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Review article

Nano-coolants for thermal enhancement in heat exchangers: A review of prospects, challenges and applications

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A R T I C L E I N F O

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A B S T R A C T

The demand for efficient thermal systems has driven significant interest in nano-coolants due to their superior thermal properties as alternatives to traditional coolants like water, ethylene glycol (EG), synthetic oils (poly-alphaolefins), and refrigerants (R134a, R410A). These coolants face operational and environmental challenges, including low heat transfer capacity, corrosion, toxicity and ecological effects that limit their efficiency under ideal conditions because of their poor thermophysical properties, which hinder their deployment. This review provides a comprehensive analysis of the prospects, challenges and applications of nano-coolants in various heat exchanger systems. Nanoparticles such as Al_2O_3, ZnO, Fe_3O_4, SiO_2 and CNTs are evaluated for their ability to enhance thermal conductivity, stability and heat transfer performance, with key factors influencing thermal enhancement, including size, shape, concentration and preparation methods, being critically examined. The study highlights applications across different heat exchanger configurations, including shell and tube, plate, double pipe, microchannel and spiral heat exchangers, which are evaluated through experimental and numerical results. Performance metrics such as Nusselt number, Reynolds number, heat transfer coefficient and overall heat transfer coefficient are discussed. In addition, the review addresses technical challenges, including agglomeration sedimentation, toxicity, increased viscosity and environmental impact, hindering widespread adoption. Furthermore, it outlines emerging prospects, including life cycle assessment, integration with renewablelar energy and the use of artificial intelligence and machine learning for predictive modeling and optimization, offering sustainable pathways for deployment and system miniaturization. The review demonstrates that, despite challenges, nano-coolants can effectively and efficiently enhance thermal exchange, impacting heat exchanger designs across various industries.

1. Introduction

Effective heat transfer is crucial across various applications in the thermal industry, as systems require efficient thermal management to ensure optimal process control and maintain adequate thermal exchange [1]. The growing energy demand in the thermal industry calls for efficient, miniaturized heating systems that minimize energy loss, making conventional cooling methods increasingly inadequate. Coolants are instrumental in reducing heat in chemical and power processes in power plants that experience high energy dissipation [2]. Cooling fluids are crucial for temperature control, as they absorb and transfer heat from a hotter to a cooler location. This ensures safety and longevity while preventing overheating and improving system efficiency [3]. Depending on the application, selecting coolants in thermal systems is crucial because money and space are limited resources [4]. As thermal systems grow in complexity, selecting efficient coolants becomes critical to achieving energy savings [3]. The nature of the working fluid affects

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Nomenclature

NP	nanoparticle
EG	ethylene glycol
ANN	artificial neural network
AI	artificial intelligence
ANFIS	adaptive Neuro-Fuzzy Inference System
FEA	finite Element Analysis
LCA	life cycle assessment
F(z)	activation function
w_i	weight
w_o	bias
x_i	neuron
MSE	mean square error
CFD	computational fluid dynamics
CNT	carbon nanotubes
GNP	graphene nanoparticle
MWCNTS	multi-walled carbon nanotubes
SHTE	shell and tune heat exchanger
PHE	plate heat exchanger
MCHE	microchannel heat exchanger
PVT	photovoltaic thermal
K	thermal conductivity ($W/m^{-1}K$)
Nu	Nusselt number
Re	Reynolds number
LMTD	logarithmic Mean Temperature Difference (K)
ΔP	pressure drop (Pas)
U	universal heat transfer coefficient ($W/m^{-2}K$)
h	convective heat transfer coefficient ($W/m^{-2}K$)
ε	effectiveness

Abbreviations and Terms

REACH	Registration, Evaluation, Authorization and Restriction of Chemicals (EU regulation)
TSCA	Toxic Substances Control Act (USA)
OSHA	Occupational Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
SDS	sodium dodecyl sulfate (common surfactant)
GA	gum arabic (stabilizer/surfactant)
PVP	polyvinylpyrrolidone (surfactant/polymer)

how well heating systems perform, which is a vital function in heat exchangers. To ensure high thermal exchange, it is necessary to develop appropriate coolants. Commercially available coolants, such as water, ethylene glycol (EG), propylene glycol (PG), and synthetic oils like polyalphaolefins (PAO) and refrigerants (R134a, R410a), differ from each other. The distinction is determined by heat dissipation capacity, environment, and operational challenges, such as low heat transfer capacity, corrosion, toxicity, and ecological effects. These limit their usefulness as coolants when used under ideal conditions.

Water is a common coolant, is ubiquitous, and can efficiently absorb and discharge heat despite its low thermal conductivity. Its viscosity allows for easy and quick transfer, which enables its adoption as a process fluid in radiators and condensers. However, its low viscosity and thermal conductivity (0.064 W/m. K) lead to ineffective heat exchange compared to other coolants. In addition, it also has a high susceptibility to corroding metal surfaces and freezing at low temperatures, creating fears among energy experts about its use [5]. Ethylene glycol (EG), another commonly used coolant with a high boiling point and solvent compatibility, is widely employed in refrigeration and automobile antifreeze [6]. Alongside other variants such as propylene glycol (PEG) and diethylene glycol (DEG), EG has disadvantages such as low heat capacity compared to water, thus decreasing the performance of systems when utilized. It also has significant health risks, leading to its discontinuation in heating, ventilation, and air conditioning (HVAC) systems.

Air is also used as a coolant in cooling towers to cool hot fluids. Its availability, non-corrosive nature, and light weight make it a popular choice for systems that value simplicity and reliability, such as air-cooled engines. However, it has a limited application range due to its low heat capacity and the noise generated by forced-air systems [6]. Oil-based coolants such as mineral or synthetic oils, like polyalphaolefins (PAO), are favored by hydraulic systems and power transformers, because they are non-corrosive and have high boiling points, which are useful in extreme weather [7]. However, oil-based coolants face drawbacks such as seal contraction, flammability risk, incompatibility with other fluids, and high viscosity under extreme conditions. The high viscosity property of this coolant can also lead to pumping challenges in extreme weather conditions [8]. The use of refrigerants, including CFCs and HCFCs, in closed-loop air conditioning is frequent because they efficiently heat and cool during the evaporation and condensation cycles. However, there are environmental concerns regarding the use of these refrigerants, such as ozone depletion potential (ODP) and global warming potential (GWP). The presence of chlorine and fluorine atoms in these emitted halocarbon refrigerants depletes the ozone layer and causes degradation of the climate [9].

"Nano-coolants enhance thermal performance due to the intrinsic properties of nanoparticles, such as high thermal conductivity, surface activity, and tunable behavior [5]. Stability, a key requirement for sustained heat transfer performance, is often achieved through mechanisms such as thermophoresis and diffusiophoresis, aided by surfactants like gum Arabic (GA), sodium dodecyl sulfate (SDS), and polyvinyl pyrrolidone (PVP), which mitigate Van der Waals attraction, particularly for hydrophobic particles like graphene [5,6]. A stable nanofluid is generally characterized by a dominant electrostatic double-layer repulsive force (EDLRF) that counters aggregation forces [11].

Nano-coolants formed by dispersing nanoparticles (NPs) in base fluids significantly improve optimization potential in industrial applications, helping reduce energy consumption and operational costs [6], [12]. Their thermal behaviour also lends itself well to computational modelling using tools such as ANSYS Fluent, OpenFOAM, and COMSOL Multiphysics [13]. According to Singh *et al.* [14] and Gupta *et al.* [15], incorporating high-conductivity NPs into base fluids like water or EG leads to improved heat exchanger performance. This enhancement supports the development of more compact and efficient configurations, particularly in shell-and-tube heat exchangers (SHTE), where Brownian motion and micro-convection effects are beneficial at higher particle loadings [16].

In addition, recent studies have introduced hybrid nano-coolants, which combine multiple types of NPs to capitalize on synergistic effects that enhance thermal conductivity, stability, and tunability [17]. These formulations often outperform single-nanoparticle systems, offering further improvements in thermophysical performance.

Nonetheless, practical implementation is challenged by issues such as increased viscosity at higher nanoparticle concentrations leads to elevated pumping power requirements [18]. Agglomeration and sedimentation, especially in hybrid systems, can compromise long-term performance [19]. Environmental and health concerns linked to nanoparticles such as silver, TiO_2, and ZnO further limit industrial scalability [20]. Moving forward, efforts must focus on optimizing nanoparticle structure, improving dispersion techniques [21] and minimizing environmental impacts to enable broader application [22].

1.1. Impacts of nanoparticles in heat transfer enhancement

Nanoparticles are particularly effective at enhancing fluid thermal properties due to mechanisms such as:

- Brownian motion, which induces micro-convection and increases thermal conductivity [23]
- Thermophoresis and diffusiophoresis, which promote particle migration in temperature and concentration gradients, aiding thermal energy dispersion [24]
- High surface area-to-volume ratios, which increase heat transfer and surface contact between fluid and pipe walls [25]

The thermal conductivity of base fluids can improve significantly with just 0.1–0.5 wt% NP concentration, as nano-coolants tend to exhibit Newtonian behaviour at low concentrations, allowing predictable flow regimes under varying conditions [26]. Composite or hybrid nano-coolants, which combine two or more types of nanoparticles (Al_2O_3-CuO or CNT-TiO_2), provide better thermal performance together than they would separately. These combinations optimize multiple properties, such as viscosity, thermal conductivity, and stability, better than single-particle dispersions [23].

1.2. Justification for this review

Over the last two decades, nano-coolants have witnessed an exponential increase in research, as shown in Fig. 1. A Scopus search using keywords such as "nano-coolants," "nanofluids," and "thermal conductivity enhancement" reveals a steep rise in published articles, particularly after 2019. This trend underscores both the academic and industrial interest in nanoparticle-based thermal management solutions.

Table 1 summarizes recent review articles (within the last five years) focusing on nano-coolants in heat exchangers. It highlights primary contributions and key limitations in the context of this review. While the reviews contribute meaningfully to their respective focus areas, several critical research gaps remain that this review uniquely addresses, such as regulations and standardization challenges, the integration of AI and optimization prospects, industrial relevance and scalability challenges. This review aims to bridge these gaps by synthesizing recent developments, identifying unresolved challenges, and proposing future research directions that support the suitability and effective deployment of nano-coolants in heat exchangers.

By integrating technical, environmental, and computational perspectives, this review aspires to serve as a reference for both academic researchers and industrial practitioners seeking to deploy nano-coolants in next-generation thermal management systems.

1.3. Scope and structure of this review

The paper is structured as follows: Section 1 introduces nano-coolants and reviews related literature from the past five years, highlighting how this work is differentiated. Section 2 presents strategies for heat transfer analysis. Section 3 covers nanoparticle synthesis, characterization, and stability techniques. Section 4 analyzes thermophysical properties and nano-coolant performance in various heat exchangers. Section 5 evaluates environmental and economic implications. Section 6 explores optimization approaches using artificial intelligence. Section 7 outlines future research directions, while Section 8 concludes the review.

2. Nano-coolants in heat exchangers

Heat exchangers are mechanical systems designed to facilitate heat transfer between two or more fluids [49]. One of the key advantages is that it ensures a significant temperature difference between the interacting fluids [38]. Understanding the heat transfer dynamics is crucial for the operation of heating and cooling systems [39]. Optimum utilization of heat exchangers is influenced by the type and composition of the transport fluid used in the structural design [40]. Research has shown that heat exchangers can be designed and operated for a reasonable cost by lowering the thermal resistance of the separating layers, increasing the heating area, or substituting an engineered fluid as the thermal transport fluid. The optimal path is to substitute engineered fluid, as demonstrated by several studies [41]. This is achieved by creating nano-coolant, which is a mixture of nanoscale particles dissolved in base fluids [34]. The study conducted by Gupta *et al.* [15] found that NPs possessing superior thermophysical properties to water can significantly enhance heat transfer rates. The authors demonstrated experimentally that adding NPs to a system improves its thermal efficiency.

Base fluids that are frequently used include oils, ethylene glycol (EG) and water [42]. Numerous investigations, such as Tahmasebiboldaj *et al.* [36]; Zolfalizadeh et al.[43]; Godasiaei et al. [44], demonstrated that nano-coolants possess strong thermal characteristics when dispersed in base fluids, which enable them to facilitate greater heat exchange in comparison to traditional working fluids. Multi-walled carbon nanotubes (MWCNTS) and graphene, which are believed to be markers of nanotechnology in thermal operations due to their highly effective thermal conductivity, were found to perform better than other nanoparticle [37]. Their utilization has been found to provide good

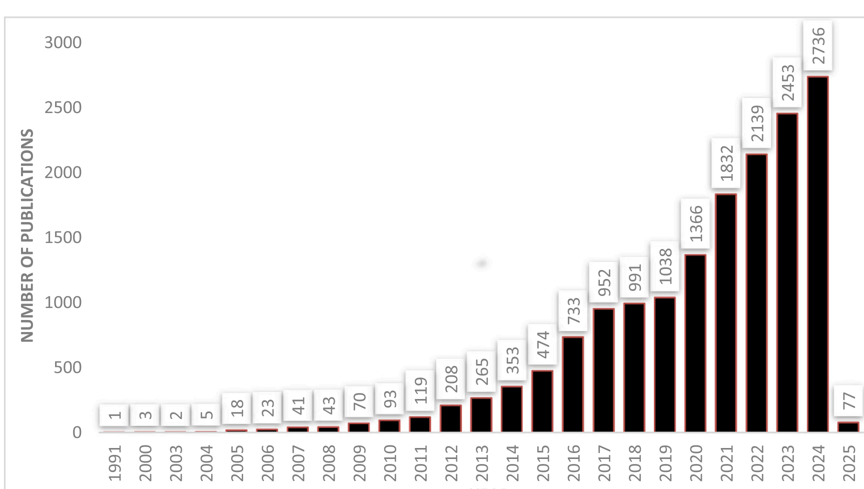

Fig. 1. Number of publications related to nano-coolants for heat transfer applications.

Table 1
Summary of recent review articles on nano-coolants in heat exchangers.

