al[74] studied how both chemical reduction and ultrasonication enable the creation of hybrid nanofluids through combined metallic (copper) and non-metallic (graphene oxide) nanoparticles. Scientists have found a way to produce hybrid nanofluids through the combination of metallic copper and non-metallic graphene oxide nanoparticles. The performance of heat transfer receives improvement through the combined actions of metallic and non-metallic nanoparticles were investigated.

3.1.2. Surface functionalization

The research by Nabil et al[75] focused on increasing base fluid stability through the implementation of metallic (such as silver) and non-metallic (including alumina) nanoparticles. The researchers surface modified silver and alumina nanoparticles into hybrid nanofluids through chemical processes. The functionalization of nanoparticle surfaces happened through this method. Surface modifications occurred through this process to both improve dispersion capabilities and prevent agglomeration effects.

3.2. Characterization techniques

3.2.1. Particle size analysis

Scientists from Fillipov et al.[76] applied TEM and DLS techniques to investigate hybrid nanofluids. Research findings illustrate both the form and size and distribution patterns of hybrid nanofluids. The optimal heat transfer performance results from this method. The study established clear understanding of how nanoparticles disperse and how homogeneous they are when dispersed in the base fluid.

3.2.2. Thermal conductivity measurement

Toghraie et al.[77] conducted thermal conductivity analysis through the utilization of a thermal conductivity analyzer to measure the thermal conductivity of hybrid nanofluids. The research examined thermal conductivity improvement from both nanoparticle composition and concentration. Thermal conductivity improvements from different concentrations received analysis which revealed the heat transfer mechanisms in this research behind heat transfer in hybrid nanofluids.

3.3. Heat transfer performance

3.3.1. Experimental investigation

The research performed by Tavakoli et al.[78] explored hybrid nanofluid heat transfer performance in a shell-and-tube heat exchanger in their experimental investigation. The research study showed how heat transfer enhancement through nanoparticle combinations was studied by testing the thermal performances of the study evaluated thermal performance between hybrid nanofluids and single-component nanofluids and base fluids.

3.3.2. Computational modeling

Research by Mashayekhi et al.[79] analyzed the flow and heat transfer properties of hybrid nanofluids in microchannel heat exchangers using computational fluid dynamics (CFD) simulations. The impacts of nanoparticle size, distribution, and concentration on pressure drop and heat transfer enhancement were clarified by the numerical analysis.

3.4. Practical applications

3.4.1. Automotive cooling systems

The research team of Ramadhan et al. [80] examined hybrid nanofluids utilization for automobile radiator cooling systems in a practical application testing environment engine cooling in automobile radiators. The research established that hybrid nanofluids function to reduce temperatures in coolant. The combination of hybrid nanofluids with vehicles enables a reduction in coolant temperatures while improving heat transfer effectiveness in engine cooling systems which leads to better engine performance and longevity .

3.4.2. Solar thermal collectors

The application of hybrid nanofluids for solar thermal collectors received research attention from Zhang et al. [81] harvest sustainable energy. Researchers studied the effectiveness with which hybrid nanofluids improve energy conversion uptake. The study evaluated thermal performance of these nanofluids while they received solar irradiation for heat transfer efficiency measurements. The complete analysis of hybrid nanofluids demonstrates successful development and functional characteristics and practical applications. Heat exchangers across multiple industries benefit from improvements in heat transfer efficiency due to encouraging developments in industries. A system's overall efficiency receives an increase from hybrid nanofluids because they enhance thermal conductivity. The process of heat transfer enhancement through hybrid nanofluids depends on selecting different nanoparticle kinds and optimizing their dispersion and concentration ratios. To fully utilize hybrid nanofluids for sophisticated thermal management applications, more study and advancement in this area are necessary.

3.4.3. Mechanisms of heat transfer enhancement in hybrid nanofluids

The main heat transfer enhancement mechanism of hybrid nanofluids results from their improved thermal conductivity properties. The study conducted by Suresh et al.[82] established that hybrid nanofluids demonstrated better thermal conductivity than individual nanofluid components. Hybrid nanofluids contain a mixture of metallic (i.e. Cu) with non-metallic (i.e. Al2O3) nanoparticles have higher thermal conductivities. A combination of nanoparticles in hybrid nanofluids creates better heat conduction efficiency. Multiple nanoparticles working together in hybrid fluid systems enhance thermal conductivity of the entire fluid. According to the several nanoparticles collaborate in the study to build efficient thermal pathways which significantly boost heat transfer abilities and transmission capacities. Research shows that hybrid nanofluids transfer convective heat at elevated rates. The research by Yarman[83] showed that graphene and silver addition to base fluids produced substantial enhancements in convective heat transfer coefficients. The base fluid received addition of nanoparticles. The thermal boundary layer close to heat transfer surfaces receives disruption when this method is applied. Heat transfer surfaces experience an enhancement when base fluids receive grapheme and silver nanoparticle additions considerable increase in convective heat transfer coefficients. The suspended nanoparticles enhance fluid the boundary layer thickness decreases because nanoparticles disturb the thermal boundary layer adjacent to heat transfer surfaces. The study demonstrates that nanoparticles perform movement through thermophoretic forces. Brownian motion together with thermophoresis together drive micro-convection and improve heat transmission. The study showed nanoparticle addition improves fluid convective properties in a positive manner. The fluid acquires better heat transport capabilities through this enhancement. The heat transfer surfaces experience modified boundary layer properties near their surfaces. The boundary layer properties close to heat transfer surfaces undergo changes after adding nanoparticles into hybrid nanofluids. Mutual nanofluids made from a mixture of TiO2 and CuO nanoparticles proved successful in reducing boundary layer thickness per Madhesh et al.[84]. The combination of TiO2 nanoparticles reduced the thermal and hydrodynamic boundary layer thickness. The boundary layer becomes thinner because of this improvement which enhances heat transfer from fluid surfaces. The nanoparticles enlarge the surface area and enhance thermal conductivity to reduce thermal resistance thus boosting heat transfer performance. Customized by combining the combination of different nanoparticles within hybrid nanofluids leads to enhanced thermophysical properties which includes specific heat capacity and viscosity. The research by Madhesh et al.[84] demonstrated that heat capacity with viscosity both decreased in the thermal and hydrodynamic boundary layer. The boundary layer thickness decreased successfully through the use of hybrid nanofluids which combined CuO and TiO2 nanoparticles. The effective heat transfer from fluid to surface becomes better because of nanoparticles which reduce boundary layer thickness. The boundary layer thickness decreases when nanoparticles employ their larger surface area together with their higher thermal conductivity. The thermal resistance decreases while heat transfer efficiency increases through these materials. The study conducted by Akilu et al.[85] demonstrated that hybrid nanofluids made from Al2O3 and CuO nanoparticle combinations displayed both elevated specific heat capacity and optimal viscosity levels beyond those of individual nanofluids. When Al2O3 and CuO nanoparticles were combined in a mixture their specific heat capacity increased while their viscosity reached peak performance. Such improved qualities affect fluid performance by enhancing both transport and thermal storage functions. The controlled pressure reduction becomes essential for heat exchanger efficiency because hybrid nanofluids keep their controllable pressure drops and carry thermal energy effectively. Heat transmission occurs at a higher rate when multiple nanoparticles work together in hybrid nanofluids. The authors evaluated the synergistic interactions that result from combining SiO2 with TiO2 nanoparticles. Research by Kumar et al.[86] showed that hybrid nanofluid surpassed nanofluids with individual particles based on stability and thermal conductivity measurements in their investigation of the synergistic effects of mixing SiO2 and TiO2 nanoparticles. The study demonstrates that adding the fluid & produces an improved supplementary heat transfer capability. Heat transfer capability reaches its maximum because the nanoparticles exhibit exceptional stability from oxide particles while retaining their exceptional thermal conductivity from metallic particles.

3.4.4. Influence of physical properties on heat transfer capability of nanofluids

Multiple physical properties determine the heat transfer capacity of nanofluids at a significant level. Heat transfer capability depends on nanoparticles dimensions and geometric forms along with their concentration level and base fluid viscosity and the way particles accumulate within the solution and the impact of heat, temperature effects, and stability. This section performs an in-depth study of the influence which these properties have on heat transfer. The research presented in several scientific publications demonstrates how heat transfer functions.