Ref.	Tittle	Nano-coolants	Focus	Key Novelty	Identified Limitations
[27] Mirahmad et al. (2025)	Beyond Thermal Conductivity: A Review of Nanofluids for Enhanced Energy Storage and Heat Transfer	Various types	To review the impacts of nanoparticles in heat transfer using mono and hybrid nano-coolants.	'Present Strategies to optimize nano-coolant formulations utilizing solid–solid phase transitions.	Broad focus with less discussion on the integration of sustainability and future directions
[28] Atofarati et al. (2024)	Nanofluids for heat transfer enhancement: a holistic analysis of research advances, technological progress and regulations for health and safety	Various types	To review thermal capacity improvements using nanofluids	To review the discussion on regulatory frameworks in nano-coolant applications.	Focuses on computational work; lacks experimental insights
[29] Huminic et al. (2024)	Application of nanofluids in heat exchangers - A state-of-the-art review	Various types	To review thermal enhancements in various types of heat exchangers	Detailed discussion on numerical methods and characterization techniques.	Limited applicability to other sectors and no discussion on environmental regulations
[30] Rehman and Park (2024)	Advances in nanofluids for tubular heat exchangers: Thermal performance, environmental effects, economics and outlook	Hybrid	To review the potential of nano-coolants in tubular heat exchangers	Detailed discussion on how turbulent flow impacts thermal exchange in a finned tube heat exchanger	Wide focus with little information on sustainability integration
[31] Tao et al. (2023)	A Review of Nanofluids as Coolants for Thermal Management Systems.	Various types	to review the potential of nanofluids as coolants in the thermal management systems of fuel cell vehicles, specifically emphasizing their heat transfer enhancement capabilities	Comprehensive review of nanofluids. It uniquely emphasizes the challenges associated with nanofluid application in heating systems.	Despite recognizing stability issues as a major obstacle, it lacks a comprehensive understanding of the influencing factors, such as temperature, pH, particle size, and concentration
[32] Ho et al. (2023)	A review on nanofluids coupled with extended surfaces for heat transfer enhancement	Various types	Review and analyse the combined effects of nanofluids and extended surfaces (fins) for heat transfer enhancement.	investigates the use of nanofluids and extended surfaces, which are rarely employed together, to achieve enhanced heat transfer performance.	Wide scope but minimal discussion on heat exchangers
[25] Baig et al. (2021)	A review of synthesis methods, properties, recent progress, and challenges	Al_2O_3/water	To review synthesis methods and discussion on advancements, and challenges	It emphasizes the future potential of nanotechnology in addressing modern challenges and advancing technology	Lacks discussion on standardization and industrial scalability
[33] Alami et al. (2023)	A critical insight on nanofluids for heat transfer enhancement.	Various types	To review the potential of thermal enhancer flids in heat exchangers	Detailed discussion on the Challenges and limitations of nanofluids.	Lacks integration of sustainability, optimization, and future directions.
[34] Ajeeb and Murshed (2022)	Nanofluids in compact heat exchangers for thermal applications: A State-of-the-art review	MWCNTs, Al_2O_3	To review the heat transfer of nanofluids in compact heat exchangers under different operation conditions	Present numerical and experimental studies using mono and hybrid nano-coolants	Lacks discussion on standardization and industrial scalability
[11] Huq et al. (2022)	Review on aqueous graphene nanoplatelet Nanofluids: Preparation, Stability, thermophysical Properties, and applications in heat exchangers and solar thermal collectors	Graphene/ water	To review thermal improvements using graphene nano-coolant in a shell and tube heat exchanger.	Demonstrates that smaller particle size aids stability by comparing several studies.	Lacks integration of sustainability, optimization, and future directions
[2] Ali and Salam (2020)	A review on nanofluid: preparation, stability, thermophysical properties, heat transfer characteristics and application	Various nano-coolants and base fluids	To present a comprehensive synthesis of techniques and characterization methods	Detailed numerical method of thermal evaluations using various nano-coolant models.	Focuses on computational work; lacks experimental insights. Lacks discussion on standardization and industrial scalability.

mechanical properties while maintaining high thermal conductivity [45].

The potential of using nano-coolants in heat exchangers is massive, as the demand for efficient, miniaturized, compact, and environmentally benign cooling fluids has soared across various industries. The advantages of nano-coolants are inexhaustible and include enhanced thermal conductivity and heat transfer rates, resulting in faster cooling with less fluid and energy consumption [20]. Nano-coolants permit the compact design of heat exchangers, which translates to lightweight, which is particularly beneficial to industries where space and weight are critical factors, such as automobiles and aerospace. Nano-coolants' tailor-specific ability makes them suitable for a variety of heat exchanger applications, including electronics cooling, semiconductor fabrication, and renewable energy. The efficiency of nano-coolants can reduce operational expenses by operating at a high convective heat transfer rate, which results in a reduction in energy inputs [46]. Nano-coolants can promote nanotechnology research by addressing particle solubility and agglomeration challenges, thereby producing cost-effective fluids that increase commercialization viability. Thus, ongoing studies present the potential to redefine thermal management solutions, leading to more efficient and sustainable designs [47]. This paper provides an in-depth review of how to thermally augment heat exchangers with nano-coolants.

2.1. Strategies for heat transfer estimation in heat exchangers

Several strategies and methods have been employed to measure heat transfer and optimize heat exchangers. Many researchers have utilized computational fluid dynamics (CFD) tools like ANSYS Fluent, COSMOL and OpenFOAM [5] to predict nanofluid behaviour in heat exchangers through numerical analysis. This considers the thermal properties of base fluid and NPs. These tools are commonly employed in both academia and industry to simulate flow and heat transfer. The intuitiveness and user-friendly graphics of the tools make it easier to set up, run and analyze simulations at a fast rate. This makes it accessible to users with limited programming experience as the tools are equipped with robust physical models for laminar, turbulent, multiphase flows and chemical reactions, making them versatile for different applications [13]. Apart from the high licensing cost of ANSYS , OpenFOAM is an open source tool and both tools are compatible with other simulation tools like SolidWorks [48]. CFD can achieve high accuracy, especially when grid resolutions with fine and appropriate boundary resolutions are set. The high dependence on grid refinement (mesh) and explicit boundary conditions makes this method less appealing for complex and chaotic flows [49].

Finite element analysis (FEA) is another technique used to solve complex heat transfer problems by breaking complex geometries down into smaller, compatible finite elements. This technique is suitable for solid mechanics and structural thermal analysis, as well as multi-layered systems where versatility is critical in handling irregular shapes and material properties [50]. The Monte Carlo method is a method similar to this, in which probabilities are used to predict the possible outcomes in complex geometries. It requires repeating an experiment several times and generates a large amount of randomized data that allows transformation using probabilities of single-point outcomes [49]. This technique is particularly suitable for irregular surfaces. The finite volume method (FVM) is another method that uses partial differential equations (PDEs) as an algebraic volume integral of PDEs to model fluid flow and heat transfer problems using conservation governing equations. Convergence terms in volume integrals are transformed into surface integrals using the divergence theorem [51]. Just like in Monte Carlo, this technique is used for complex geometries as it can handle both structured and unstructured mesh types. This makes it highly flexible as the mesh density is known to have a linear relation to the quality of results and computation time [52].

Artificial intelligence (AI) and machine learning (ML) algorithms are increasingly being used in thermal analysis to predict heat transfer performance in linear systems. An artificial neural network (ANN) is a mathematical algorithm that is based on the human brain. The ability to learn patterns from data and improve over time without explicit programming is what makes it a cluster of networks of neurons. This makes it an effective tool for regression and pattern recognition. A typical ANN is structured into three main layers, as illustrated in Fig. 2. The input layer receives raw data, the hidden layer processes and transforms the data and the output layer provides the final result.

Each neuron (x_i) receives input using the weighted sum calculation; which is multiplied by the weight (w_i) and the sum with bias (w_o).

$$z = w_o + \sum_{1=1}^{n} w_i x_i$$

where x_i is the input value, w_i is the weight of each input, and w_o is the

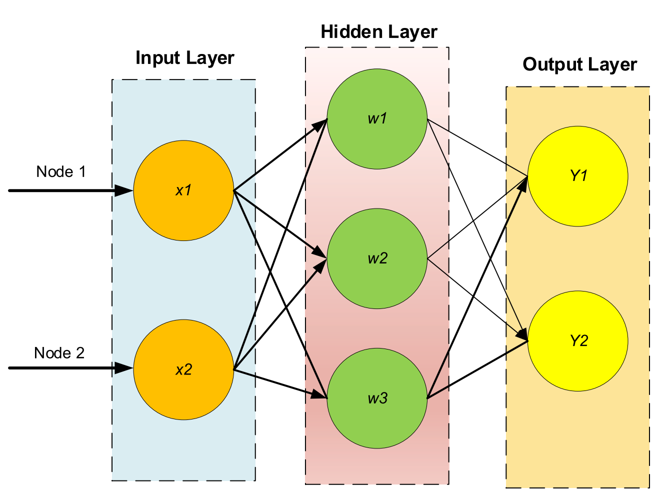

Fig. 2. ANN architecture.

bias (a constant).

The neuron applies the activation function *f(z)* to the weighted sum. This introduces a non-linearity that allows the network to learn complex patterns using common activation functions such as the:

$$\text{Sigmoid function,}\quad F(z) = \frac{1}{1+e^{-z}}, ReLU = f(z) = \max(0, z), \tanh(z) = \left(\frac{e^z - e^{-z}}{e^z + e^{-z}}\right)$$

Data flows from input to hidden layers follows forward propagation, where the output of the hidden layer becomes input for the output layer. The initial phase of training involves adjusting the weight and biases to reduce errors, which is frequently calculated using mean square error (MSE). Optimization is done using gradient descent, an algorithm that trains machine learning models [18].

ANN is often called a black box model due to the hidden layer's opaque nature, which means its decision-making processes are not transparent. Limited experimental data limits the acceptability of ANN and other machine learning algorithms' results, just like other methods. Inconsistencies arise when the data are sourced from different sources and complicate machine learning algorithms, causing a decrease in prediction accuracy. The need for substantial domain expertise complicates the creation of interpretable models for heat transfer in nanofluids. ANN has no exact law to determine the best solution, as the best solution is determined by trial and error [18]. ANN requires hardware with parallel or dual processors, approaching equipment-dependent [53]. The process of converting domain expertise into ML-friendly features is often not easy, as problems must be converted into values before being introduced into the ANN. This depends on the user's proficiency [54]. The utility of machine learning models may be limited if they are trained on a specific range of situations and do not generalize well to other ranges, such as nanofluid behaviors with different shapes, sizes, and concentrations [18].

The choice of a technique depends on the nature of the problem, the availability of data and the complexity of the model, as each method has strengths in a specific depth. CFD is capable of simulating physics-based phenomena with accuracy and detail due to its use of fundamental equations such as Navier-Stokes and energy conservation to model physical processes. Machine learning (ANN) is highly effective in an environment where data is available, as the training of data depends on the quantity and quality of the data. This allows for fast prediction, which is ideal for real-time applications. ANN models are highly dependent on data, which can lead to inaccurate results and low tolerance for complex physics if they haven't encountered similar scenarios in training.

A hybrid approach of combining CFD and ANN has been studied by Du *et al.* [55], where CFD developed high-fidelity data and ANN performed the analysis with high accuracy and efficiency. Recently, heat transfer in tubes with turbulent airflow and fluidized bed reactors has been modeled using ANN and CFD [56]. Using this approach, Yaici [57] performed a thermal-hydraulic investigation of plate-fin tube heat exchangers. A high-performance index of 9–31 % was reported by Mohebbi *et al.* [16] and 37 % when CNT or graphene NPs (GNP) are utilized [43]. Additionally, artificial tools such as fuzzy logic, adaptive neuro-fuzzy inference systems (ANFIS), and other machine learning algorithms such as genetic algorithms (GA) have been developed and deployed for heat transfer estimation [58]. Godasiaei *et al.* [44] deployed hybrid machine learning, using Python as a programming language with CFD (Eulerian and Lagrangian methods that consider the concentration of NPs to calculate diffusion and convection fluid flow in the liquid phase). This enables a deeper understanding of the Al_2O_3/-water nanofluid in a shell and tube heat exchanger.

Additionally, powerful statistical models such as Gaussian process regression (GPR), linear regression and support vector machine (SVM) have been used to accurately model the thermal conductivity of nanofluids using temperature [59] concentration and particle size as input functions [60]. The authors claim that the models achieved a root-mean-square error of 1.46 for large deviations and 0.97 for high accuracy in the dataset. Furthermore, the study developed a mathematically customizable model for various nanofluids that utilize thermal properties. Moreover, Ruhani *et al.* [61] used a combination of statistical modeling and experimental analysis to compare and analyze the thermal increase of cerium oxide nanofluid powder at different temperature readings. Results demonstrated that ANN could more precisely predict thermal behavior, and testing revealed higher thermal conductivity. A statistical investigation was carried out on the thermal enhancement of hybrid Al_2O_3-CuO nanofluid using a two-dimensional governing equation to examine it at 1000 W/m^2 heat flux [62]. The findings showed a consistent increase in the Nusselt number, typically greater than 1.2 times that of conventional fluid when the concentration rises by 0.5 %.

Utilization of CFD, ML, FEA, and programming languages has advanced the understanding and increased optimization prospects of heat transfer in nano-coolant-based heating devices. CFD and FEA are valuable tools for understanding complex fluid dynamics and temperature fields. Intricate temperature fields and fluid dynamics can be uncovered through accurate control over boundary conditions and spatial resolution in CFD and FEA. Artificial intelligence (AI), particularly machine learning, has made it possible to design and operate heat exchangers more efficiently and uncover hidden patterns in large datasets. Despite the need for a significant number of resources, experimental research is still necessary to validate theoretical and computational models and ensure that AI and CFD simulations accurately reflect real-world behavior. The integration of these techniques creates a powerful, interdisciplinary approach to optimizing nanofluid heat exchangers, resulting in increased performance and efficiency in a variety of applications.

2.2. Factors that influence heat transfer using nanoparticles

Heat transfer is a thermal process where energy moves from a hotter region to a cooler region. The phenomenon is influenced by the temperature gradient. The process is akin to the osmotic behaviour of fluid concentration. The heat moves from higher to lower temperature regions in various forms, such as conduction, convection, and radiation, to reach equilibrium. Fig. 3 depicts heat transfer flow, which is critical in engineering as it relies on the thermal conductivity of materials [63].

To enhance the thermal properties of base fluids (water and EG), NPs (1–100 nm) are utilized for heat transfer. The improved thermal conductivity and convective heat transfer of the resultant fluids improve heat dissipation in applications such as heat exchangers, as the NPs exhibit random movements (Brownian motion). The collision of particles experienced during this mixing allows the particles to pick up energy packs [64]. Recently, factors like thermophoresis (colloidal movement of particles in fluid due to temperature gradient in fluid) [65] and diffusiophoresis (motion of suspended particles due to concentration gradient) of NPs have been identified to help distribute heat more evenly [66]. Over the last decade, experimental research on thermophoresis and diffusiophoresis has grown significantly, leading to the development of autonomous micromachines [63].

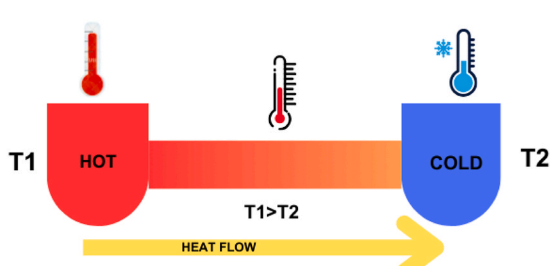

Fig. 3. Convective and conductive heat transfer.

Numerous studies have shown that the concentration, size, form, orientation, and type of NPs, along with the quality of base fluids, play a critical role in determining the rate of heat transfer [33]. Pooja [67] and Afshari et al. [68] support this claim, who observed that heat transfer is more closely linked with size than concentration in experimental or numerical studies. Furthermore, research by Singh and Sarkar [45], and Zhang *et al.* [69] demonstrated that the shape orientations of NPs have a greater impact on thermal enhancement than other parameters. However, Alami et al. [33] reported that the methods utilized in both investigations may have failed to adequately account for the changeable variables associated with NPs.

Despite the above-mentioned considerations, some obstacles inhibit the widespread commercialization and extensive implementation of NPs in heat transfer estimation in heat exchangers. NPs have the same fouling effects as conventional working fluids. The limitation is because many studies rely on simple energy equations ($q/\Delta T$), which fail to fully capture the complexity of convective heat transfer. The practicality of NPs is limited by their high production costs and non-reusable nature, particularly in the case of gold and diamond. Accurate heat transfer prediction is hindered by the inability to validate heat transfer models through experimentation. The use of NPs is less appealing due to their behavioral and unstable interactions, which result in agglomeration and sedimentation [33].

To address these difficulties, surface treatment and coatings with surfactants or polymers are utilized to prevent fouling by reducing agglomeration and improving dispersion. This strategy extends the equipment's life span. With the use of machine learning, large datasets of experimental and simulation results can be analyzed, leading to improved reliability and opportunities for optimization. To reduce costs, alternative, less-expensive NPs such as Al_2O_3, SiO_2, Fe_3O_4, CuO, or CNT can be used to replace expensive materials like diamond and gold. The adoption of these NPs over others stems from the combination of performance, cost, stability, environmental considerations and relevance in recent and future nanofluid research as illustrated in Table 2.

Also, the adoption of scalable techniques such as sol-gel, flame pyrolysis, and chemical vapour deposition (CVD) can reduce costs [70]. Stability of nano-coolants can be improved by using hybrid or composite NPs [21], as they offer synergetic stability improvements over single NPs [71]. By using benchmarks and procedure standards, it will be easier to predict heat transfers using nano-coolants with accuracy. Similarly, testing procedures would enhance consistency and reliability [72]. By adopting these strategies, major challenges facing nanoparticle-based heat transfer systems can be addressed, which will enhance their appeal for potential widespread use.

Nano-coolants have demonstrated strong potential to enhance the thermal performance of heat exchangers due to their superior thermophysical properties. This makes modeling techniques such as CFD and AI effective tools for estimating heat transfer, offering opportunities for continued research to optimize nano-coolant systems for practical and scalable applications.

3. Synthesis of nanoparticles

As depicted in Fig. 4, there are three primary strategies for synthesizing NPs. Khan *et al.* [76] conducted a study utilizing the physical strategy, also known as the top-down approach. The process involves lithography, arc discharge techniques, sonication, laser ablation, sputtering, mechanical milling, pulse wire discharge, and the breaking down of materials to their atomic sizes by applying force. While the method is effective for NPs with macroscopic links, it is not suitable for particles with complex sizes and shapes. Since grinding using a ball mill is an easy process, the mechanical method is the most efficient and economical method for commercialization [77]. NPs created through mechanical milling may have inconsistent shapes and sizes, which can reduce stability and lead to agglomeration [78]. However, cost-effectiveness and scalability make it an attractive option, especially for non-specialized

Table 2
Justification for selected nanoparticles used in nano-coolants.

Ref	NPs	Relevance	Stability	Environmental Impact
[22]	Al_2O_3	Widely studied due to its low cost, moderate thermal conductivity and wide application areas, making it a common nanomaterial in many studies.	High stability when surfactants such as Sodium Dodecyl Sulfate (SDS) are utilized.	Low toxicity
[22]	ZnO	offers high thermal conductivity, ease of synthesis, and high availability, making them suitable for both hybrid and heat transfer analysis.	Moderate stability with base fluids	Nontoxic, non-flammable and eco-friendly.
[19]	SiO_2	Excellent chemical stability, cost-effective, ease of synthesis and high ability to impact heat transfer despite low thermal conductivity.	High stability with base fluids	Low toxicity is often used in biocompatibility
[73]	CNT	Despite its high production cost, the exceptional heat transfer potential at low concentrations makes it prime for heat transfer analysis.	Low needs surfactants	considerable respiratory concerns.
[74, 75]	Fe_3O_4	Offers a unique magnetic field and is suitable for magnetohydrodynamics (MHD) studies.	High stability in base fluids	Low

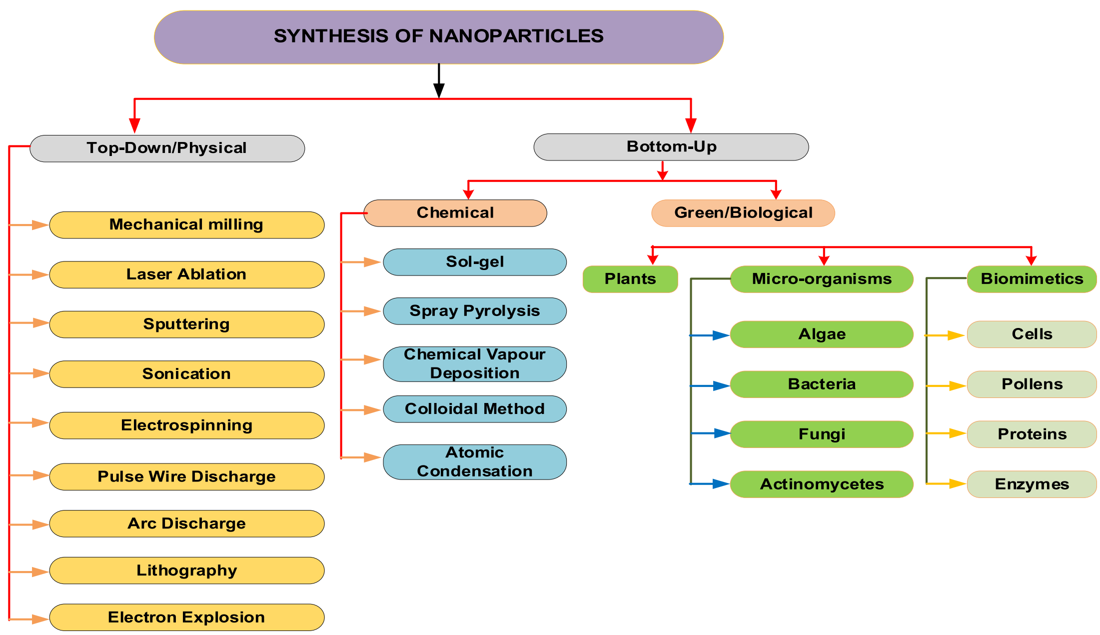

Fig. 4. Synthesis techniques.

heat transfer applications [79]. The term ’bottom-up methods’ refers to both chemical and biological approaches. The biological approach is called ’green synthesis’ [79] because it uses plant parts as reducing agents in a reaction with precursor salt.

NPs synthesized via green methods are an emerging field as they tend to have good biocompatibility and fewer toxic residues, which is beneficial for eco-friendly and biomedical applications. Despite green synthesis yielding stable NPs, it may be necessary to perform additional surface treatments to ensure long-term stability and thermal performance in nano-coolants. Although it requires a lot of energy, researchers are increasingly interested in using this method to produce NPs without using harmful chemicals because of its environmentally friendly approach [80]. The process of chemical vapour deposition (CVD) involves combining a precursor gas with a substrate and decomposing it under controlled temperature and pressure to produce NPs. This method can produce NPs that are extremely pure, uniform, and have specific sizes and shapes, which are ideal for enhancing thermal conductivity in nano-coolants. The controlled size and uniformity improve dispersion stability, reducing the likelihood of agglomeration and ensuring that thermal conductivity is consistently high. However, CVD is costly and primarily suited to high-performance applications where cost is less of a concern [81]. Different synthesis methods produce NPs with unique characteristics that influence the thermal conductivity, stability, and heat transfer capabilities of nano-coolants. Table 3 shows how specific synthesis methods affect the properties of nano-coolants.

Other areas that are currently being developed in nano synthesis include life cycle assessment (LCA) of nano-coolants and nanoparticle integration with renewable energy systems. However, there is limited research on the life cycle assessment (LCA) of nano-coolants.

Table 3
Effect of synthesis techniques on nanoparticles and nano-coolants.

Synthesis Technique	Effect on Nanoparticles	Nano-coolant effect
Laser Ablation	High purity, narrow size and good dispersion	Improved stability and heat transfer. Suitable or high-performance uses
Mechanical	Irregular particle size and shape. Ideal or bulk production	Cost-effective with low stability
Sol-gel	Control over size and shape	Improved dispersion and ideal for high-performance operations
Chemical Vapour Deposition (CVD)	High control over size and shape. High control	High thermal conductivity, stability and very expensive
Sputtering	Moderate control over shape and size	Improved heat transfer
Atomic layer Deposition	Good control over shape and size	Improved heat transfer and durability in high-temperature applications
Green synthesis	Biocompatible and eco-friendly with moderate control over size	Stable for wide applications

Environmental impact studies from synthesis to disposal are crucial because NP LCA will allow for informed decision-making for sustainable deployment [82]. In the last decade, there has been a rapid increase in the number of published LCA studies. This indicates a comprehensive approach to studying the potential environmental and human health effects of nanomaterials that are released into the environment.

LCA is a useful technique because it can reveal hidden patterns and trade-offs between performance and environmental costs (toxicity and energy demand). Additionally, it provides a framework for the adoption of nano-coolants with minimal environmental impact in the industry. According to Grimaldi *et al.* [83], LCA is crucial for examining nanomaterial recycling potential. Salieri *et al.* [84] and Nizam *et al.* [85] recognized three knowledge gaps in modeling LCA analysis: (1) Inadequate knowledge on the functional unit that encompasses all nanomaterial functions. (2) A lack of life cycle inventory (LCI) and data creation techniques; and (3) a lack of characterization factors (CF) for released nanomaterials. These fields provide prospects for further study into nano-coolants as sustainable technologies in heat transfer applications.

Furthermore, NP integration with renewables is an emerging area that represents increased energy efficiency. Systems such as solar collectors and wind turbines may benefit greatly from nano-coolants' high heat dissipation [47]. The integration of NPs with renewable energy research results in significant improvements in sustainability and energy security. Multiple studies have shown that various types of nano-coolants (Al_2O_3/water, CuO/water, and TiO_2/water) can increase heat transfer in solar systems [86]. The present problem in studying the heat-dissipation performance of nano-coolants in renewable systems is sustainability, as NPs settle in systems after their life cycle, indicating the instability of nano-coolants. Furthermore, high production and deployment costs, as well as material compatibility (acidic environments or high-temperature applications) [87], provide research opportunities.

The challenges and underexplored fields highlighted in this paper present exciting opportunities for expanding nano-coolant research. In addition, research in LCA would also provide an opportunity for further research on the environmental responsibility of nano-coolants and understanding the integration of renewable energy to improve system efficiencies and drive global energy transitions. These two areas are a promising frontier for nano-coolant research's future.

3.1. Regulatory frameworks applicable to nano-coolants in real-world applications

Using nanoparticles (NPs) in heat transfer systems, especially as nano-coolants, can greatly improve how well they work and allow for smaller designs. However, this advancement must align with emerging regulatory frameworks and safety standards to ensure environmental protection, occupational health, and sustainable deployment. As global investment in nanotechnology is projected to exceed USD 100 billion by 2025 [88], the integration of NPs into real-world applications necessitates compliance with established regulatory frameworks and safety standards to ensure environmental safety, occupational health, and long-term sustainability [89]. Concerns such as nanoparticle leaching, bioaccumulation, and air or water contamination have prompted regulatory bodies across North America, Europe, and Asia to develop frameworks for safer nanomaterial usage. This has led to the study of nano-ecotoxicology, which is a new discipline that evaluates the impact of NPs, as undesirable effects can arise, leading to environmental and health hazards. Although most current frameworks do not explicitly target nano-coolants, their classification as engineered nanomaterials means they are subject to chemical, occupational, and environmental regulations. This includes nanofluids used as coolants in industrial heat exchangers.

Countries such as the USA, Canada and the United Kingdom and organizations like the European Union have begun to ask questions on "how" companies procure and dispose of nanomaterials from different products. This pragmatic effort seeks to guide the responsible use of nano-coolants in thermal systems. Globally, the regulatory and safety framework is still evolving, with several authorities having developed preliminary guidance for the application of nano-coolants. Here are some of the key regulations and guidelines related to nanotechnology:

3.1.1. United States of America (USA)

A plethora of organizations have developed nano-regulations, including the Environmental Protection Agency (EPA), authorized by the Toxic Substances Control Act (TSCA) of 1976, to regulate and screen chemical products imported into the USA to mitigate unreasonable health and environmental risks [90]. Also, the agency regulates nanotechnology in agriculture by providing pre-manufacturing notifications for new nanomaterials, while the regulation of biotechnology products is governed by the U.S. Department of Agriculture (USDA). The Food and Drug Administration (FDA) and the Consumer Product Safety Commission (CPSC) require the collection of information about new and existing nanomaterials within 90 days [91].

3.1.2. European Union (EU)

The European Chemical Agency (ECHA) and the European Food Safety Authority (EFSA) regulate nanotechnology applications, including those related to engineered nanomaterials used in thermal management systems such as heat exchangers. The regulations mandate companies to submit specific nanomaterial information, such as physicochemical properties, toxicology and ecotoxicological data, to the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) committee that registers nanomaterials produced or imported at a rate higher than one ton per year. Accordingly, the ECHA categorizes these nanomaterials according to how harmful they are by creating an inventory of labels to inform consumers [92].

3.1.3. Canada and Asia-Pacific

Canadian legislators adopted the incorporation of nanotechnology into the Canadian Environmental Protection Act (CEPA) to ensure effective usage of nanotechnology to protect humans and the environment [93]. The legislation provides for the risk assessment procedures to be applied before a nanomaterial is introduced to the market, which received support from the public. The Korean government implemented REACH in 2015 to consolidate the European Union's REACH program by developing an incentive act like the Ministry of Environmental Waste Control and Chemical Toxicity Law to promote nanotechnology developments. Similarly, Japan, realizing the sustainable growth of nanotechnology, introduced the Council for Science, Technology and Innovation to promote the safe utilization of nano-products to the public [94]. In a similar trend, African governments have begun to develop formal policy frameworks governing nanotechnology research and development [95].

3.1.4. International standards

Organizations such as the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) have developed recommendations and control measures for exposure to certain nanomaterials, as they recommend certain measures for controlled usage of nanomaterials such as TiO_2, which, when inhaled, cause respiratory challenges [96]. In 2010, the American Society for Testing of Materials (ASTM), the world's largest standards organization, published its standard framework (ASTM E2996–15) for the adoption of nanomaterials in work environments by ensuring disclosure of information on nanoparticles in research, laboratory and other professional environments [97]. The ISO/TS 12901–2:2014 and ISO/TR 12885:2018 standards offer a control banding approach to workplace risk management, recommending tiered protective strategies based on exposure level and material toxicity [98].

3.1.5. Implications for nano-coolants

Rather than being assigned a distinct class, nano-coolants are generalized under the broad nanomaterials. Their deployments and handling in industrial heat exchangers usually fall under work protection regulations like the use of personal protective equipment (PPE) while handling and proper storage and waste disposal protocol, which engineers must ensure when designing and scaling nano-coolant in commercial heat transfer systems.