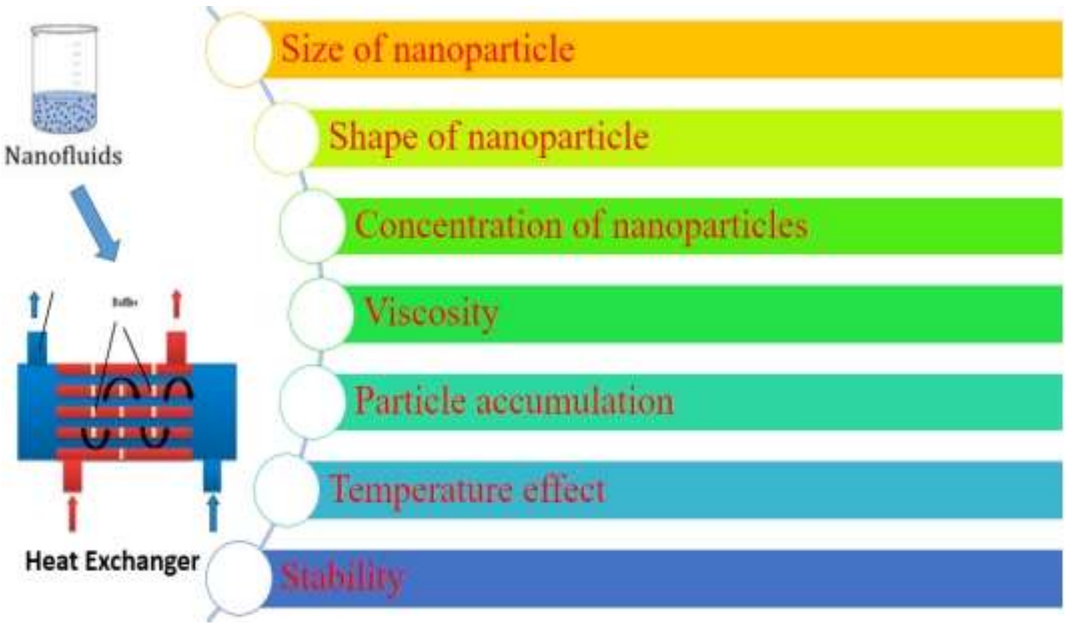

Figure 8. Physical parameters effecting on the heat transfer of nanofluids[86]

3.5. Size of nanoparticles

Physical properties effect on Nanofluids ability to transfer heat depend heavily on nanoparticle dimension scale together with their geometric shape and content level and physical characteristics- viscosity, particle aggregation, and other physical properties- stability and the impacts of temperature. This section examines in detail the findings from numerous published research about the subject. These characteristics impact heat transport. Particle size represents the major factor which affects thermal conductivity and overall heat transfer performance of nanofluids. Smaller nanoparticles often their size enables them to expose more surface area compared to their volume. The efficiency of thermal conductivity increases when nanoparticles become smaller in size. Research by Tan et al.[87] indicates that smaller nanoparticles perform thermal conductivity more efficiently compared to larger ones. The enhanced thermal energy transfer arises from the fact that small particles enable better energy transmission because they possess greater surface exposure. Azizian et al.[88] established that better thermal conductivity results from smaller-particle nanofluids. The thermal conductivity enhanced because Brownian motion increased while interparticle distance decreased particle distance. The research by Beck et al.[89] shows that particle size reduction leads to increased phonon interactions improving nanofluids thermal conductivity. The research conducted by Keblinski et al.[90] demonstrates how nanofluids perform when compared to larger particles. The heat transfer performance reached remarkable enhancement because of the presence of smaller particles when compared to larger particles of nanoparticles smaller than 100 nm. The research by Buongiorno et al.[91] demonstrated that nanoparticles of reduced size provide superior stability to suspensions. The suspension stability increases and thermal conductivity grows leading to better heat transfer performance.

3.6. Shape of nanoparticles

The base fluid interaction characteristics and surface area of nanoparticles change because of their shape. Heat transfer rates depend on the shape of nanoparticles since shape affects their interaction dynamics. Essajai et al.[92] conducted research which indicates the contact surface area of rod-shaped nanoparticles remains larger because these nanoparticles possess an extended aspect ratio. The thermal conductivity of nanofluids becomes greater when using rod-shaped nanoparticles instead of spherical nanoparticles. Because their cylindrical shape enables better alignment and enhanced contact when nanoparticles move through fluid flow which leads to improved heat transmission. Heat transfer occurs better with rods than spheres according to research conducted by Hamid et al.[93].

Sabu et al.[94] Researchers found that thermal conductivity rises higher when using platelet-shaped nanoparticles because they distribute better within fluids while maintaining a greater total surface contact area. Yahyaee et al.[95] Thermal performance gets enhanced through the use of ellipsoidal nanoparticles based on their specific shape. Spherical particles offer greater surface interaction with fluids because of their elongated design. Zahmatkesh et al.[96] reported that nanofluids containing tubular nanoparticles displayed enhanced thermal conductivity and stability, attributing it to the unique surface area and interaction dynamics of tubular shapes.

3.7. Concentration of nanoparticles

The concentration of nanoparticles within the base fluid significantly impacts the thermal conductivity and viscosity of nanofluids. Awais et al.[97] found that increasing the concentration of nanoparticles results in a higher thermal conductivity of the nanofluid, up to an optimal point beyond which the benefits diminish due to increased viscosity and potential aggregation. Ferrouillat et al.[98] observed that a higher concentration of nanoparticles enhances the thermal conductivity but noted a concurrent rise in viscosity, which may adversely affect the convective heat transfer coefficient. Awais et al.[97] demonstrated that while higher nanoparticle concentrations improve thermal properties, the increase in viscosity necessitates careful optimization to avoid reduced fluid flow efficiency. Urmi et al.[99] highlighted that optimal concentrations of nanoparticles maximize heat transfer by balancing enhanced thermal conductivity with manageable viscosity levels. Mintsa et al.[100] showed that moderate concentrations of nanoparticles improve heat transfer efficiency without significantly compromising the flow characteristics of the fluid.

3.8. Temperature effect

The thermal conductivity and viscosity of nanofluids are strongly influenced by temperature, which in turn affects the efficiency of heat transmission. and others. According to Khan et al.[101], the thermal conductivity of the temperature-dependent growth of nanofluids suggests improved heat transfer capacities at higher operating temperatures. According to Duangthongsuk et al.[102], nanofluids perform better in high-temperature applications because their rate of thermal conductivity increase with temperature is larger than that of traditional fluids. Higher temperatures increase thermal conductivity, but they also decrease viscosity, which can promote convective heat transfer even more, as Ilyas et al.[103] showed. According to Zapata et al.[104], careful thermal management is required to maximize nanofluid performance due to the interaction between temperature, viscosity, and thermal conductivity. Chon et al.[71] came to the conclusion that in order to maximize efficiency, heat transfer systems design and operation must take temperature impacts on nanofluid characteristics into account.

3.9. Stability

For nanofluids to have constant thermal characteristics and efficient heat transmission over time, stability is crucial. Stable nanofluids have consistent thermal conductivity and viscosity, which guarantees dependable heat transfer capability, according to Qamar et al.[105].According to Hordy et al. [106], by avoiding sedimentation and aggregation, functionalization processes and surfactants can improve the stability of nanofluids. According to Yasmin et al. [107], stable nanofluids preserve a consistent distribution of nanoparticles, which is essential for effective heat transfer. According to Eastman et al.[108] stable nanofluids maintain excellent thermal properties during extended periods thus qualifying them for prolonged applications them for long-term uses. The stability of nanofluid-based heat transfer devices depends on their formulation for achieving better thermal performance. Stable nanofluids present long-term thermal characteristics that qualify them for extended usage according to Eastman et al.[108]. Numerous factors such as surface modifications together with optimal particle sizing serve as essential stability enhancement techniques according to Jang et al.[109]. Heat transfer capacity improvement of nanofluids requires the use of essential optimization strategies. In conclusion, a number of physical the ability of nanofluids to conduct heat depends directly on their physical attributes. For nanofluid-based, nanofluids require proper design and formulation of heat transfer systems to reach improved thermal performance designed and formulated

Table 2. Various studies on theoretical models for the thermal conductivity of nanofluids