3.1.6. Knowledge gaps and future works

There are significant challenges to the acceptance of nano-coolants as a cooling fluid in laboratories and industrial applications. These include a lack of a nano-specific exposure limit for NPs in nano-coolants. Although an impressive effort has been made by OSHA to limit exposure of TiO_2 to 2.4 mg/m^3, while exposure limits for other NPs are undefined, creating ambiguity for industrial implications. Non-availability of unified international standards for nanofluid classification and waste disposal is also lacking, and there is a shortage of data on toxicology and environmental data of NPs, especially CNTs, in thermal studies.

Translating nano-coolants from laboratory-scale discovery to industrial-scale implementation requires a thorough regulatory outlook. The responsible use of nano-coolants in thermal systems will be guided by the use of current safety frameworks (such as REACH, NIOSH, and ISO standards) in conjunction with focused environmental risk evaluations and lifecycle analyses. To guarantee performance and safety, regulatory agencies must collaborate with engineers and researchers

Various synthesis techniques have been explored, underscoring the growing importance of life cycle assessment (LCA) and regulatory frameworks in ensuring the safe and sustainable deployment of nano-coolants in industrial applications. As research progresses, aligning synthesis methods with environmental standards and integrating them into renewable energy systems will be essential for scalability and commercialization.

4. Nano-coolants

Nano-coolant is a specially designed fluid created by suspending NPs, which are typically between 10 and 100 nm in size [99]. Commonly called a nanofluid. The NPs improve thermal interactions and raise the nano-coolant heat transfer capacity by many folds [100]. Despite the encouraging possibilities, stability problems such as sedimentation and aggregation of NPs in liquids tend to restrict the range of applications. According to Pandya *et al.* [47], sedimentation is primarily seen in the two-step approach for nanofluid preparation and the authors recommended switching to the one-step method, with surfactants as a countermeasure. However, the high surface area ratio of nano-coolants leads to a rise in pump requirements because of system clogging. Key essential characteristics of nano-coolants that promote heat transfer were revealed by Ajeeb *et al.* [34], Kumar *et al.* [101] and Gupta *et al.* [102]. These traits include significant enhancement in heat transmission because of nanofluids' potential to greatly improve heat conduction. This is far above and beyond expected values and theoretical predictions, which is in the magnitude of 1.21 times compared to pure water [103]. Nanofluids retain their Newtonian behavior and stability for months without sedimentation when stabilizing chemicals are used [35]. Lastly, particle size unlike micrometer-sized particles, NPs allow for greater heat transfer. It was shown that the concentration and size of the particles affect heat transfer. Higher thermal conductivity is generally encouraged by smaller sizes.

4.1. Nano-coolant preparation methods

The need to develop enhanced thermal enhancers (nano-coolants) or nanofluids has led to the development of methods to prepare nano-coolants. Fig. 5 depicts the widely used method for preparing a nanofluid. Nanofluids are commonly produced using both one-step and two-step techniques [104]. Other techniques have also been used to make nanofluids, including chemical vapor deposition [34], premixed flame, and arc discharge, [105]. Each of these techniques requires chemical treatments to enhance stability in base fluids [34]. According to Traciak and Zyla [106], water and glycol (EG) are the most frequently used base fluids. For efficient heat transfer in heating systems [107], it is highly recommended to use fluids with good thermal conductivity that are less viscous, as shown in Table 4. Water's high thermal conductivity value makes it the most widely used base fluid.

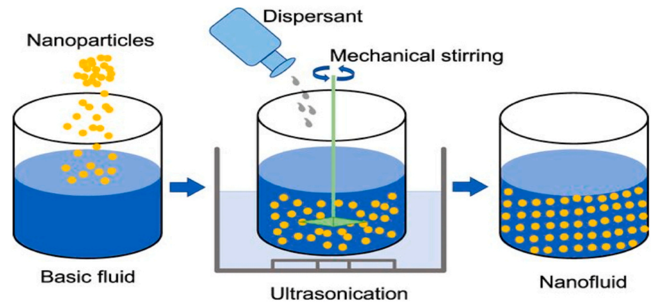

Fig. 5. Nanofluid preparation method [108].

4.1.1. Single-step method

The in-situ method, known as single single-step method, is a method in which NPs are produced and dispersed simultaneously in one single step [109] This technique involves simultaneously manufacturing and dispersing NPs in a single step [42]. Vapour deposition techniques and liquid chemical procedures are the most frequently employed methods. These techniques make NPs more stable; agglomeration is usually minimized, and nanoparticle storage, drying, and dispersion are usually ignored [109]. One of the major drawbacks of this technology is that it is limited to low-vapor-pressure fluids and cannot be cost-effective for commercial scale-up [100]. In this method, a magnetic stirrer or an ultrasonic generator is used to break up nanoparticle clusters and produce stable solutions, resulting in greater dispersion rates with reduced sedimentation. This is illustrated in Fig. 6.

Controlling the size and shape of NPs using this method is challenging and could affect the uniformity of the nanofluid's properties. The selection of base fluids for specific operations is limited by the high temperatures or pressures that some base fluids may not be able to tolerate [119]. The one-step technique's main drawback is that the nanofluid becomes impure due to the remaining reactants from an incomplete reaction. Despite the drawbacks, this process is becoming more and more popular because it is simple to use and produces high-performance nanofluids that are stable and uniform. The improved thermal properties of nanofluids have led to their widespread use in cooling and heating devices [19]. To improve dispersion rates and reduce sedimentation, several researchers have used a magnetic stirrer and an ultrasound generator to break down nanoparticle clusters and create stable solutions [47,117].

This method offers significant advantages in producing stable and effective nanofluids, eliminating the need for separate syntheses and dispersions. It improves heat conductivity and stability by lowering agglomeration and sedimentation and guaranteeing uniform particle

Table 4
Properties of base fluids Ajeeb et al. [34].

Fluid	Viscosity (mPas)	Thermal Conductivity (W/m.k)	Specific heat (J/kg K)	Density (kg/m^3)
Water	0.89	0.604	4183	998.2
Ethylene Glycol	5.378	0.216	2.46	1054.8
Oil	2.89	0.143	2.84	867

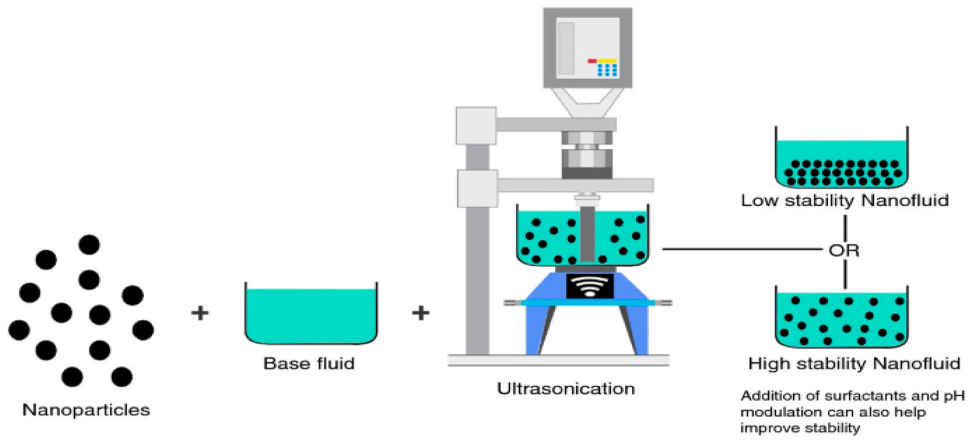

Fig. 6. One-step preparation method [110].

distribution throughout the fluid. Unlike the two-step process, it provides minimal control over size and shape. Therefore, further research is required to increase the variety of materials available and increase the viability of commercialization.

4.1.2. Two-step method

In a two-step process, NPs are scattered in the base fluid before sonicating the mixture to create a nanofluid [40]. The two-step procedure is the most preferred and easiest method in nanotechnology for the commercial production of nanofluids (see Fig. 7). This is accomplished by employing the magnetic guiding technique to disperse nano-sized particles in water, a common base fluid [111]. Research by Gupta *et al.* [10] and Herrera et al. [39] showed that the dispersion of NPs causes the formation of strong van der Waals forces, which enable neutral molecules to cluster and clog systems. To lessen this issue Prashant *et al.* [101], Borode *et al.* [105] and Kumari *et al.* [112] proposed the use of anionic surfactants (sodium dodecyl sulfate SDBS and sodium dodecylbenzene sulfate SDS), or cationic surfactants (cetrimonium bromide CTAB), and non-ionic surfactants (Triton X-100, PVP) and tannic acid, which are positively charged surfactants. This method is most effective when there is a higher concentration of NPs than 20 %.

The method's flexibility in selecting base fluids makes it highly versatile for different applications. Additionally, it could attain high concentrations, which are sought after in various thermal applications. Like the single-step method, NPs tend to agglomerate, which reduces surface area and hinders enhanced nanofluid synthesis. While surfactants (SCD, CTAB, SDBS) can enhance stability, they also lead to an increase in viscosity that could impact the fluid's thermal conductivity [113].

Since the tendency of the NPs to aggregate leads to sedimentation, channel clogging, and a reduction in the thermal conductivity of the nanofluid, the reliability of nanofluid adoption prepared either through a one-step or two-step method remains a significant challenge in nanotechnology [114]. Zeta potential analysis is widely used, among many others, to evaluate the stability of a nanofluid. The stability threshold is achieved when the zeta potential is greater than 25 mV, regardless of whether it's positive or negative. Tested modifications include altering the surface of the nanomaterial, adding surfactants to the nanofluids, modifying the pH, and extending the ultrasonication time. To effectively create a stable nanofluid, one can use surfactants as a rapid and low-cost method [2]. Nonetheless, several variables are considered to prevent sedimentation or agglomeration and ensure the stability of nanofluids. This includes the choice of base fluid, the type of nanoparticle, the duration of mixing and sonication, and the quantity of surfactant [102].

In preventing sedimentation, Kumara *et al.* [112] utilized inert gases to prevent the formation of metallic oxides, as exposure of freshly synthesized NPs to oxygen leads to oxidation, reducing the desired thermal and electrical properties of NPs. Kapicioglu *et al.* [115] prepared Al_2O_3/ethylene glycol nanofluid for ground heat exchangers using the sol-gel method. Sumesh *et al.* [116] prepared Al_2O_3/water nanofluid using green synthesis. Bhattad *et al.* [117] prepared Al_2O_3/TiO_2 hybrid nanofluid via ultrasonication. Kamalnayan *et al.* [37] prepared a reduced graphene oxide-Al_2O_3 hybrid nanofluid via the two-step technique. Alklaibi *et al.* [118] prepared hybrid Fe_3O_4/MWCNT coated MWCNT/water via chemical precipitation and sonicated in distilled water using a two-step method. Singh *et al.* [45] synthesized hybrid Al_2O_3/MWCNT via two-step heat transfer analysis using a tubular heat exchanger. Despite the advantages of bulk manufacturing, surfactants or ultrasonication are frequently required to combat the problem of agglomeration and sedimentation, which can lead to a decrease in stability. Even though the process is being considered, the technique is nonetheless reliable and expandable, particularly when used with stabilizers (surfactants) to enhance fluid stability and dispersion in heat transfer applications. Table 5 depicts the comparison between the two methods.

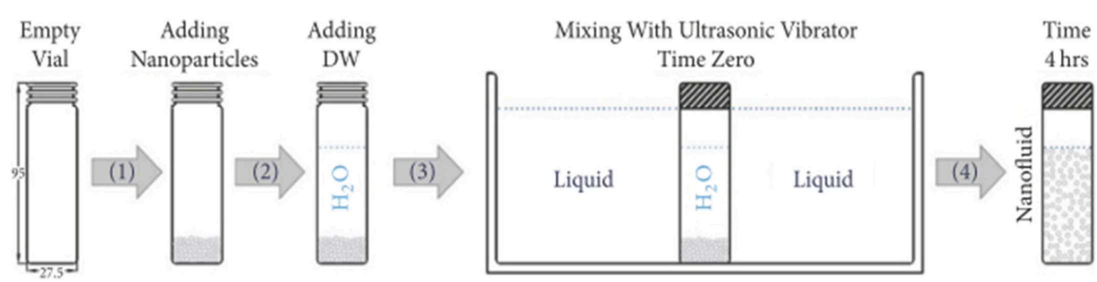

Fig. 7. Schematic procedure of the Two-step method [109].

Table 5
Comparison of single-step and two-step methods.

Ref.		Single-Step method	Two-Step method
[101]	Stability	Highly stable due to in-situ procedure. High dispersion with minimum agglomeration	Moderate stability. High risk of agglomeration. Cheap cost. Often requires surfactants
[112]	Cost	High cost of production due to specialized equipment.	Moderate cost as NPs are produced separately
[119]	Scalability	Limited scalability due to high-cost for industrial setup	High scalability as large quantities can be produced

4.2. Application of nano-coolants in heat transfer studies

High thermal performance is frequently achieved with the use of nano-coolants or nanofluids in heat transfer investigations by researchers due to their improved thermophysical characteristics [118]. A study by Huq *et al.* [11] states that nanofluid, which is employed as a heat transmission fluid, is created by dispersing NPs in a base fluid. Using both experimental and numerical techniques, it has been demonstrated that NPs greatly speed up heat transfer rates. This section displays research findings on various heat exchangers and nanoparticle types that were assessed and published by the authors of multiple studies.

Shell and tube heat exchangers, or SHTEs, are the most popular types of heat exchangers used in companies such as power plants, marine, and food sectors, and so on. Its simple design and ease of operation make it the best heating/cooling system for a variety of applications. Cruz *et al.* [120] studied the hydrothermal enhancement of 29 nm copper oxide NPs dispersed in distilled water "CuO/water" nanofluid moving through a compact heat exchanger. By increasing the loading concentration, there was a 48 % thermal improvement and a twofold decrease in pressure. Thus, included models with a 0.1–1 % vol concentration and Reynolds numbers (Re) ranging from 17,000 to 71,000. Multi-wall carbon nanotubes (MWCNTs) were assessed by Hassan *et al.* [121] for their potential to improve an Armfield heat exchanger unit with 0.5–2 % volume concentrations and 2500–12,500 Reynolds number. A 76.4 % thermal enhancement and a 58.6 % enhancement in the Nusselt number were reported at a concentration of 2 %. It is believed that heat exchange in heat exchangers can be improved by using high concentrations of NPs. However, as noted by Ajeeb and Murshed [47] and Ali *et al.* [48], this enhancement increases the pressure drop of pumping machines, with additional studies by Pandya *et al.* [47] and Gupta *et al.* [107] all documenting comparable outcomes.