Ref.	Nanofluids Investigated	Theoretical Model	Key equations	Key Findings	Remarks
[91]	Various metaloxide nanofluids	Convectivetransport in nanofluids	-----	Enhanced thermal conductivity due to Brownian motion and thermophoresis	Emphasized the importance of nanoparticle-fluid interactions
[110]	Cu/ethylene glycol, Al2O3/water	EffectiveMedium Theory (EMT)	$K_{eff} = k_f\ (1 + 3\emptyset(\frac{Kn-Kf}{Kp+2Kf}))$	Predicted significant enhancement in thermalconductivity with increasing nanoparticle concentration	Validation with experimental datashowed good agreement
[111]	Al2O3, CuO in water	Effective Medium Approximation (EMA)	$K_{eff}=K_f(\frac{Kp+2Kf+2\emptyset(Kp-Kf)}{Kp+2Kf-\emptyset(Kp-Kf)})$	Model based on particlemotion and interfacial resistance	Highlighted the role ofparticle size and volume fraction
[112]	Cu/water, CuO/water	Nanoparticle aggregation model	---	Accounted for the effect of nanoparticle clusteringon thermal conductivity	Improved accuracy inpredicting thermal conductivity at higherconcentrations
	Theoreticalbasis for composites	Classical mixture theory	$K_{eff}=K_f(\frac{Kp+2Kf+2\emptyset(Kp-Kf)}{Kp+2Kf-\emptyset(Kp-Kf)})$	Provided foundational model for effective thermal conductivity of heterogeneous materials	Often used as a baseline for comparison with nanofluid data
[113]	Various two- phase systems	Empirical correlation	$K_{eff}=K_f\ (\frac{Kp+(n-1)Kf+(n-1)\emptyset(Kp-Kf)}{Kp+(n-1)Kf-\emptyset(Kp-Kf)})$	Introduced shape factor toaccount for non-spherical particles	Model adjustments necessary for nanofluidapplications
[114]	Al2O3, CuO in water	ModifiedMaxwellmodel	$K_{eff} = k_f\ (1 + 3\emptyset\left(\frac{Kp-Kf}{Kp+2Kf-\emptyset(Kp-Kf)}\right) + 2\emptyset(\frac{t_k}{d_p}))$	Incorporated particle sizeand interfacial layer effects	Better agreement with experimental results fornanofluids
[115]	Various metaland oxide nanofluids	Fractaltheory	$K_{eff} = k_f\ (1 + \emptyset {C_f}^{1-df}\left(\frac{K_p}{K_f} - 1\right)$	Modeled thermal conductivity based on fractal dimensions ofaggregates	Addressed the complexity of nanoparticle dispersionstates
[116]	Al2O3/water,SiO2/water	Thermal conductivity and particle shape model	$K_{eff} = k_f\ (1 + \emptyset\left(\frac{Kp-Kf}{Kp+2Kf}\right) f(shape))$	Investigated the effect of particle shape on thermal conductivity enhancement	Showed significantinfluence of aspect ratio on thermalperformance
[117]	Generalreview	Theoretical analysis of mechanisms	---	Discussed variousmechanisms like Brownian motion, interfacial thermal resistance, and clustering	Provided comprehensive understanding of factors influencing thermal conductivity

4. Challenges of hybrid nanofluids in heat exchangers

The innovative heat-transfer fluid known as hybrid nanofluids serves as a promising solution because of its emerging popularity. The combination of nanoparticles creates superior thermal performance in heat exchanger systems. These fluids, which incorporate multiple nanoparticles this introduction of multiple types into a base fluid present the chance for substantial heat transfer enhancements. Researchers continue to show significant interest in these nanofluids since their thermal performance has already been proven. The widespread implementation of enhanced conductors faces various obstacles that prevent broad scalability of their usage in real-world heat exchanger systems.

4.1. Stability and agglomeration

The literature demonstrates that stability issues of hybrid nanofluids continue to appear repeatedly prolonged periods of operation. Numerous researchers [118] have demonstrated that hybrid nanofluids exhibit strong tendencies toward aggregation according to their reports. The sedimentation of nanoparticles inside the fluid together with their agglomeration leads to reduced heat transfer efficiency. Heat exchanger performance suffers as well as operational issues develop from fouling and clogging within its channels.

4.2. Optimal concentration and composition

Research to identify the correct hybrid nanofluid concentration levels along with composition types stands as a major challenge. Research [119] demonstrates the complex mechanisms which multiple nanoparticle types and base fluids interact during use. Achieving the desired balance between thermal conductivity enhancement and fluid stability necessitates meticulous experimentation and thermal modeling requires researchers to analyze size, shape and surface characteristics of hybrid nanofluids.

4.3. Cost and scalability

The economic feasibility and scalability of hybrid nanofluids for industrial-scale heat exchanger. The preparation and synthesis of hybrid nanofluid systems prove complex and expensive to produce. The production of nanofluids requires complex procedures for nanoparticle synthesis as well as dispersion. The successful practice implementation of hybrid nanofluids demands solving their cost and scalability problems in real-world heat exchanger systems [120].

4.4. Corrosion and compatibility

Hybrid nanofluids encounter significant problems because of corrosion and material incompatibility issues which lead to long-lasting performance difficulties. The use of hybrid nanofluids affects the operational lifespan of heat exchangers. Investigations [121] have highlighted the Nanoparticles show the ability to worsen corrosion processes which affect metallic heat exchangers components. Furthermore, the interaction between nanoparticles and heat exchanger materials necessitates through compatibility studies to mitigate potential adverse effects on system integrity.

4.5. Other applications of nanoparticles/nanofluids

Recent advancements in nanotechnology have led to the integration of various nanomaterials and nanofluids into thermal systems to enhance energy efficiency and performance. For instance, **nanocomposite materials** [122] and **SiO_2/TiO_2 coatings** [123] have been employed in **solar cookers** to improve thermal absorption and retention. In the field of alternative fuels, **Mn(II) supramolecular complex nanoparticles** **[124]** have been utilized in **diesel–biodiesel blends**, contributing to improved combustion characteristics and engine performance.

In solar desalination technologies, several innovative enhancements have been reported:

- A **parabolic distiller** integrated with **aluminum oxide (Al_2O_3) nanoparticles** [125] demonstrated improved thermal efficiency.
- **Photovoltaic thermal (PVT) systems** have been enhanced using a variety of nanoparticles [126], improving both electrical and thermal outputs.
- The incorporation of **titanium dioxide (TiO_2) nanoparticles** into the basin water of **solar stills** has shown significant performance gains [127].

Moreover, novel working fluids and heat transfer technologies have been explored:

- **Carbon nanotube (CNT)-based nanofluids** synthesized with **deep eutectic solvents (DES)** [128]have been investigated for their superior thermal conductivity.
- Use of **nanofluids in microchannel heat sinks** [129] and **microplate heat exchangers** [130] has shown promising improvements in compact thermal management systems.
- **Silver nanoparticles and nanofluids** have been tested for **bioactivation in solar stills** [131], enhancing both distillate yield and water quality.

Additional enhancements include:

- **Solar stills** with **nanofluid and dripping arrangements** [132] to optimize evaporation-condensation mechanisms.
- **Stability assessments** of Al_2O_3 nanofluids in aqueous solutions [133], ensuring long-term performance reliability.
- Applications of **hybrid nanofluids** in heat transfer systems [134], combining the thermal advantages of multiple nanoparticle types.
- Studies on the **effect of surfactants** on the **viscosity of graphite-water nanofluids** [135], critical for flow and heat transfer efficiency.

Other notable applications involve:

- **Nanorefrigerants** in domestic **refrigeration systems** [136] for improved COP and energy savings.
- **Al_2O_3/water–ethylene glycol nanocoolants** in **automotive radiators** [137] to boost heat dissipation.
- Integration of **nanodiamonds and various nanoparticles** into solar desalination units [138], and various nanofluids/nanoparticles in the Solar still [140]
- The use of **ultrasonically synthesized MgZnO nanoparticles** [139] for their superior optical and thermal properties.

5. Conclusion

Hybrid nanocomposite creation and utilization shows swift growth in research fields because of significant potential across various industries. The review explores numerous synthesis approaches which influence hybrid nanocomposite development. Al-Zn hybrid nanocomposites demonstrate specific advantages along with specific constraints in addition to multiple other hybrid nanocomposites. MWCNT-HEG, TiO2-CNT, Au-CNT, Graphene-MWCNT, Cu-TiO2, Al2O3-Cu, MWCNT-Fe3O4, Ag-MWNT, and Silica-MWCNT. Hybrid nanocomposites display one-of-a-kind thermal along with electrical and mechanical characteristics. The structural characteristics along with exceptional mechanical properties enable these materials for electronics cooling applications as well as biomedical devices applications. and other advanced technological fields. Despite the promising applications, the synthesis of hybrid nanocomposites encounters barriers connected to scaling production while maintaining stability standards and controlling costs effectively. Researchers need to conduct more studies for optimizing production methods as well as clarifying underpinning synthesis processes. Research needs to establish the fundamental principles which control the improved features exhibited by these materials. Collaborative efforts in material science and the potential of hybrid nanocomposites requires engineering solutions to solve these existing obstacles and reach complete results. New advances are expected through ongoing research in this area. High-performance applications experience significant advancements because of this research which advances innovation as well as efficiency within different domains.

Funding

From Rashtrasant Tukadoji Maharaj Nagpur University , Nagpur Under University Research Project Scheme

Conflict of interest

The authors declare there is no confilt of interest.

Ethical Considerations

Not applicable

References

1. Li, H., Ali, A. B. M., Hussein, R. A., Singh, N. S. S., Abdullaeva, B., Ahmad, Z., Salahshour, S., Baghoolizadeh, M., & Pirmoradian, M. (2025). Prediction of the thermophysical properties of Ag-reduced graphene oxide-water/ethylene-glycol hybrid nanofluids using different machine learning methods. Case Studies in Thermal Engineering, 69, 106038. https://doi.org/10.1016/j.csite.2025.106038
2. M. Bernagozzi, A. Georgoulas, N. Miche, and M. Marengo, "Heat pipes in battery thermal management systems for electric vehicles: A critical review," Appl. Therm. Eng., vol. 219, p. 119495, 2023.
3. B. I. Master, K. S. Chunangad, A. J. Boxma, D. Kral, and P. Stehlik, "Most frequently used heat exchangers from pioneering research to worldwide applications," Heat Transf. Eng., vol. 27, no. 6, pp. 4–11, 2006.
4. K. Azeez, Z. A. Ibrahim, and A. M. Hussein, "Thermal conductivity and viscosity measurement of ZnO nanoparticles dispersing in various base fluids," J. Adv. Res. Fluid Mech. Therm. Sci., vol. 66, no. 2, pp. 1–10, 2020.
5. H. Younes, M. Mao, S. M. S. Murshed, D. Lou, H. Hong, and G. P. Peterson, "Nanofluids: Key parameters to enhance thermal conductivity and its applications," Appl. Therm. Eng., vol. 207, p. 118202, 2022.
6. R. Bhatia, S. Garg, and P. Attrid, "Sol-gel-based synthesis of metal oxide nanoparticles for air and water purification," in Smart Ceramics, Jenny Stanford Publishing, 2018, pp. 275–301.
7. R. Manimaran, K. Palaniradja, N. Alagumurthi, S. Sendhilnathan, and J. Hussain, "Preparation and characterization of copper oxide nanofluid for heat transfer applications," Appl. Nanosci., vol. 4, pp. 163–167, 2014.
8. T. Xing et al., "Ball milling: a green mechanochemical approach for synthesis of nitrogen doped carbon nanoparticles," Nanoscale, vol. 5, no. 17, pp. 7970–7976, 2013.
9. V. Fuskele and R. M. Sarviya, "Recent developments in nanoparticles synthesis, preparation and stability of nanofluids," Mater. Today Proc., vol. 4, no. 2, pp. 4049–4060, 2017.
10. B. Sharma, S. K. Sharma, S. M. Gupta, and A. Kumar, "Modified two-step method to prepare long-term stable CNT nanofluids for heat transfer applications," Arab. J. Sci. Eng., vol. 43, pp. 6155–6163, 2018.
11. M. M. Husein and N. N. Nassar, "Nanoparticle preparation using the single microemulsions scheme," Curr. Nanosci., vol. 4, no. 4, pp. 370–380, 2008.
12. C. T. J. Low, R. G. A. Wills, and F. C. Walsh, "Electrodeposition of composite coatings containing nanoparticles in a metal deposit," Surf. Coatings Technol., vol. 201, no. 1–2, pp. 371– 383, 2006.
13. A. Badawi, M. G. Althobaiti, S. S. Alharthi, A. N. Alharbi, A. A. Alkathiri, and S. E. Alomairy, "Effect of zinc doping on the structure and optical properties of iron oxide nanostructured films prepared by spray pyrolysis technique," Appl. Phys. A, vol. 128, no. 2, p. 123, 2022.
14. S. Wang et al., "Surface functionalization of metal and metal oxide nanoparticles for dispersion and tribological applications-a review," J. Mol. Liq., p. 122821, 2023.
15. Z. Zhang, Y. Wu, Z. Wang, X. Zou, Y. Zhao, and L. Sun, "Fabrication of silver nanoparticles embedded into polyvinyl alcohol (Ag/PVA) composite nanofibrous films through electrospinning for antibacterial and surface-enhanced Raman scattering (SERS) activities," Mater. Sci. Eng. C, vol. 69, pp. 462–469, 2016.