Similarly, Zolfalizadeh *et al.* [43] investigated the hydrothermal properties of GNP in an STHE. The researchers produced three different nanofluid concentrations: 0.01 %, 0.03 %, and 0.06 %. Their findings demonstrated improved convective heat transfer at high particle concentrations compared to water, with comparable outcomes for volumetric flow rates and Reynolds numbers. The study's novel findings revolve around the impact of artificial NPs on heat transfer, potentially leading to better thermal efficiency and performance in multiple applications. In addition, the authors carried out a detailed experimental investigation to analyze the impact of graphene on the thermal convective heat transfer coefficient. CuO and Al_2O_3 nanoparticle's thermophysical properties were evaluated by Sattar *et al.* [124] in comparison to a mixed CuO- Al_2O_3-laced nanofluid at concentrations of 0.5–5 % and a velocity of 0.5–2 kg/s. The findings indicate that the Al_2O_3 and CuO- Al_2O_3 NPs had a 16 % and 20 % improvement in the heat transfer rates and coefficients, respectively. The relevance of the study shows that mixing two or more NPs can result in a higher heat transfer rate.

Perumal *et al.* [125] investigated the relationship between volume concentration and conjugate heat transfer of silicon oxide (SiO_2) NPs versus ZrO_2, TiO_2, and Al_2O_3 NPs. The study explores the use of NPs to enhance heat transfer in STHE by focusing on thermal conductivity and efficiency. The NPs' strong thermal conductivity motivated Talipova *et al.* [126] optimization effort. Their investigation focused on how packing porosity and pipe diameter affected heat flow and pressure drop in SHT. Critical information that can be used to improve performance, increase efficiency, and drive the development of heat exchanger systems for transportation networks is provided by their research. Many machine learning models, such as ANFIS, ANN, particle swarm optimization (PSO), multi-objective genetic algorithm (MOGA), and others, have been developed to mimic flow behavior in a variety of heat exchanger systems that use a wide spectrum of NPs. Yacine *et al.* [127] employed multi-objective function analysis to study the optimal hydrothermal properties of SiO_2, whereas [128] deployed MOGA to alter tube orientations. The two studies found higher thermal increases, and Onyiriuka [129] suggests the use of artificial intelligence technologies, which yield better results than CFD.

In a similar manner, PHE plate heat exchangers (PHE) have been utilized for several investigations. The investigations were conducted to examine the thermohydraulic properties of NPs, with a specific focus on their effect on the size, shape, and concentration of nanomaterials. Issa *et al.* [130] investigated the effectiveness of Al_2O_3 NPs in a plate heat exchanger that is influenced by flow and discovered that as the fluid shifts from laminar to turbulent flow, the concentration increases, resulting in more heat transfer. The author found that the presence of strong turbulence in the PHE inflow causes high heat transfer rates due to the concentration of NPs, which is an interesting aspect of the study.

In a study conducted by Sundar *et al.* [40], the thermohydraulic effects of a nanofluid consisting of carbon-based nano-diamond particles were experimentally investigated. The parameters investigated were 0–1 % volume concentration, 140–610 Reynolds number, 0.05–0.183 kg/s flow rate, and 895–3882 Peclet numbers, respectively. With an increasing particle concentration, the authors reported an enhanced heat transfer coefficient of 32.5 %, an improved Nusselt number of 35.11 %, and a 22.8 % increase in pressure drop, as well as a 19 % rise in pump power. Additionally, it was observed that the generated thermal entropy and frictional entropy decreased and increased simultaneously. Gupta *et al.* [10] recorded a maximum thermal gain of 1767.91 W/m^2K using WO_3/water nanofluid at a volume fraction (φ) of 0.3–0.5 % in a triple tube heat exchanger. Comparable results were reported by Alklabi *et al.* [118] and Bahiraei *et al.* [131].

In a separate study, Bose *et al.* [132] investigated cryogenic fluid in a PHE running in laminar flow utilizing CuO, Al_2O_3, Fe_2O_4, and MWCNT as the base fluid. The authors discovered that using NPs resulted in a 25–30 % improvement in performance with negligible pressure drop. The study's originality reveals the potential use of NPs in liquids with low boiling points. Furthermore, Bhattad *et al.* [117] investigated the correlation between fluid temperature and particle concentration in an Al_2O_3-TiO_2 hybrid nanofluid in a PHE. The significant improvement recorded lends credence to the theory that fluid viscosity is a critical parameter in thermal studies [133]. Furthermore, the study revealed that viscosity is affected by various variables, such as particle concentration, base fluid characteristics, volume flow rate, and the thermal properties of nanomaterials [122].

Another type of heat exchanger used in the processing industry is the double-tube heat exchanger (hairpin). Since their commercialization, double-tube heat exchangers have been widely utilized in industrial processes due to their simplicity and low cost, while delivering high transfer rates and low-pressure drops. Several computational and experimental studies have been conducted using various kinds of NPs [135]. Kavitha *et al.* [136] studied the thermal augmentation of CuO/-water nanofluid at a volume concentration of 0.04 % over a limited temperature range. According to the authors, the increase in particle concentration led to a noticeable 11.6 % increase in performance. It also demonstrated that the size orientation, and concentration of NPs are important factors in improving heat transfer, as previously reported by Saleh *et al.*[137]. Additionally, Singh and Sarkar [14] used several tapered wire-coil turbulator coil designs to study the hydrothermal performance of an Al_2O_3+MgO hybrid nanofluid. The findings indicated that using coil inserts with hybrid nanofluid instead of water resulted in superior thermal exchange of over 45 %, similar to the observation made by Said et al. [138]. Hybrid nanofluid is stated to have lower entropy generation and 1.69 times better thermal performance than Al_2O_3 nanofluid. In a separate study Jafarzad and Heyhat [139] reported that the thermal enhancement in an air-driven double-tube heat exchanger was 27–92.50 % with nanoparticle concentration ranging from 0.50 % to 0.50 % [123].

Relatedly, Karimi *et al.* [140] employed a two-phase model approach to examine how metallic tape inserts affect the hydrothermal performance of double-tube heat exchangers with different pitch ratios. According to the findings, the pitch ratio and metal tape selection had a significant impact on the pressure drop and heat transfer coefficient [141], which provides excellent opportunities for optimization. The significance of material selection, rather than just its nature, in enhancing heat transfer was emphasized by the researchers. The research provides valuable insights into the design of processes and equipment for industrial use. Additionally, by successfully evaluating the fluid properties of an Al_2O_3/water nanofluid in a complex double tube heat exchanger, Raei and Peyghambarzadeh [142] addressed an existing gap in the literature. The area of fully developed turbulent flow regimes in double tube heat exchangers is understudied in comparison to simpler geometries. Under other circumstances, the authors observed a 16 % increase and a 1.2 performance factor, which gave researchers in the field significant knowledge about the differences in convective heat transfer coefficients.

High-performance devices such as microchannel heat exchangers (MCHE) are usually lightweight and small. They are utilised in specific applications where weight is considered, such as space exploration [170]. Due to the trend towards system miniaturization, micro-channel heat exchangers are popular and widely known for their high heat removal rate. As a result of this, a growing number of scientific investigations are being carried out to improve efficiency. The performance of a unique graphene quantum dot (GQDs) nanofluid in microchannel heat exchangers (MCHE) was investigated by Jamshidmofid *et al.* [143] using the finite volume technique. The fluid was run at a concentration of 0.5 % and a Reynolds number of 50–200, while water was run at a Reynolds number of 100. The authors observed a 14 % improvement in performance at 50–100 Reynolds numbers with an 8 % penalty in pressure drop. Despite the difference in Reynolds numbers between 150 and 200, a noticeable decrease in pressure was observed. The authors recommended that the use of graphene for nanofluid be restricted to a maximum of 50–100 Reynolds numbers for optimal performance.

In a heat exchanger equipped with trapezoidal baffles, Bahiraei and Monavari [144] conducted the numerical investigation of the hydrothermal performance indices of a boehmite (y-AlO(OH)) nanofluid containing five distinct nanoparticle forms. The result showed a decrease in the performance index, but an increase in the heat transfer coefficient, heat transfer rate, and efficacy at higher nanoparticle concentrations. Mazaheri *et al.* [145] used a simulation model of two phases to numerically analyze a new micro-channel heat exchanger (MCHE) that utilizes Al_2O_3 nanofluid. The authors observed that at low flow rates and volume concentrations of NPs, there is a significant destruction of exergy (more than 61 %); on the other hand, high flow rates promote high thermal and frictional entropy creation of 11.7 %.

Another study was conducted by Alsagri and Moradi [146] to investigate the heat transfer in rotating tubes of MCHE using the homotopic perturbation approach, in addition to ordinary differential equations (ODEs) and the Koo-Kleinstreuer-Li (KKL) model. The study revealed that the temperature gradient decreased as the thermal characteristics of the fluid increased at low Reynolds numbers. The study's initial finding demonstrated that Lorentz forces reduced velocity while increasing Reynolds number. Along these lines, Mazaheri et al. [145] used a two-phase simulation to analyze the second law performance of a unique four-layer micro-channel heat exchanger (MCHE) employing Al_2O_3 nanofluid. To identify the energy point that has the lowest deterioration due to nanoparticle suspension, the study evaluated the reduction of energy destruction. The findings demonstrated that while higher flow rates produced more thermal and frictional entropy, increasing the volume fraction (φ) at low flow rates increased exergy destruction. Additionally, the water and nanofluid's thermal irreversibility was reduced by 11.7 % and 61.6 %, respectively.

Fig. 8 depicts the fluid pass-way and temperature profile of a 6-way microchannel MCHE heat exchanger. The cooling effect of a 1–3 % volume concentration TiO_2/water coolant was simulated in the exchanger using Ansys-Fluent by Waqas et al. [147]. According to the author, the finite volume technique (FVM) resulted in a 12–14 % increase in heat transmission for volume concentrations of 1–3 vol%. In the author's opinion, higher Reynolds numbers and intake velocities are the causes of the enhancement. These implications result from increased particle collisions caused by high loadings, which account for high thermal efficiency.

Al-Fatlawi and Niazmand [148], examined the heat transfer analysis of TiO_2, Al_2O_3, and hybrid TiO_2-Al_2O_3 nanofluids in a recent work, emphasizing the significance of particle shape and concentration. Their overall performance was assessed through the analysis of heat resistance, pumping power, and pressure drop. The modelling results indicate that the hybrid nanofluid's thermal conductivity increases linearly by 18 % at a particle concentration of 4 %, whereas the mono nanofluid's increases by 12 %. The results of the study are important because they show that the thermal conductivity of similar NPs is not significantly affected by the type of base fluid utilized.

In a similar development, plate heat exchangers (PHEs) are frequently employed in chemical facilities due to their high effectiveness, which results from a high area-to-volume ratio with minimal pressure drop, and a self-cleaning mechanism with less fouling. These attractive advantages have led to several studies, such as the assessment of the thermohydraulic potential of MWCNT and GNP in a single-tube heat exchanger by Dayou *et al.* [149]. The analysis was accomplished by adjusting the flow rate of the system between 1.5–2.5 L/min with particle loading of 0.1–0.35 %. According to the author, multiwalled carbon nanotubes have a lower heat transfer coefficient compared to graphene nanotubes. Reviewing the manufacturing method, thermophysical characteristics, and potential applications of GNPs in a single-tube heat exchanger, Bahiraei and Monavari [150] conducted studies on aqueous GNP nanofluids and reported 30 % and 26 % thermal enhancement over water at 0.1 % concentration. Also, Afshari *et al.* [151] reported a 12.3 % improvement using hybrid TiO_2-Al_2O_3/water over mono TiO_2/water in a 16-plate heat exchanger.

The flow behavior of TiO_2 in a single-phase convective system was investigated by Zhong *et al.* [152]. The key limitations of the stability of NPs were studied, and it was found that TiO_2/water nanofluid demonstrated a 4.3 % enhancement in single-tube systems without surfactant application. The authors highlighted deviations in empirical correlations, which are rarely reported in the measurements of nanoparticle viscosity and conductivity. The ability of NPs to revolutionize heat transfer technology and improve the effectiveness of heating devices in single-tube systems is presented by Ajeeb and Murshed [34], who have exhaustively reviewed nanoparticle applications for tube heat exchangers.

Zeinali *et al.* [153] demonstrated that Al_2O_3/H_2O generated the highest thermal efficiency and that the linear exergy destruction is proportional to particle concentration when viscosity increases. The thermal performance of several nanofluids in spiral heat exchangers was numerically evaluated by the authors. The authors explain how NPs in heat-exchanging systems can increase concentration, thermal improvement, and pressure drop by enhancing their viscosity and velocity. This study's conclusion implies that nanofluid causes frequent shell replacement, which increases operating expenses. The oxidative activity

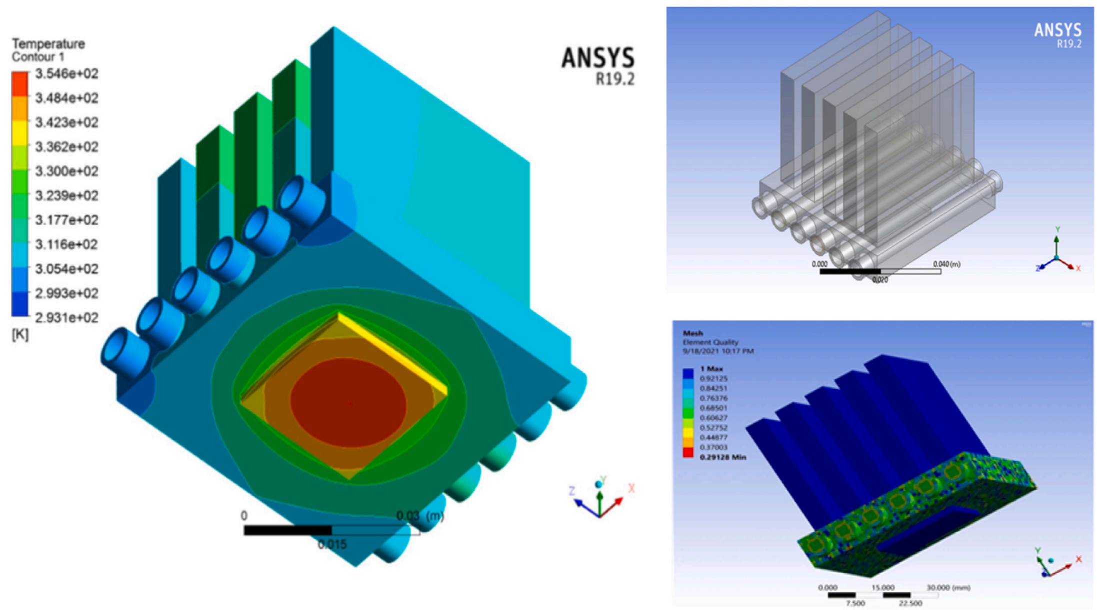

Fig. 8. Temperature profile of 6-way microchannel heat exchanger.

of NPs may be the reason why the quick breakdown of the metal surface is caused by nanomaterials. Through experiments, Razak *et al.* [154] examined the thermal performance of CuO/H_2O nanofluid in a spiral heat exchanger and found that the Nusselt number, heat transfer coefficient, and Reynolds number increased with the increase in particle loading. As previous studies have demonstrated, friction factors increase as laminar flow turns turbulent, and because nanofluid has a high viscosity, this increase is more pronounced than in water. Similar to this, Sundar *et al.* [40] enhanced the thermal efficiency of PHE by using an experimental nanodiamond/water nanofluid. The concentration, Reynolds numbers and Peclet number ranged from 0 % to 1.0 %, 140–610, and 895.78–3882.72, respectively. In comparison with deionized water, the authors found increases of 32.50 %, 55.47 %, 35.11 %, 22.80 %, and 18.83 % in the total heat transfer coefficient, heat transfer coefficient, Nusselt number, pressure drop, and pumping power, respectively. Consequently, they showed increased efficacy and number of transfer units (NTU) at a 1 vol% concentration of 14.14 % and 32.81 %, respectively. Zheng *et al.* [155] used PHE to assess the thermal performance of different nanofluids of Al_2O_3, SiC, CuO and Fe_3O_4 with particle sizes of 30 nm, 40 nm, 30 nm, and 25 nm at 0.05–1.0 wt% concentration and 3–9 lim/min rate. Fe_3O_4/water emerged as the top nanofluid, while CuO/water had the worst thermal performance. Fe_3O_4/water demonstrated a 21.9 % increase in thermal efficiency and a 10.1 % increase in pressure drop compared to deionized water. The study also emphasizes how back pressure limits particle loading because of an increase in viscosity. The use of nanofluids at higher concentrations is hindered by this phenomenon, leading to lower performance.