16. J. Li et al., “Precipitation behavior and mechanical properties of Al-Zn-Mg-Cu matrix nanocomposites: Effects of SiC nanoparticles addition and heat treatment,” Mater. Charact., vol. 172, p. 110827, 2021, doi: https://doi.org/10.1016/j.matchar.2020.110827.
17. D. Bokov et al., “Nanomaterial by Sol-Gel Method: Synthesis and Application,” Adv. Mater. Sci. Eng., vol. 2021, p. 5102014, 2021, doi: 10.1155/2021/5102014.
18. D. An et al., “Synthesis of Zn2SnO4 via a co-precipitation method and its gas-sensing property toward ethanol,” Sensors Actuators B Chem., vol. 213, Jul. 2015, doi: 10.1016/j.snb.2015.02.042.
19. S. Jingyu, H. Jianshu, C. Yanxia, and Z. Xiaogang, “Hydrothermal Synthesis of Pt- Ru/MWCNTs and its Electrocatalytic Properties for Oxidation of Methanol,” Int. J. Electrochem. Sci., vol. 2, Jan. 2007.
20. X.-D. Wang, K. Vinodgopal, and G. Dai, “Synthesis of Carbon Nanotubes by Catalytic Chemical Vapor Deposition,” 2019. doi: 10.5772/intechopen.86995.
21. H. Paloniemi et al., “Layer-by-Layer Electrostatic Self-Assembly of Single-Wall Carbon Nanotube Polyelectrolytes,” Langmuir, vol. 22, pp. 74–83, Feb. 2006, doi: 10.1021/la051736i.
22. H. Yang, B. Yang, W. Chen, and J. Yang, “Preparation and Photocatalytic Activities of TiO2- Based Composite Catalysts,” Catalysts, vol. 12, no. 10. 2022. doi: 10.3390/catal12101263.
23. A. S. Ali, A. Mohammed, and H. Saud, “Hydrothermal Synthesis of TiO2 /Al2O3 Nanocomposite and its Application as Improved Sonocatalyst,” Int. J. Eng. Technol., vol. 7, pp. 22–25, Nov. 2018, doi: 10.14419/ijet.v7i4.37.23607.
24. B. Gao, G. Chen, and G. Puma, “Carbon nanotubes/titanium dioxide (CNTs/TiO2) nanocomposites prepared by conventional and novel surfactant wrapping sol–gel methods exhibiting enhanced photocatalytic activity,” Appl. Catal. B Environ., vol. 89, pp. 503–509, Jul. 2009, doi: 10.1016/j.apcatb.2009.01.009.
25. A. Abdulghani and R. Hussain, “Synthesis of Gold Nanoparticles Via Chemical Reduction of Au (III) Ions by Isatin in Aqueous solutions: Ligand Concentrations and pH Effects,” Baghdad Sci. J., vol. 11, pp. 1201–1216, Sep. 2014.
26. S. Shahrokhian and S. Rastgar, “Electrochemical deposition of gold nanoparticles on carbon nanotube coated glassy carbon electrode for the improved sensing of tinidazole,” Electrochim. Acta, vol. 78, pp. 422–429, Feb. 2012, doi: 10.1016/j.electacta.2012.06.035.
27. D. Bogdal, S. Bednarz, and K. Matras-Postołek, “Microwave-Assisted Synthesis of Hybrid Polymer Materials and Composites,” 2014. doi: 10.1007/12_2014_296.
28. M. Salim et al., “Characterization Techniques for Hybrid Nanocomposites Based on Graphene and Nanoparticles,” 2021, pp. 23–69. doi: 10.1007/978-981-33-4988-9_2.
29. J. Zhu et al., “Multifunctional Polyimide/Graphene Oxide Composites via In Situ Polymerization,” J. Appl. Polym. Sci., vol. 131, May 2014, doi: 10.1002/app.40177.
30. S. Pansri and S. Noothongkaew, “MWCNTs/r-GO hybrid films fabricated by layer by layer assembly for supercapacitor electrodes,” J. Energy Storage, vol. 22, pp. 153–156, Apr. 2019, doi: 10.1016/j.est.2019.02.009.
31. R. Nankya and K.-N. Kim, “Sol–Gel Synthesis and Characterization of Cu–TiO2 Nanoparticles with Enhanced Optical and Photocatalytic Properties,” J. Nanosci. Nanotechnol., vol. 16, pp. 11631–11634, Nov. 2016, doi: 10.1166/jnn.2016.13564.
32. L. O. Asmin and L. Isa, “SYNTHESIS AND CHARACTERIZATION OF STRUCTURALNANOCOMPOSITE TITANIUM DIOXIDE COPPER-DOPED USING THE IMPREGNATION METHOD,” Spektra J. Fis. dan Apl., vol. 5, pp. 21–30, Apr. 2020, doi: 10.21009/SPEKTRA.051.03.
33. A. Ayal, A. Hashim, A. Mohammed, A. Farhan, A. M. Holi, and L. ying chin, “Electrochemical Deposition of Cu-Nanoparticle-Loaded CdSe/TiO2 Nanotube Nanostructure as Photoelectrode,” J. Electron. Mater., vol. 50, Jul. 2021, doi: 10.1007/s11664-021-09062-9.
34. D. Ying and D. Zhang, “Processing of Cu–Al 2O 3 metal matrix nanocomposite materials by using high energy ball milling,” Mater. Sci. Eng. A-structural Mater. Prop. Microstruct. Process. - MATER SCI ENG A-STRUCT MATER, vol. 286, pp. 152–156, Jun. 2000, doi: 10.1016/S0921-5093(00)00627-4.
35. S. A. Hassanzadeh-Tabrizi and E. Taheri-Nassaj, “Sol–Gel Synthesis and Characterization of Al2O3–CeO2 Composite Canopowder,” J. Alloy. Compd. - J Alloy. Compd., vol. 494, pp. 289– 294, Apr. 2010, doi: 10.1016/j.jallcom.2010.01.012.
36. P. Shanmugapriya, S. Vijayaraghavan, B. Karthikeyan, and T. Rajamurugan, “Surface modification of nanocomposite Al2O3/Gr/HAP coating for improving wear and corrosion behaviour on Ti–6Al–4V alloy using sol–gel technique,” Multiscale Multidiscip. Model. Exp. Des., vol. 4, pp. 1–11, Sep. 2021, doi: 10.1007/s41939-021-00089-3.
37. Z.-F. Yang, L. Li, C.-T. Hsieh, and R.-S. Juang, “Co-precipitation of magnetic Fe 3 O 4 nanoparticles onto carbon nanotubes for removal of copper ions from aqueous solution,” J. Taiwan Inst. Chem. Eng., vol. 82, Nov. 2017, doi: 10.1016/j.jtice.2017.11.009.
38. W. Quanjie, Y. Wang, B. Duan, and M. Zhang, “Modified Sol-Gel Synthesis of Carbon Nanotubes Supported Titania Composites with Enhanced Visible Light Induced Photocatalytic Activity,” J. Nanomater., vol. 2016, pp. 1–6, Jan. 2016, doi: 10.1155/2016/3967156.

39. Y. Zhang, Z. Wang, Y. Ji, S. Liu, and T. Zhang, “Synthesis of Ag nanoparticle–carbon nanotube–reduced graphene oxide hybrids for highly sensitive non-enzymatic hydrogen peroxide detection,” RSC Adv., vol. 5, Apr. 2015, doi: 10.1039/C5RA04246A.
40. A. Grewal, K. Kumar, S. Redhu, and S. Bhardwaj, “Microwave assisted synthesis: a green chemistry approach,” Int. Res. J. Pharm. Appl. Sci., vol. 3, pp. 278–285, May 2013.
41. R. Winkler, “Developement of an ‘all-in-one’ approach for the synthesis of silica-based hybrid materials,” 2019.
42. D.-H. Nam et al., “High-Temperature Chemical Vapor Deposition for SiC Single Crystal Bulk Growth Using Tetramethylsilane as a Precursor,” Cryst. Growth Des., vol. 14, no. 11, pp. 5569– 5574, Nov. 2014, doi: 10.1021/cg5008186.
43. G. Mariani, R. Schweins, and F. Gröhn, “Electrostatic Self-Assembly of Dendrimer Macroions and Multivalent Dye Counterions: The Role of Solution Ionic Strength,” Macromolecules, vol. 49, no. 22, pp. 8661–8671, Nov. 2016, doi: 10.1021/acs.macromol.6b00565.
44. M. Oraei, H. Mostaan, and Mjij. Rafiei, “The effect of Al2O3 reinforcement particles on the corrosion behavior of Al (Zn) solid solution matrix,” Int. J. Mater. Res., vol. 109, no. 11, pp. 1020–1026, 2018.
45. M. Kirchhoff, U. Specht, and G. Veser, “Engineering high-temperature stable nanocomposite materials,” Nanotechnology, vol. 16, no. 7, p. S401, 2005.
46. Z. Zhang, J. Qin, W. Zhang, Y.-T. Pan, D.-Y. Wang, and R. Yang, “Synthesis of a novel dual layered double hydroxide hybrid nanomaterial and its application in epoxy nanocomposites,” Chem. Eng. J., vol. 381, p. 122777, 2020.
47. V. Mani, S.-M. Chen, and B.-S. Lou, “Three dimensional graphene oxide-carbon nanotubes and graphene-carbon nanotubes hybrids,” Int. J. Electrochem. Sci., vol. 8, no. 10, pp. 11641–11660, 2013.
48. A. Chatterjee and D. Hansora, “Graphene based functional hybrid nanostructures: preparation, properties and applications,” in Materials Science Forum, Trans Tech Publ, 2016, pp. 53–75.
49. K. C. Kemp et al., “Environmental applications using graphene composites: water remediation and gas adsorption,” Nanoscale, vol. 5, no. 8, pp. 3149–3171, 2013.
50. E. R. Morales et al., “Physical properties of the CNT: TiO2 thin films prepared by sol–gel dip coating,” Sol. Energy, vol. 86, no. 4, pp. 1037–1044, 2012.
51. Y. L. Pang, S. Lim, H. C. Ong, and W. T. Chong, “A critical review on the recent progress of synthesizing techniques and fabrication of TiO2-based nanotubes photocatalysts,” Appl. Catal. A Gen., vol. 481, pp. 127–142, 2014.
52. H. Li, L. Sun, and W. Li, “Application of organosilanes in titanium-containing organic– inorganic hybrid coatings,” J. Mater. Sci., vol. 57, no. 29, pp. 13845–13870, 2022.
53. A. Arvinte, I.-A. Crudu, F. Doroftei, D. Timpu, and M. Pinteala, “Electrochemical codeposition of silver-gold nanoparticles on CNT-based electrode and their performance in electrocatalysis of dopamine,” J. Electroanal. Chem., vol. 829, pp. 184–193, 2018.
54. Y.-J. Kim et al., “A seed-mediated growth of gold nanoparticles inside carbon nanotube fibers for fabrication of multifunctional nanohybrid fibers with enhanced mechanical and electrical properties,” Nanoscale, vol. 11, no. 12, pp. 5295–5303, 2019.
55. A. Kumar, Y. Kuang, Z. Liang, and X. Sun, “Microwave chemistry, recent advancements, and eco-friendly microwave-assisted synthesis of nanoarchitectures and their applications: a review,” Mater. Today Nano, vol. 11, p. 100076, 2020.
56. S. Sharma and B. P. Singh, “Mechanical Properties of Graphene–Carbon Nanotube Reinforced Hybrid Polymer Nanocomposites,” 2021.
57. H. J. Salavagione, A. M. Díez-Pascual, E. Lázaro, S. Vera, and M. A. Gómez-Fatou, “Chemical sensors based on polymer composites with carbon nanotubes and graphene: the role of the polymer,” J. Mater. Chem. A, vol. 2, no. 35, pp. 14289–14328, 2014.
58. M. Yang, Y. Hou, and N. A. Kotov, “Graphene-based multilayers: Critical evaluation of materials assembly techniques,” Nano Today, vol. 7, no. 5, pp. 430–447, 2012.
59. A. Rodríguez-Álvarez, S. Silva-Martínez, and C. A. Pineda-Arellano, “Influence of copper and iron transition metals in the photocatalytic activity of titanium dioxide microspheres,” J. Photochem. Photobiol. A Chem., vol. 444, p. 115016, 2023.
60. J. O. Olowoyo, M. Kumar, T. Dash, S. Saran, S. Bhandari, and U. Kumar, “Self-organized copper impregnation and doping in TiO2 with enhanced photocatalytic conversion of H2O and CO2 to fuel,” Int. J. Hydrogen Energy, vol. 43, no. 42, pp. 19468–19480, 2018.
61. K. Liu, Y. Song, and S. Chen, “Defective TiO 2-supported Cu nanoparticles as efficient and stable electrocatalysts for oxygen reduction in alkaline media,” Nanoscale, vol. 7, no. 3, pp. 1224–1232, 2015.
62. F. Shehata, A. Fathy, M. Abdelhameed, and S. F. Moustafa, “Preparation and properties of Al2O3 nanoparticle reinforced copper matrix composites by in situ processing,” Mater. Des., vol. 30, no. 7, pp. 2756–2762, 2009.
63. A. Mitra and G. De, “Sol-gel synthesis of metal nanoparticle incorporated oxide films on glass,” in Glass Nanocomposites, Elsevier, 2016, pp. 145–163.
64. P. Fauchais and A. Vardelle, “Thermal sprayed coatings used against corrosion and corrosive wear,” Adv. plasma spray Appl., vol. 10, p. 34448, 2012.

65. N. M. Malima, S. J. Owonubi, G. B. Shombe, and N. Revaprasadu, “Synthesis of Magnetic Carbon Nanotubes and Their Composites,” in Handbook of Magnetic Hybrid Nanoalloys and their Nanocomposites, Springer, 2022, pp. 233–272.
66. S. Liu, B. Yu, S. Wang, Y. Shen, and H. Cong, “Preparation, surface functionalization and application of Fe3O4 magnetic nanoparticles,” Adv. Colloid Interface Sci., vol. 281, p. 102165, 2020.
67. S. Nezamdoust, D. Seifzadeh, and Z. Rajabalizadeh, “PTMS/OH-MWCNT sol-gel nanocomposite for corrosion protection of magnesium alloy,” Surf. Coatings Technol., vol. 335, pp. 228–240, 2018.
68. F. Lorestani, Z. Shahnavaz, P. Mn, Y. Alias, and N. S. A. Manan, “One-step hydrothermal green synthesis of silver nanoparticle-carbon nanotube reduced-graphene oxide composite and its application as hydrogen peroxide sensor,” Sensors Actuators B Chem., vol. 208, pp. 389–398, 2015.
69. A. Farokhi-Fard, B. Golichenari, M. M. Ghanbarlou, S. Zanganeh, and F. Vaziri, “Electroanalysis of isoniazid and rifampicin: Role of nanomaterial electrode modifiers,” Biosens. Bioelectron., vol. 146, p. 111731, 2019.
70. D. M. Clifford, C. E. Castano, and J. V Rojas, “Supported transition metal nanomaterials: Nanocomposites synthesized by ionizing radiation,” Radiat. Phys. Chem., vol. 132, pp. 52–64, 2017.
71. S. J. Palm, G. Roy, and C. T. Nguyen, “Heat transfer enhancement with the use of nanofluids in radial flow cooling systems considering temperature-dependent properties,” Appl. Therm. Eng. vol. 26, no. 17–18, pp. 2209–2218, 2006.
72. C. Tarcizo da Cruz, A. Brasil, L. O. Ladeira, and M. Houmard, “Influence of the nanostructure of silica supports on the growth and morphology of MWCNTs synthesized by CCVD method,” Ceram. Int., vol. 45, no. 10, pp. 13297–13307, 2019.
73. Z. Yuan, X. Xiao, J. Li, Z. Zhao, D. Yu, and Q. Li, “Self-assembled graphene-based architectures and their applications,” Adv. Sci., vol. 5, no. 2, p. 1700626, 2018.
74. W. T. Urmi, A. S. Shafiqah, M. M. Rahman, K. Kadirgama, and M. A. Maleque, “Preparation methods and challenges of hybrid nanofluids: a review,” J. Adv. Res. Fluid Mech. Therm. Sci., vol. 78, no. 2, pp. 56–66, 2021.
75. M. F. Nabil, W. H. Azmi, K. A. Hamid, N. N. M. Zawawi, G. Priyandoko, and R. Mamat, “Thermo-physical properties of hybrid nanofluids and hybrid nanolubricants: a comprehensive review on performance,” Int. Commun. Heat Mass Transf., vol. 83, pp. 30–39, 2017.
76. S. K. Filippov et al., “Dynamic light scattering and transmission electron microscopy in drug delivery: a roadmap for correct characterization of nanoparticles and interpretation of results,” Mater. Horizons, vol. 10, no. 12, pp. 5354–5370, 2023.
77. D. Toghraie, V. A. Chaharsoghi, and M. Afrand, “Measurement of thermal conductivity of ZnO–TiO 2/EG hybrid nanofluid: effects of temperature and nanoparticles concentration,” J. Therm. Anal. Calorim., vol. 125, pp. 527–535, 2016.
78. M. Tavakoli and M. R. Soufivand, “Performance evaluation criteria and entropy generation of hybrid nanofluid in a shell-and-tube heat exchanger with two different types of cross-sectional baffles,” Eng. Anal. Bound. Elem., vol. 150, pp. 272–284, 2023.
79. R. Mashayekhi, E. Khodabandeh, O. A. Akbari, D. Toghraie, M. Bahiraei, and M. Gholami, “CFD analysis of thermal and hydrodynamic characteristics of hybrid nanofluid in a new designed sinusoidal double-layered microchannel heat sink,” J. Therm. Anal. Calorim., vol. 134, no. 3, pp. 2305–2315, 2018.
80. A. I. Ramadhan, W. H. Azmi, R. Mamat, E. Diniardi, and T. Y. Hendrawati, “Experimental investigation of cooling performance in automotive radiator using Al2O3-TiO2-SiO2 nanofluids,” Automot. Exp., vol. 5, no. 1, pp. 28–39, 2022.
81. J. Qu, R. Zhang, Z. Wang, and Q. Wang, “Photo-thermal conversion properties of hybrid CuO- MWCNT/H2O nanofluids for direct solar thermal energy harvest,” Appl. Therm. Eng., vol. 147, pp. 390–398, 2019.
82. S. Suresh, K. P. Venkitaraj, P. Selvakumar, and M. Chandrasekar, “Effect of Al2O3–Cu/water hybrid nanofluid in heat transfer,” Exp. Therm. Fluid Sci., vol. 38, pp. 54–60, 2012, doi: https://doi.org/10.1016/j.expthermflusci.2011.11.007.
83. H. Yarmand et al., “Graphene nanoplatelets–silver hybrid nanofluids for enhanced heat transfer,” Energy Convers. Manag., vol. 100, Aug. 2015, doi: 10.1016/j.enconman.2015.05.023.
84. D. Madhesh, R. Parameshwaran, and S. Kalaiselvam, “Experimental investigation on convective heat transfer and rheological characteristics of Cu–TiO2 hybrid nanofluids,” Exp. Therm. Fluid Sci., vol. 52, pp. 104–115, 2014.
85. S. Akilu, A. T. Baheta, M. A. M. Said, A. A. Minea, and K. V Sharma, “Properties of glycerol and ethylene glycol mixture based SiO2-CuO/C hybrid nanofluid for enhanced solar energy transport,” Sol. Energy Mater. Sol. Cells, vol. 179, pp. 118–128, 2018.
86. R. S. Kumar, R. Narukulla, and T. Sharma, “Comparative effectiveness of thermal stability and rheological properties of nanofluid of SiO2–TiO2 nanocomposites for oil field applications,” Ind. Eng. Chem. Res., vol. 59, no. 35, pp. 15768–15783, 2020.
87. M. L. G. Ho, C. S. Oon, L.-L. Tan, Y. Wang, and Y. M. Hung, “A review on nanofluids coupled with extended surfaces for heat transfer enhancement,” Results Eng., vol. 17, p. 100957, 2023, doi: https://doi.org/10.1016/j.rineng.2023.100957.
88. R. Azizian, H. Aybar, and T. Okutucu, “Effect of nanoconvection due to Brownian motion on thermal conductivity of nanofluids,” Jan. 2009.