The turbulence effects of vertical and parallel springs in a PHE using two nanofluid samples of Al_2O_3/water and CuO/water prepared using the two-step approach was investigated by Peker *et al.* [156]. According to the author, Al_2O_3/water accounts for the best performance, and this is attributed to the thermal gains for parallel and vertical spring insertion of 76.1 % and 69.9 %, respectively. Comparing this study to that of Zheng *et al.* [155], which was previously evaluated, the thermal conductivity of the nanomaterial is more crucial for thermal enhancement than particle size, provided that the nanoparticle size is between one and one hundred nanometers. In addition to the type of heat exchanger, which has its design concerns and constraints, the use of nano-coolants also depends on the nature of the nanofluid. In addition, the efficiency of nano-coolants in heat exchangers depends on the nature of the coolant and other factors such as concentration, flow conditions, physical properties of NPs, as well as the synthesis method and rheological properties. Table 6 summarizes the benefits and drawbacks of some of the heat exchangers that have been reviewed. Furthermore, it can be concluded that scientific studies have demonstrated the viability of nano-coolants to enhance thermal performance in heat exchangers. In Table 7, further findings of published journal papers using different

Table 6
Advantages and disadvantages of reviewed heat exchangers.

Ref.	Type of heat exchanger	Advantages	Disadvantages
[107] [157] [158]	Shell and Tube	High heat transfer efficiency in high-pressure applications. Easy maintenance and flexible design.	Large size and weight require more space for installation. Limited efficiency, which increases energy losses.
[159]		High durability and adaptability for a wide range of fluids and temperatures	High susceptibility to fouling and limited thermal efficiency in low-pressure applications.
[158]	Plate	Compact design with high heat transfer. Easy maintenance with high-temperature control. Cost-effective and flexible in the removal or addition to adjusting heat transfer	Limited pressure and temperature range. High corrosion and fouling susceptibility. Short life span due to leakages.
[160]	Double tube	Simple and inexpensive. Easy to clean and fabricate. Highly reliable for a wide application range.	Limited heat transfers due to low surface area. Intolerant of dirty fluids. Difficult to clean.
[161]	Micro-channel	High heat transfer in a small volume. High efficiency in compact systems. Small and lightweight. Corrosion resistant	Complex design. Highly Expensive. Fouling and blockages. Flow instabilities due to design.
[162]	Single tube	Low maintenance cost. Easy design and fabrication. High-pressure and temperature range. Easy inspection and disassembly.	Highly expensive. Fouling. Requires regular maintenance. Less efficient than plate. Requires more space to open the tubes.

Table 7
Comparative analysis of recent experimental and numerical studies on nano-coolants in various heat exchanger types, showing nanoparticle types, concentrations, and observed performance improvements.

Ref.	Analysis Type	Heat exchanger	Base fluid	NPs	NPs size (nm)	Conc. (vol%)	Enhancement (%)	Remark
[163]	Numerical	Shell and tube	Water	Hybrid (CuO/ZnO)	N/A	0.01–0.1	18.45–22.11	Hexagonal tube orientation provides higher heat transfer due to increased surface area.
[164]	Numerical	PHE	water	SiO_2	N/A	0.08	16.63	Evaluated to height-to-width (h/w) of tubes to significantly impact heat transfer more than pitch-to-length
[148]	Numerical	Double tube	water	TiO_2, Al_2O_3 and TiO_2-Al_2O_3	N/A	0–4	10.4–18.6	The study demonstrated that base fluids have an insignificant effect on the thermal conductivity of similar NPs.
[165]	Numerical	PHE	water	Tungsten carbide (WC)	N/A	0.4	166–191	Rare use of WC nanoparticles; results show high versatility across moderate to high Re ranges (3240–8840), applicable to real-world conditions.
[166]	Experimental	PHE	water	Al_2O_3-SiC Al_2O_3-MgO Al_2O_3-CuO Al_2O_3-MWCNT	4:1	0.1	31.2	The study examined several Al_2O_3 hybrid NFs and observed that Al_2O_3-MWCNT (4:1) hybrid nanofluid achieved 31.2 % enhancement with minimal pump work increase (0.08 %), yielding a 12.46 % performance index improvement.
[167]	Experimental	Shell and tube	Water	Ag/water	143	2.5	32	The study demonstrated a 32 % enhancement that highlights the synergetic effects of nanoparticle concentration and flow rate on thermal efficiency and validates the potential of silver nanofluids for energy-efficient cooling applications due to improved thermal properties.
[168]	Experimental	Double tube	water	-	N/A	-	315	The study explored the impact of different twist ratios. Results show significant enhancements in heat transfer, with Nusselt numbers increasing by 219 %–315 % compared to plain pipes, and a maximum thermal performance factor (TPF) of 3.06. The study highlights the optimization potential of twist ratios for designing heat exchangers with improved efficiency.
[169]	Experimental	Microchannel	Acetone	Carbon-Acetone	50	0.1	73	Increase in friction factor (FF) and pressure drop (PD) due to augmented particle loading. Micro-scale phenomena like Brownian motion and thermophoresis account for thermal enhancement
[155]	Experimental	Microchannel	water	Zirconia	N/A	0.1–0.3	40.1	At a 0.3 wt% nanofluid concentration, the heat transfer coefficient improved by 40.1 %, and the pressure drop increased by 67 % compared to the base fluid. These enhancements are attributed to enhanced thermal conductivity, intensified Brownian motion, thermophoresis effects, and increased viscosity, which elevated frictional forces within the microchannel heat exchanger.

nano-coolants, regardless of the synthesis methods employed to produce them, are presented. By adding nano-coolants to these systems, thermal performance is improved, resulting in increased sustainability and lower energy requirements.

4.3. Real-world applications and industrial case studies of nano-coolants

While extensive numerical and experimental studies have evaluated thermal enhancement using nanofluids, recent real-world applications are increasingly demonstrating their industrial potential.

4.3.1. Solar photovoltaic thermal (PVT) systems

Nanofluids have been integrated into solar PVT systems to improve collector efficiency and heat absorption. For example, a pilot study by Lee et al. [171] demonstrated a 21.3 % and 15.14 % increase in thermal efficiency using CuO/water and Al_2O_3/water nanofluids, respectively. These enhancements were attributed to improved convective heat transfer and greater solar absorption in regions with high irradiance as observed by Farhan et al. [172] who achieved 54.53 % using ZnO nanofluid. Additionally, Ravi Kulkarni et al., [173] reported a 32 % improvement in convective thermal performance of a shell-and-tube heat exchanger using AgNP-enhanced nanofluids. This pilot-scale application underscores the potential of noble metal nanoparticles in traditional exchanger geometries. On a broader scale, companies such as BrightSource Energy, a U.S.-based solar technology firm, have deployed graphene nanomaterials in solar cells [174] to enhance light absorption and energy conversion [175]. Bright Solar, another firm in the Netherlands, has explored AgNPs in sustainable agriculture [176].

4.3.2. Automotive thermal management

In the automotive sector, CuO and Al_2O_3-based nanofluids have shown considerable promise. Pilot-scale radiator tests indicated thermal performance enhancements of up to 15 % and 25 %, respectively, when compared to conventional coolants [177]. These improvements contribute to better engine heat dissipation and improved fuel economy. In industrial applications, Tesla (the world's leading sustainable firm) has successfully utilized nanofluids using carbon nanotubes as nano-coatings in the development of batteries to improve corrosion resistance [178]. Also, Thermo Fisher Scientific, a manufacturer of nanotechnology equipment, has developed a wide range of nanoparticles for research and industrial applications [179].

4.3.3. Industrial heat exchangers and cooling towers

Pilot-scale refinery studies utilizing ZnO nanofluids demonstrated a 20 % increase in the overall heat transfer coefficient and reduced fouling in shell-and-tube heat exchangers [180]. Similarly, Javadpour *et al.* [4] evaluated nanofluids in a pilot cooling tower and found that MWCNTs/water outperformed TiO_2/water nanofluids with a thermal performance improvement of 28 % versus 4.7 %. They also identified 0.0069 wt% as an optimal concentration for MWCNTs in such systems.

4.3.4. Electronic and semiconductor cooling

In data center cooling systems, hybrid nanofluids such as Al_2O_3-MWCNT in deionized water have been applied to reduce CPU temperature hotspots by up to 12 %, enhancing local heat transfer coefficients [180]. Wahyuono and Arsana [181] also demonstrated the effectiveness of Al_2O_3, SiO_2, and TiO_2 nanofluids in a pilot-scale heat exchanger by optimizing baffle design, resulting in significantly improved thermal efficiency. In turbine systems, Almertejy et al. [182] reported a 15.6 % increase in intercooler performance when nanofluids were used, highlighting their potential in gas turbine applications. In the semiconductor industry, companies like Taiwan Semiconductor Manufacturing Company (TSMC) have reportedly explored the use of specialized nanofluids (e.g., "Hydromx") for high-performance cooling in chip manufacturing processes [183]. Similarly, General Electric (GE) has been involved in the development of germanium (Ge)-based nanofluids to enhance thermal conductivity in energy systems [184].

These industrial and pilot-scale studies demonstrate the transition of nanofluids from laboratory environments to practical thermal management systems. Applications range from solar energy and automotive radiators to data centers and industrial heat exchangers. The reported thermal performance enhancements (ranging from 10–32 %) underscore the potential of nano-coolants in improving energy efficiency, reducing system size, and supporting sustainable thermal system design.

The thermophysical behavior of nano-coolants across multiple heat exchanger types, supported by both numerical and experimental studies, confirms their significant potential to enhance thermal efficiency, particularly in shell-and-tube systems. While these enhancements are promising, challenges such as increased pressure drop due to higher viscosity and material compatibility issues must be addressed for effective industrial deployment.

5. Investigated thermophysical properties

5.1. Thermal conductivity (k)

The ability of nano-coolants to transfer heat efficiently is determined by their thermal conductivity, which is a critical property in heat transfer applications. According to numerous studies, NPs outperform conventional fluids in terms of heat dissipation [101]. Several thermal conductivity models have been developed. According to Pramanand *et al.* [185], one of them was introduced by Maxwell, who looked at mixes of liquids and solids and proposed energy equations to compute the rates of heat transfer in liquid-solid solutions [186]. Fig. 9 highlights enhancements from various studies utilizing different nano-coolants. The increases result from nanoparticle concentration, turbulence, and Brownian motion effects, confirming the performance benefits of superior thermal properties.

Bahiraei and Monavari [150] demonstrate that the thermal conductivity increases with Reynolds number, even if the particles' shape is

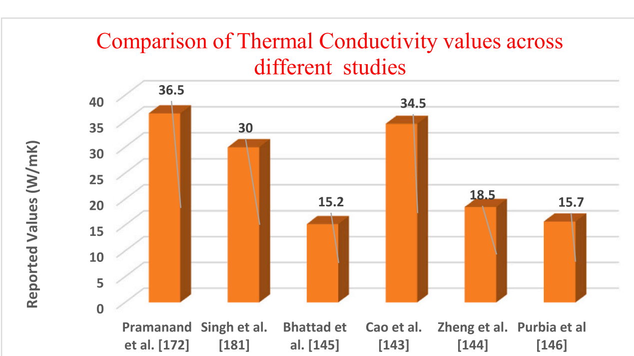

Fig. 9. Reported enhancements in thermal conductivity by various studies using different nano-coolants.

not considered. This is supported theoretically by Brownian motion, which is the randomized movement of NPs in a base fluid [187]. This phenomenon accounts for the high thermal continuity of nanomaterials due to the collision of particles as they undergo various motions in fluids. Rationally, it has been demonstrated that evaluation models such as the Timofeeva model, the Yu and Choi model, and the Hamilton and Crosser models can calculate heat transfer rates at varying particle concentrations. This approach has been used in almost every numerical and experimental study [148]. Singh and Sarkar [45] used an Al_2O_3+MWCNT hybrid nanofluid at 8000–40,000 Reynolds numbers and 5–25 lit/m flow rates to determine the impact of V-cut enhancers on the thermal conductivity of PHE. Their observation was that increasing flow rates enhanced thermal performance. This is to be expected, given that high flow rates cause high turbulence [188].

Additionally, studies by Cao *et al.* [189] and Zheng *et al.* [190], using an Al_2O_3 and CuO hybrid nanocomposite have shown a remarkable thermal conductivity of 36.5 % at 3 lit/min with different intake temperatures compared to other nanofluids. Bhattad *et al.* [191] also showed a 15.2 % improvement in heat transfer and a similar increase in Reynolds number. Singh *et al.* [192] claim that the increased circulation of NPs, which is caused by improvements in their thermophysical properties and physical motion in base fluids, leads to enhanced conductivity. This assertion aligns with the study by Purbia *et al.* [193].

Thermal conductivity is greatly impacted by NPs. As a result, heat exchange becomes more efficient, which is essential for cooling and heating systems. The rate at which heat energy can pass through a substance is largely determined by its thermal conductivity [194]. In engineering applications where effective heat transfer is essential, it has a major impact on design, as it is a measure of a material's ability to conduct heat [195]. Thermal conductivity is noted to promote correct modeling, guide material selection, and underpin calculations of heat transfer rate, all of which are required for developing dependable and efficient thermal systems. Therefore, it is essential to comprehend and optimize how heat moves through materials [196].

5.2. Nusselt and reynolds number (Nu & Re)

In heat transfer, Nusselt and Reynolds numbers are significant performance indicators for heat exchangers. Both are dimensionless numbers that are crucial for analyzing and predicting heat transfer behavior as they facilitate understanding how heat is transferred between a solid boundary and a fluid in motion. Offering optimization of thermal systems [197]. While the Nusselt number (Nu) is an indicator of the effectiveness of the heating system as it specifies the dominant mode of heat transfer (ratio of convective to conductive heat transfer), the Reynolds number characterizes the fluid into a laminar, transitional, or turbulent flow regime [198]. In heat transfer, these parameters are evaluated to ensure proper selection and design of high transfer systems. As the Reynolds number increases, the Nusselt number decreases because a higher Reynolds number implies higher flow rates, which leads to increased heat transfer [199]. Kumar and Sahoo [200] investigated the performance evaluation of a PHE fitted with turbulator inserts and Fig. 10 compares the Nusselt number enhancements across studies. Higher values are observed in hybrid nano-coolants and turbulence-inducing configurations, where few studies have shown that the use of turbulator inserts raises the Reynolds and Nusselt numbers at high concentrations, which results in a notable increase in thermal conductivity. This has also been observed by Mohammed *et al.* [201]. However, it is connected to particle shapes, as investigated by Bahiraei and Monavari [144], where both Reynolds and Nusselt numbers are found to be important in the evaluation of heat transfer rates. Additional studies by Jeevanandam *et al.* [202], Bahiraei and Monavari [150], Mourdikoudis, Pallares [203] and Shah *et al.* [204] reported similar findings.

Rajput *et al.* [122] utilized CNT and CuO NPs in a twin-pipe heat exchanger operating at 2–4 L/min to understand the impact of the

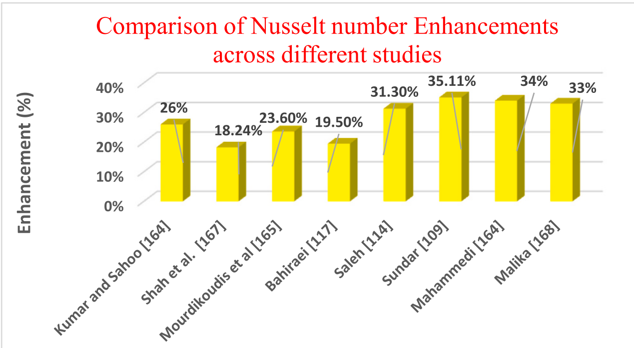

Fig. 10. Comparison of nusselt number improvement across studies.

Nusselt number (Ne). The investigation revealed that twin pipe heat exchangers had lower Nusselt values than shell and tube heat exchangers. Additionally, when the Nusselt numbers of different nanofluids at different particle concentrations were evaluated by Sundar *et al.* [40] and Saleh and Sundar [134], Nusselt numbers were shown to increase linearly with concentration and Reynolds number (Re). According to Malika *et al.* [205], Nusselt values for hybrid nanofluids fluctuate around 55 % between simulations and experimental tests, suggesting that nanofluids can improve heat transmission.

5.3. Overall heat transfer coefficient (U)

The overall heat transfer coefficient (U) is a significant parameter that measures the efficiency of heat transfer through a material. In thermal management, it plays a crucial role in designing and analyzing heating devices. It is often determined to enable optimized designs when efficiency, surface area, flow rate, and material nature are critical aspects that provide foundational metrics for enhancing thermal performance [206]. Across various studies, nano-coolants have demonstrated the ability to significantly increase U by enhancing convective heat transfer through particle-induced turbulence, improved fluid thermal conductivity, and greater heat surface interaction [207].

As shown in Fig. 11, these variations in U reflect differences in nanoparticle type, concentration, and system configuration. For example, Bashtani *et al.* [103] reported a 70.1 (W/m^2k) using Al_2O_3/-water nano-coolant in a pipe heat exchanger, while Abu-Hamden, N *et al.* [208] also demonstrated improvements in U using Al_2O_3 nanofluids, reporting an average coefficient of 62 $W/m^2\cdot K$. Turbulence promoters such as baffles and enhanced surface structures also contribute significantly to performance improvements. Notably, machine learning and computational tools like ANSYS-Fluent and ANFIS have been employed to predict U values with high accuracy, suggesting a trend toward integrating AI into performance estimation frameworks [102].

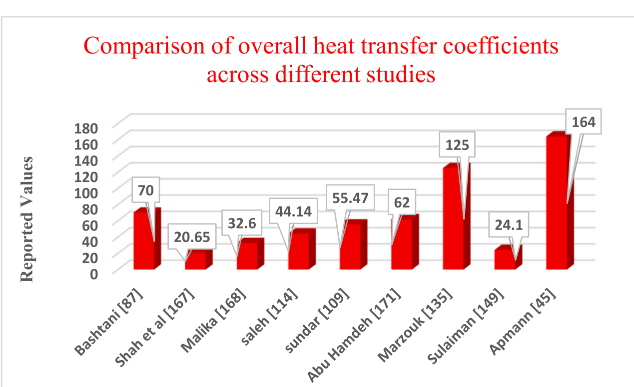

Fig. 11. Reported overall heat transfer coefficients using different nano-coolants.

To this end, Bahiraei and Monavari [209], numerically analyzed the heat transfer coefficient values at varying nanoparticle loadings in a shell heat exchanger fitted with baffles. The authors reported noticeable increases in the sizeable presence of NPs due to turbulence created by the baffles. Similar improvement was reported by Jayesh and Mukkamala [210]. The heat transfer coefficient of GNP nanofluid in an STHE was also studied by Fares *et al.* [211], and a heat transfer coefficient of 1.30 W/m^2K was achieved. These results were confirmed by Dimitriou *et al.* [87] and Abu-Hamden, N *et al.* [208].

5.4. Effectiveness of heat exchangers

Effectiveness (ε) is a measure used to express how effectively heat is transferred between two objects to maximum heat transfer. The term heat exchanger efficiency applies to the ratio of actual to maximum heat transfer [199]. It is a key evaluated parameter, as a higher value corresponds to better efficiency [139]. The estimation of the (ε) enables the optimal design of various configurations of heat exchangers. The traditional method of calculating effectiveness relied on log mean temperature difference (LMTD) and number of transfer units (NTU). However, studies have increasingly emphasized the dynamic approaches of data-driven and machine learning algorithms (ANN, GA) to handle the complexities of changing operational conditions with high speed and accuracy [212].

Most reviewed articles utilize CFD analysis (ANSYS-Fluent), which remains a valuable tool, especially in multi-flow, multi-phase conditions and complex geometries. CFD, like machine learning, has a high level of flexibility in real-time estimation and provides insights into temperature gradients and turbulent effects. Studies have demonstrated that the use of multiple NPs has a significant impact on effectiveness, as demonstrated by a study by Olabi *et al.* [213]. The author has demonstrated that combining CFD and data-driven machine learning models can improve predictive accuracy and computational efficiency. The effectiveness of heat exchangers increases with the Reynolds and Nusselt numbers, as demonstrated by Bahiraei and Monvari [209]. Similarly, effectiveness is dependent on the configuration of the heat exchanger, flow rate, and temperature differences between hot and cold fluids, as stated by Alshahrani *et al.* The author revealed that a surge in temperature differences at the inlet and exit of the heat exchangers causes an increase in effectiveness. Findings by Ouyang *et al.* [214], Bahiraei and Mazaheri [215] and Lee [80] all numerically investigated the effectiveness and discovered effectiveness to be dependable on nanoparticle shapes, volume concentration and the conductive effect of heat exchanger fabrication materials.

5.5. Viscosity of nanofluid (μ)

In heat transfer, fluid viscosity is essential as it directly influences heat transfer, pressure drop and overall efficiency. Given that it affects fluid dynamics and flow regimes, its calculation enables effective control over performance and operational costs, especially in viscous fluids [216]. The rheological study of nanofluids is not well-documented, unlike their thermal conductivity. However, a study by Thianpong *et al.* [187] found that there is a significant link between the viscosity of nanofluid and its thermal performance and concentration, as reported by Yashawantha [217]. This assertion is supported by Ali *et al.* [42], who compared the thermal enhancement of TiO_2 nanofluid made with water-mixed ethylene glycol (more viscous) and distilled water (less viscous). The study revealed that distilled water had a higher convective heat transfer rate than the water-ethylene glycol mixture. The reason is that less viscous water has higher thermal conductivity and facilitates better mixing and flow properties, leading to thinner thermal boundary layers and lower energy requirements. According to Esfe *et al.* [26] a rise in viscosity causes a corresponding increase in pressure drop. Bahiraei and Monavari [144] and Yilmaz *et al.* [218] have found that viscosity is significantly impacted by the morphologies of NPs. The viscosity effect was examined by Obonnaya *et al.* [219] and Pal [220], who found that viscosity increases the power needed for pumps, resulting in higher energy consumption. According to Hajatzadeh *et al.* [221]. Several researchers have made assumptions and used different values for the viscosity of nanofluids, but few have used experimental evidence to confirm viscosity correlations.

5.6. Pressure drop (ΔP)

Pressure drop is a significant factor in determining the performance of any heat exchanger system that uses fluids as the heat exchange media. For this reason, adding NPs can alter base fluid characteristics and pressure drop [217]. Accurate pressure drop estimation is crucial for designing better systems that can minimize energy demand and ensure system compatibility. Numerous studies have explored empirical methods like the Darcy-Weisbach equation and CFD models like ANSYS-Fluent under steady-state conditions. However, as systems become more complex and demand high-performance systems, empirical methods have proven to be less attractive. To address this, Nadda *et al.* [222] employed a hybrid CFD-machine learning method, and it has proven to be highly effective in systems with non-uniform geometries and transient flow regimes. Fig. 12. Illustrate the pressure drop associated with nano-coolant usage in various studies. Shirzad *et al.* [223] observed a substantial pressure drop increase of up to 47.8 % when using CuO-ZnO hybrid nanofluids. Borode *et al.* [224] recorded a 39 % increase. These observations emphasize the impact of nanoparticle loading and flow regime on system resistance, highlighting the need for optimized design to balance thermal gain with pumping cost.

According to Shirzad *et al.* [223], the pressure in a single-phase laminar flow decreased significantly when volume fractions (φ) of CuO-ZnO hybrid nanofluid increased in response to higher flow rates and nanoparticle concentrations. This implies that the concentration of particles necessitates the use of a pump. In this scenario, it is common to trade off high thermal performance and higher running expenses for pressure drop [186]. Yashawantha [217] observed through experimental research that the pressure in an Al_2O_3 nanofluid decreased with the increase in particle density and Peclet number. Operational costs are generally negatively impacted by pressure drop, as demonstrated by several investigations [223]. Singh and Gupta [226] and Omri *et al.* [227] have demonstrated that pressure drop increases in tandem with nanoparticle concentration.

Thermophysical parameters critical to the performance of nano-coolants were evaluated, demonstrating that these nano-coolants significantly enhance heat transfer. However, challenges such as increased viscosity and pressure loss must be carefully optimized to strike a balance between thermal efficiency and operational costs in practical heat exchanger applications.

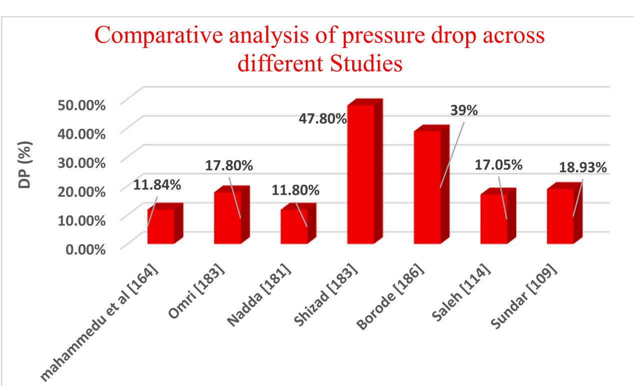

Fig. 12. Comparative analysis of pressure drops increases (%) reported in different studies using various nano-coolants.

6. Research gaps and future directions in nano-coolant applications

Numerous numerical and experimental studies have demonstrated the significant thermal performance improvements offered by nano-coolants. However, a critical evaluation of the current literature reveals several key challenges that continue to hinder the transition of nanofluid technologies from laboratory settings to widespread industrial applications. The following subsections outline the most pressing research gaps and opportunities that require targeted investigation to advance the field.

6.1. Research gaps

6.1.1. Standardization and stability challenges

A persistent issue in nanofluid research is the lack of standardization in formulation and characterization. Studies report a wide range of nanoparticle sizes, shapes, and base fluid types, alongside varying surfactants and sonication procedures [151]. These inconsistencies lead to unreliable and irreproducible thermophysical property measurements, which hinder meaningful comparison across studies and impede scalability [203]. Moreover, nanoparticle agglomeration and sedimentation present ongoing challenges, particularly in practical thermal systems subjected to fluctuating temperatures, turbulent flow, and long residence times [226]. As noted by Borode *et al.* [224], even with surface functionalization and surfactant use, maintaining long-term colloidal stability, especially for metallic and carbon-based nanoparticles like CNTs, remains difficult due to their inherent hydrophobicity [229].

6.1.2. Scalability and compatibility constraints

Although lab-scale investigations have shown promise, real-world industrial implementations of nano-coolants remain scarce [33]. Challenges such as compatibility with existing heat exchanger materials, fouling behavior, regulatory barriers, and high costs continue to limit commercial viability [226]. There is a pressing need for pilot-scale studies in sectors such as power generation, HVAC, and medical cooling systems to validate laboratory results [230].

While it is generally accepted that nano-coolants enhance thermal conductivity compared to conventional fluids, the mechanisms responsible for this enhancement, such as Brownian motion, thermophoresis, liquid layering, and nanoparticle clustering, are not universally agreed upon. These mechanisms likely vary under different flow regimes and material configurations, contributing to inconsistent results [226]. The high production cost of synthetic nanoparticles, particularly carbon nanotubes and graphene, remains a major obstacle. Existing synthesis techniques are not yet cost-effective for large-scale deployment, making these materials unsuitable for widespread industrial use at present [231].

6.1.3. Limitations in numerical simulation

Many numerical studies rely on simplified single-phase models that do not capture the complex interactions between particles and fluids, such as slip velocity, agglomeration dynamics, and thermal coupling effects [48]. These simplifications introduce significant uncertainty in heat transfer predictions, especially in turbulent or multiphase flow regimes where nanoparticle behavior plays a crucial role [232]. Furthermore, there is a notable lack of experimental validation for many simulation-based findings. Without real-world corroboration, the practical relevance of such models remains uncertain.

6.1.4. Optimization complexities

Hybrid nanofluids offer promising avenues for optimization, as they can combine the advantages of different nanoparticle types. However, the interaction effects between dissimilar particles often result in trade-offs, such as reduced stability or increased viscosity. Optimizing such systems requires balancing thermal enhancement against cost, pump power, and long-term reliability.

Bahiraei *et al.* [233] emphasize the need for artificial intelligence (AI)-driven optimization techniques to identify the most effective nanoparticle combinations and concentrations tailored to specific thermal applications.