89. M. Beck, Y. Yuan, P. Warrier, and A. Teja, “The effect of particle size on the thermal conductivity of nanofluids,” J. Nanoparticle Res., vol. 11, pp. 1129–1136, Jul. 2008, doi: 10.1007/s11051-008-9500-2.
90. P. Keblinski, J. A. Eastman, and D. G. Cahill, “Nanofluids for thermal transport,” Mater. Today, vol. 8, no. 6, pp. 36–44, 2005, doi: https://doi.org/10.1016/S1369-7021(05)70936-6.
91. J. Buongiorno, “Convective Transport in Nanofluids,” J. Heat Transfer, vol. 128, no. 3, pp. 240– 250, Aug. 2005, doi: 10.1115/1.2150834.
92. R. Essajai, A. Mzerd, N. Hassanain, and M. Qjani, “Thermal conductivity enhancement of nanofluids composed of rod-shaped gold nanoparticles: Insights from molecular dynamics,” J. Mol. Liq., vol. 293, p. 111494, 2019, doi: https://doi.org/10.1016/j.molliq.2019.111494.
93. L. Hamid and H. Zerradi, “The Effect of the Liquid Layer Around the Spherical and Cylindrical Nanoparticles in Enhancing Thermal Conductivity of Nanofluids,” J. Heat Transfer, vol. 141, Dec. 2018, doi: 10.1115/1.4042329.
94. A. S. Sabu, A. Wakif, S. Areekara, A. Mathew, and N. A. Shah, “Significance of nanoparticles’ shape and thermo-hydrodynamic slip constraints on MHD alumina-water nanoliquid flows over a rotating heated disk: The passive control approach,” Int. Commun. Heat Mass Transf., vol. 129, p. 105711, 2021, doi: https://doi.org/10.1016/j.icheatmasstransfer.2021.105711.
95. A. Yahyaee, P. Vatankhah, and H. Sørensen, “Effects of nanoparticle size on surface dynamics and thermal performance in film boiling of Al2O3 water-based nanofluids,” Colloids Surfaces A Physicochem. Eng. Asp., vol. 696, p. 134267, 2024, doi: https://doi.org/10.1016/j.colsurfa.2024.134267.
96. I. Zahmatkesh et al., “Effect of nanoparticle shape on the performance of thermal systems utilizing nanofluids: A critical review,” J. Mol. Liq., vol. 321, p. 114430, Oct. 2020, doi: 10.1016/j.molliq.2020.114430.
97. M. Awais, A. A. Bhuiyan, S. Salehin, M. M. Ehsan, B. Khan, and M. H. Rahman, “Synthesis, heat transport mechanisms and thermophysical properties of nanofluids: A critical overview,” Int. J. Thermofluids, vol. 10, p. 100086, 2021, doi: https://doi.org/10.1016/j.ijft.2021.100086.
98. S. Ferrouillat, A. Bontemps, O. Poncelet, O. Soriano, and J. Gruss, “Influence of nanoparticle shape factor on convective heat transfer and energetic performance of water-based SiO2 and ZnO nanofluids,” Appl. Therm. Eng., vol. 51, pp. 839–851, Mar. 2013, doi: 10.1016/j.applthermaleng.2012.10.020.
99. W. Urmi, P. D. M. M. Rahman, K. Kadirgama, Z. Malek, and W. Safiei, “A Comprehensive Review on Thermal Conductivity and Viscosity of Nanofluids,” J. Adv. Res. Fluid Mech. Therm. Sci., vol. 91, pp. 15–40, Feb. 2022, doi: 10.37934/arfmts.91.2.1540.
100. S. Sadripour and A. J. Chamkha, “The effect of nanoparticle morphology on heat transfer and entropy generation of supported nanofluids in a heat sink solar collector,” Therm. Sci. Eng. Prog., vol. 9, pp. 266–280, 2019, doi: https://doi.org/10.1016/j.tsep.2018.12.002.
101. ,J. P. Abraham, J. M. Gorman, and W. J. B. T.-A. in H. T. Minkowycz, Eds., Elsevier, 2024, pp. 101–128. doi: https://doi.org/10.1016/bs.aiht.2024.05.001.
102. W. Duangthongsuk and S. Wongwises, “Measurement of temperature-dependent thermal conductivity and viscosity of TiO2-water nanofluids,” Exp. Therm. Fluid Sci., vol. 33, no. 4, pp. 706–714, 2009, doi: https://doi.org/10.1016/j.expthermflusci.2009.01.005.
103. E. Abu-Nada, “Effects of variable viscosity and thermal conductivity of Al2O3–water nanofluid on heat transfer enhancement in natural convection,” Int. J. Heat Fluid Flow, vol. 30, no. 4, pp. 679–690, 2009.
104. S. K. Pathak, R. Kumar, V. Goel, A. K. Pandey, and V. V Tyagi, “Recent advancements in thermal performance of nano-fluids charged heat pipes used for thermal management applications: A comprehensive review,” Appl. Therm. Eng., vol. 216, p. 119023, 2022.
105. S. U. Ilyas, R. Pendyala, M. Narahari, and L. Susin, “Stability, rheology and thermal analysis of functionalized alumina-thermal oil-based nanofluids for advanced cooling systems,” Energy Convers. Manag., vol. 142, pp. 215–229, 2017.
106. C. Zapata-Hernandez, G. Durango-Giraldo, D. López, R. Buitrago-Sierra, and K. Cacua, “Surfactants versus surface functionalization to improve the stability of graphene nanofluids,” J. Dispers. Sci. Technol., vol. 43, no. 11, pp. 1717–1724, 2022.
107. A. Qamar et al., “Preparation and dispersion stability of aqueous metal oxide nanofluids for potential heat transfer applications: a review of experimental studies,” J. Therm. Anal. Calorim., pp. 1–24, 2020.
108. N. Hordy, D. Rabilloud, J.-L. Meunier, and S. Coulombe, “High temperature and long-term stability of carbon nanotube nanofluids for direct absorption solar thermal collectors,” Sol.Energy, vol. 105, pp. 82–90, 2014.
109. H. Yasmin, S. O. Giwa, S. Noor, and H. Ş. Aybar, “Influence of preparation characteristics on stability, properties, and performance of mono-and hybrid nanofluids: Current and future perspective,” Machines, vol. 11, no. 1, p. 112, 2023.
110. J. A. Eastman, S. U. S. Choi, S. Li, W. Yu, and L. J. Thompson, “Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles,” Appl. Phys. Lett., vol. 78, no. 6, pp. 718–720, Feb. 2001, doi: 10.1063/1.1341218.
111. S. P. Jang and S. U. S. Choi, “Role of Brownian motion in the enhanced thermal conductivity of nanofluids,” Appl. Phys. Lett., vol. 84, no. 21, pp. 4316–4318, May 2004, doi: 10.1063/1.1756684.
112. Y. Xuan and Q. Li, “Investigation on Convective Heat Transfer and Flow Features of Nanofluids,” J. Heat Transf. Asme - J HEAT Transf., vol. 125, Feb. 2003, doi: 10.1115/1.1532008.

113. R. L. Hamilton and O. K. Crosser, “Thermal Conductivity of Heterogeneous Two-Component Systems,” Ind. Eng. Chem. Fundam., vol. 1, no. 3, pp. 187–191, Aug. 1962, doi: 10.1021/i160003a005.
114. W. Yu and S. U. S. Choi, “The Role of Interfacial Layers in the Enhanced Thermal Conductivity of Nanofluids: A Renovated Maxwell Model,” J. Nanoparticle Res., vol. 5, no. 1, pp. 167–171, 2003, doi: 10.1023/A:1024438603801.
115. X.-Q. Wang and A. S. Mujumdar, “A review on nanofluids - part I: theoretical and numerical investigations,” Brazilian Journal of Chemical Engineering, vol. 25. scielo , 2008.
116. E. Timofeeva, J. Routbort, and D. Singh, “Particle shape effect on thermophysical properties of alumina nanofluids,” J. Appl. Phys., vol. 106, p. 14304, Aug. 2009, doi: 10.1063/1.3155999.
117. P. Keblinski, S. R. Phillpot, S. U. S. Choi, and J. A. Eastman, “Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids),” Int. J. Heat Mass Transf., vol. 45, no. 4, pp. 855–863, 2002, doi: https://doi.org/10.1016/S0017-9310(01)00175-2.
118. E. Ponticorvo, M. Iuliano, C. Cirillo, A. Maiorino, C. Aprea, and M. Sarno, “Fouling behavior and dispersion stability of nanoparticle-based refrigeration fluid,” Energies, vol. 15, no. 9, p. 3059, 2022.
119. J. Forth, P. Y. Kim, G. Xie, X. Liu, B. A. Helms, and T. P. Russell, “Building reconfigurable devices using complex liquid–fluid interfaces,” Adv. Mater., vol. 31, no. 18, p. 1806370, 2019.
120. A. Ibrahim, H. Peng, A. Riaz, M. A. Basit, U. Rashid, and A. Basit, “Molten salts in the light of corrosion mitigation strategies and embedded with nanoparticles to enhance the thermophysical properties for CSP plants,” Sol. Energy Mater. Sol. Cells, vol. 219, p. 110768, 2021.
121. Z. Zahra, Z. Habib, S. Hyun, and M. Sajid, “Nanowaste: Another future waste, its sources, release mechanism, and removal strategies in the environment,” Sustainability, vol. 14, no. 4, p.2041,2022.
122. Palanikumar, G., Shanmugan, S., Chithambaram, V., Gorjian, S., Pruncu, C. I., Essa, F. A., Kabeel, A. E., Panchal, H., Janarthanan, B., Ebadi, H., Elsheikh, A. H., & Selvaraj, P. (2021). Thermal investigation of a solar box-type cooker with nanocomposite phase change materials using flexible thermography. Renewable Energy, 178, 260–282. https://doi.org/10.1016/j.renene.2021.06.022
123. Thamizharasu, P., Shanmugan, S., Gorjian, S. et al. Improvement of Thermal Performance of a Solar Box Type Cooker Using SiO2/TiO2 Nanolayer. Silicon 14, 557–565 (2022). https://doi.org/10.1007/s12633-020-00835-1
124. Elkelawy, M., Etaiw, S. E. H., Bastawissi, H. A. E., Marie, H., Elbanna, A., Panchal, H., Sadasivuni, K., & Bhargav, H. (2020). Study of diesel-biodiesel blends combustion and emission characteristics in a CI engine by adding nanoparticles of Mn (II) supramolecular complex. Atmospheric Pollution Research, 11(1), 117–128. https://doi.org/10.1016/j.apr.2019.09.021
125. Saleh, B., Essa, F.A., Aly, A. et al. Investigating the performance of dish solar distiller with phase change material mixed with Al2O3 nanoparticles under different water depths. Environ Sci Pollut Res 29, 28115–28126 (2022). https://doi.org/10.1007/s11356-021-18295-4
126. M. Vaka, R. Walvekar, A. K. Rasheed, M. Khalid and H. Panchal, "A Review: Emphasizing the Nanofluids Use in PV/T Systems," in IEEE Access, vol. 8, pp. 58227-58249, 2020, doi: 10.1109/ACCESS.2019.2950384.
127. Parikh, R., Patdiwala, U., Parikh, S., Panchal, H., & Sadasivuni, K. K. (2021). Performance enhancement using TiO2 nano particles in solar still at variable water depth. International Journal of Ambient Energy, 43(1), 4037–4044. https://doi.org/10.1080/01430750.2021.1873853
128. Walvekar, R., Chen, Y. Y., Saputra, R., Khalid, M., Panchal, H., Chandran, D., Mubarak, N. M., & Sadasivuni, K. K. (2021). Deep eutectic solvents-based CNT nanofluid – A potential alternative to conventional heat transfer fluids. Journal of the Taiwan Institute of Chemical Engineers, 128, 314–326. https://doi.org/10.1016/j.jtice.2021.06.017
129. Thakre, Shekhar, Pandhare, Amar, Malwe, Prateek D., Gupta, Naveen, Kothare, Chandrakant, Magade, Pramod B., Patel, Anand, Meena, Radhey Shyam, Veza, Ibham, Natrayan L., and Panchal, Hitesh. "Heat transfer and pressure drop analysis of a microchannel heat sink using nanofluids for energy applications" Kerntechnik, vol. 88, no. 5, 2023, pp. 543-555. https://doi.org/10.1515/kern-2023-0034
130. Dharmakkan, N., Srinivasan, P. M., Muthusamy, S., Jomde, A., Shamkuwar, S., Sonawane, C., Sharma, K., Alrubaie, A. J., El Shafay, A. S., & Panchal, H. (2023). A case study on analyzing the performance of microplate heat exchanger using nanofluids at different flow rates and temperatures. Case Studies in Thermal Engineering, 44, 102805. https://doi.org/10.1016/j.csite.2023.102805
131. Kumar, R., Chanda, J., Elsheikh, A. H., Ongar, B., Khidolda, Y., PraveenKumar, S., Panchal, H., & Shanmugan, S. (2023). Performance improvement of single and double effect solar stills with silver balls/nanofluids for bioactivation: An experimental analysis. Solar Energy, 259, 452–463. https://doi.org/10.1016/j.solener.2023.05.012
132. Panchal, H., & Sadasivuni, K. K. (2020). Experimental investigation on solar still with nanomaterial and dripping arrangement. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 47(1), 1886–1896. https://doi.org/10.1080/15567036.2020.1834647
133. Mehta, B., Subhedar, D., Panchal, H., & Sadasivuni, K. K. (2023). Stability and thermophysical properties enhancement of Al_2O_3–water nanofluid using cationic CTAB surfactant. International Journal of Thermofluids, 20, 100410. https://doi.org/10.1016/j.ijft.2023.100410

134. Vidhya, R., Balakrishnan, T., Kumar, B. Suresh, Palanisamy, R., Panchal, Hitesh, Angulo-Cabanillas, Luis, Shaik, Saboor, Saleh, B., Alarifi, Ibrahim M., An Experimental Study of ZrO2-CeO2 Hybrid Nanofluid and Response Surface Methodology for the Prediction of Heat Transfer Performance: The New Correlations, Journal of Nanomaterials, 2022, 6596028, 11 pages, 2022. https://doi.org/10.1155/2022/6596028
135. Yalçın, G., Huminic, G., Huminic, A., Panchal, H., & Dalkılıç, A. S. (2024). Investigation on the effect of surfactants on the viscosity of graphite–water-based nanofluids. Journal of Molecular Liquids, 398, 124197. https://doi.org/10.1016/j.molliq.2024.124197
136. Pipwala, H., Kapadia, R., Panchal, H., Singh, B., Malwe, P. D., Kumar, A., Makki, E., & Giri, J. (2024). Performance investigation of a direct-cooled refrigerator with CuO-R600a as a nanorefrigerant. Case Studies in Chemical and Environmental Engineering, 9, 100569. https://doi.org/10.1016/j.cscee.2023.100569
137. Subhedar DG, Ramani BM, Chauhan KV, et al. Experimental study on the variation of car radiator frontal area using Al2O3/water-ethylene glycol nano coolant. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. 2023;238(4):1800-1808. doi:10.1177/09544089231159994
138. Vijay Kishorbhai Mehta, Hitesh Panchal, Bharat Singh, Laveet Kumar, Revolutionizing solar water distillation: maximizing efficiency with pyramid solar stills enhanced by fins, evacuated tubes, nanomaterial, and phase change materials—a comprehensive review, International Journal of Low-Carbon Technologies, Volume 19, 2024, Pages 1996–2009, https://doi.org/10.1093/ijlct/ctae116
139. Alqsair, U. F., Abdullah, A. S., El-Shafay, A. S., & Panchal, H. (2023). Optimization and numerical study of the effect of using nanodiamond and nickel nanoparticles in solar desalination using two-phase mixture method and VOF. Engineering Analysis with Boundary Elements, 155, 432–439. https://doi.org/10.1016/j.enganabound.2023.06.036
140. Pandiyaraj, S., Murali, M., Muthusamy, S., & Panchal, H. (2023). Ultrasonically synthesized MgZnO nanoparticles for enhanced piezo-photocatalysis and MgZnO/p-Si heterojunction diode characteristics. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 45(1), 762–776. https://doi.org/10.1080/15567036.2023.2172483