6.2. Future research directions

To bridge the gap between laboratory success and industrial application, the following research areas require immediate attention:

I. **Nanofluid Stability**: Investigate the effects of pH, temperature, particle size, and concentration on long-term dispersion. Improved dispersion techniques such as ultrasonic treatment, pH control, and chemical surfactants should be systematically evaluated [234].
II. **Standardization and Benchmarking**: Develop international protocols for nanofluid preparation, stability testing, and thermophysical property measurement. Such standards are essential for cross-study reproducibility and industrial acceptance [233].
III. **Long-Term Durability**: Assess erosion and abrasion effects of nanofluids in continuous operation, especially within micro-channels and compact heat exchangers. This is vital to ensure the reliability and longevity of thermal systems [31].
IV. **Environmental and Lifecycle Assessments**: Conduct lifecycle analyses (LCA) and toxicological studies to evaluate the environmental impact of nano-coolants. Certain NPs (Ag, TiO_2, ZnO) are toxic to aquatic life and pose respiratory risks. Their environmental fate and long-term health impacts remain underexplored, hindering regulatory approval and commercialization [85].
V. **AI and Multi-Objective Optimization**: Apply machine learning algorithms for real-time control and optimization of nanofluid parameters. Current efforts remain insufficient, especially in capturing nonlinear behavior in complex, variable-load heat transfer scenarios [9].

Although nano-coolants hold tremendous promise for enhancing the efficiency of thermal systems, a range of unresolved scientific, technical, and regulatory issues must be addressed to realize their full potential. Interdisciplinary research that combines materials science, fluid dynamics, computational modeling, and environmental science is necessary to develop a cohesive framework for advancing nano-coolant technologies from experimental novelty to industrial reality.

7. Innovative methods to improve heat transfer

Innovative methods are being employed to improve the estimation of heat transfer in heat devices. Artificial intelligence (AI) tools are one of the strategies that can be deployed. To accomplish this task, several algorithms and AI models have been developed, including the utilization of ANN. By using data from previous experiments to train algorithms and models, this method can accurately predict thermohydraulic properties [235]. By using ANN and support vector regression (SVR), Adun *et al.* [236] predicted the thermal conductivity of hybrid nanofluids and achieved high accuracy in both models with a R^2 of 0.99997 for ANN and R^2 of 0.99788 for SVR. Similarly, Sadeghzadeh *et al.* [237] deployed an ANN algorithm to predict the conjugate heat transfer of TiO_2-Al_2O_3/water NPs synthesized using the sol-gel technique to develop a nanocomposite of 20 % Al_2O_3 and 80 % TiO_2 prepared at 1.5 % volume concentration. The ANN results revealed a 25 % increase in thermal conductivity.

The use of AI tools has enabled accurate heat transfer analyses involving NPs in heating systems. Tools like multi-layer perception neural networks (MLPNNS) have shown exceptional performance. Mamand, [238] has also employed Adaptive neuro-fuzzy inference systems (ANFIS) as an AI tool to predict pressure drops in nanoparticle distribution in base fluid, and they reported superior results to the CFD method. The relationship between pressure, temperature, and concentration in convective flows in heating devices can be understood more effectively through ANFIS [221]. A study by Efse *et al.* [239] had successfully use ANFIS to numerically determine the conjugate heat transfer value of CuO nanofluid and reported a remarkable relationship with a 0.999 regression correlation. Other smart, intelligent artificial tools have been studied by Sepehrnia *et al.* [240].

Another AI tool, fuzzy logic, utilizes fuzzy logic operations to perform model predictions and generate decision-making tasks. The AI tool has found wide-ranging applications in thermoregulation, aircraft system control, robotics, and other control systems [235]. In addition, the use of machine learning models enables the recognition of flow patterns in complex heat exchangers [225]. In micro-channels, where the CFD technique struggles to find connections between parameters such as pressure and concentration, the ANN or ANFIS can easily fill the gap by analyzing the CFD results and providing insight into boundary conditions [241].

AI and machine learning applications in heat transfer analysis improve accuracy and efficiency, making systems more resilient and adaptive to changing conditions. AIs, unlike CFD, are adept at handling the complexities of dynamic flow conditions [228]. Particularly, ANN, ANFIS and MLPNNs. These tools are highly adaptive to address CFD limitations in handling multi-phase fluid conditions. By utilizing experimental data, crucial hydrothermal properties can be predicted more precisely, resulting in faster real-time analysis of complex fluid regimes. These tools not only improve prediction by reducing computational time, but they also facilitate the efficient design of thermal applications, marking a significant improvement over analytical techniques.

7.1. Challenges and limitations of nano-coolants for heat transfer analysis

Significant challenges face NPs dispersed in the base fluid. Stability is a primary concern because NPs tend to become unstable over time and require constant renewal expenses [242]. A significant obstacle lies in the dependability of heat transfer estimation models, as disparate models produce inconsistent outcomes for identical NPs, rendering them untrustworthy for complex analysis [243]. The majority of research on nanoparticulates in heat exchangers is conducted through numerical methods to obtain experimental validation. Cautious thought must be given to the environmental impact of NPs, of which there have been few studies, as well as to the economies of scale for commercial production [188]. The use of convective heat transfer equations is not sufficient to compute heat transfer coefficients, leading to the creation of new correlation models using AI [244].

In nanoparticle production procedures, key limitations are commonly encountered: Poor solubility of NPs in base fluids tends to cause agglomeration or sedimentation [243], leading to clogging and corrosion of materials [245]. Economic limitations: The production of NPs is associated with high production costs, especially for synthetic materials such as graphene and carbon nanotubes, along with some metals such as Au (gold) and diamond NPs [246]. Characterization requirements: All synthesized NPs are usually characterized to measure thermal conductivity, viscosity, and particle distribution, which are necessary to understand their behavior. Such procedures are expensive and time-consuming. Nanoparticle shape complexity: heterogeneous NPs present technical difficulties as their distinct shapes and sizes discretely impact heat transfer, as observed by Bahiraei and Monavari [150], who investigated thermal enhancement using non-identical NPs.

Additionally, most NPs studied are produced by diverse techniques, and most numerical studies use a variety of equations that require experimental validation to model their thermophysical properties [247]. A concise database with preparation techniques and up-to-date thermophysical property data is needed for numerical analysis. Promoting experimental investigations is necessary to confirm numerical results and gain a thorough understanding of nanofluid improvements in heat exchangers. To efficiently analyze the thermophysical properties, a nanocomposite made of many NPs should be studied. Since limited information is available, additional research into the rheology of single and composite nanofluids is necessary. As a potential energy-saving method, it is important to consider the pollution and toxicity of nanofluids. By addressing these limitations, the use of NPs as convective nanofluid material in heat transfer analysis can be advanced.

Research has shown that AI and ML tools, such as ANN, ANFIS, and fuzzy logic, hold great promise for predicting and optimizing heat transfer in nano-coolant systems. While these models improve accuracy and reduce computation time, challenges like high computational costs and limited experimental validation remain. Advancing nano-coolants as a reliable solution will depend on addressing these limitations.

8. Conclusion

The deployment of NPs in thermal analyses on heat exchangers is assessed thoroughly, both experimentally and numerically. It is established from the literature that nanoparticles dispersed in a fluid have a noticeable effect on the efficiency of heat exchangers. Most of the improvements are attributed to the increased thermal properties of NPs. The results of experimental and numerical investigations are presented and findings from reviewed articles indicate that the overall heat transfer coefficient (OHTC) is enhanced, with a slight penalty of greater pressure drop at higher volume concentrations. Moreover, as the concentrations and flow rates of nanoparticles increase, so do the Nusselt number, Reynolds numbers, Prandtl numbers, and heat exchanger effectiveness. According to these performance indicators, nanoparticles are the most suitable material for thermal augmentation. However, the advancement of nanoparticle utilization hinges on addressing the regulatory, environmental and scalability limitations inherent in nanomaterials and studying underexplored fields such as life cycle assessment and renewable system integration.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used QuillBot, and Chatgpt and to improve the readability and language of the manuscript. After using these tools the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] H.C.S. Lunga, T. Sithebe, V.R. Veeredhi, The effectiveness of nanoparticles in coolants a state of the art, Mater. Today Proc. 92 (2) (2023) 1497–1500, https://doi.org/10.1016/j.matpr.2023.06.003.
[2] A.R.I. Ali, B. Salam, A review on nanofluid: preparation, stability, thermophysical properties, heat transfer characteristics and application, SN Appl. Sci. 2 (10) (2020), https://doi.org/10.1007/s42452-020-03427-1.
[3] G. Wong, et al., Recent progress and evolution of coolant usages in conventional machining methods: a comprehensive review, Springe Lond. (2022), https://doi.org/10.1007/s00170-021-08182-0.
[4] R. Javadpour, S.Z. Heris, Y. Mohammadfam, S.B. Mousavi, Optimizing the heat transfer characteristics of MWCNTs and TiO2 water-based nanofluids through a novel designed pilot-scale setup, Sci. Rep. 12 (1) (2022) 1–23, https://doi.org/10.1038/s41598-022-19196-3.
[5] R. Barai, D. Kumar, A. Wankhade, Heat transfer performance of nanofluids in heat exchanger: a review, J. Therm. Eng. 9 (1) (2023) 86–106.
[6] A.A. Akbar, et al., Insight into the role of nanoparticles shape factors and diameter on the dynamics of rotating water-based fluid, Nanomaterials 12 (16) (2022) 1–17, https://doi.org/10.3390/nano12162801.
[7] A. Rahbar, N. Bahri-Laleh, M. Nekoomanesh-Haghighi, Microstructural study on low viscosity poly-α-olefin oils synthesized via AlCl3/H2O cationic system in the present of xylene and heptane solvents, Fuel 302 (2021) 121111, https://doi.org/10.1016/j.fuel.2021.121111.
[8] P. Nowak, K. Kucharska, M. Kamiński, Ecological and health effects of lubricant oils emitted into the environment, Int. J. Environ. Res. Public Health 16 (16) (2019), https://doi.org/10.3390/ijerph16163002.
[9] T.W.B. Riyadi, et al., Nanofluid heat transfer and machine learning: insightful review of machine learning for nanofluid heat transfer enhancement in porous media and heat exchangers as sustainable and renewable energy solutions, Results Eng. 24 (2024) 103002, https://doi.org/10.1016/j.rineng.2024.103002.
[10] S.K. Gupta, S. Gupta, T. Gupta, A. Raghav, A. Singh, review on recent advances and applications of nanofluids in plate heat exchanger, Mater. Today Proc. 44 (34) (2021) 229–241.
[11] T. Huq, H. Chyuan, B. Teng, K. Yuen, S. Newaz, Review on aqueous graphene nanoplatelet nanofluids: preparation, Stability, thermophysical Properties, and applications in heat exchangers and solar thermal collectors, Appl. Therm. Eng. 210 (48) (2022) 1–31.
[12] A. Kumar, S. Javed, H.F. Oztop, Z. Said, N.S. Pandya, Experimental and numerical investigation on the thermal performance of triple tube heat exchanger equipped with different inserts with WO3 / water nanofluid under turbulent condition, Int. J. Therm. Sci. 164 (298) (2021) 1–14.
[13] M.M. Aslam Bhutta, N. Hayat, M.H. Bashir, A.R. Khan, K.N. Ahmad, S. Khan, CFD applications in various heat exchangers design: a review, Appl. Therm. Eng. 32 (2012) 1–12, https://doi.org/10.1016/j.applthermaleng.2011.09.001.
[14] S.K. Singh, J. Sarkar, Improving hydrothermal performance of hybrid nanofluid in double tube heat exchanger using tapered wire coil turbulator, Adv. Powder Technol. 31 (5) (2020) 1–10.
[15] S.K. Gupta, H. Verma, N. Yadav, review on recent development of nanofluid utilization in shell & tube heat exchanger for saving of energy, Mater. Today Proc. 54 (5) (2022) 579–589.
[16] J. Mohebbi, R. Alizadeh, A. Fattahi, M.H. Doranehgard, E. Alhajri, N. Karimi, Analysis of transport processes in a reacting flow of hybrid nanofluid around a bluff-body embedded in porous media using artificial neural network and particle swarm optimization, J. Mol. Liq. 313 (2020) 1–14.
[17] A. Riaz, et al., A numerical analysis of the transport of modified hybrid nanofluids containing various nanoparticles with mixed convection applications in a vertical cylinder, Front. Phys. 10 (2022) 1–11, https://doi.org/10.3389/fphy.2022.1018148.
[18] M.G.M. Abdolrasol, et al., Artificial neural networks based optimization techniques: a review, Electron 10 (21) (2021), https://doi.org/10.3390/electronics10212689.
[19] M. Rejvani, A. Heidari, S. Seadodin, Simultaneous effects of MWCNT and SiO2 on the rheological behavior of cooling oil and sensitivity analysis, Heliyon 9 (2) (2023) e12942, https://doi.org/10.1016/j.heliyon.2023.e12942.
[20] H.W. Xian, N.A.C. Sidik, R. Saidur, Hybrid nanocoolant for enhanced heat transfer performance in vehicle cooling system, Int. Commun. Heat. Mass Transf. 133 (2022) 105922, https://doi.org/10.1016/j.icheatmasstransfer.2022.105922.
[21] B. Gülmüş, B. Muratçobanoğlu, E. Mandev, F. Afshari, Experimental and numerical investigation of flow and thermal characteristics of aluminum block exchanger using surface-modified and recycled nanofluids, Int. J. Numer. Methods Heat. Fluid Flow. 33 (8) (Jan. 2023) 2685–2709, https://doi.org/10.1108/HFF-12-2022-0721.
[22] I. Elbadawy, F. Alali, J.F. Derakhshandeh, A. Dinc, M. Abouelela, and W. Al-Kouz, "Effect of Al2O3, SiO2, and ZnO Nanoparticle Concentrations Mixed with EG–Water on the Heat Transfer Characteristics through a Microchannel," 2023. doi: 10.3390/pr11072015.
[23] N. Asokan, P. Gunnasegaran, V. Vicki, Experimental investigation on the thermal performance of compact heat exchanger and the rheological properties of low concentration mono and hybrid nanofluids containing Al 2 O 3 and CuO nanoparticles, Therm. Sci. Eng. Prog. 20 (8) (2020) 100–127.
[24] M. Armstrong, S. Mahadevan, N. Selvapalam, C. Santulli, S. Palanisamy, C. Fragassa, Augmenting the double pipe heat exchanger efficiency using varied molar Ag ornamented graphene oxide (GO) nanoparticles aqueous hybrid nanofluids, Front. Mater. 10 (2023) 1–15.
[25] S.N. Baig, N. Baig, I. Kammakakam, W. Falath, Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges, Mater. Adv. 2 (2021) 1821–1871.
[26] M. Hemmat Esfe, S. Esfandeh, M. Hassan Kamyab, D. Toghraie, Analysis of rheological behavior of MWCNT-Al2O3 (10:90)/5W50 hybrid non-Newtonian nanofluid with considering viscosity as a three-variable function, J. Mol. Liq. 341 (2021) 117375, https://doi.org/10.1016/j.molliq.2021.117375.
[27] A. Mirahmad, R. Shankar Kumar, B. Pato Doldán, C. Prieto Rios, J. Díez-Sierra, Beyond thermal conductivity: a review of nanofluids for enhanced energy storage and heat transfer, Nanomaterials 15 (4) (2025), https://doi.org/10.3390/nano15040302.
[28] E.O. Atofarati, M. Sharifpur, and Z. Huan, "Nanofluids for heat transfer enhancement: a holistic analysis of research advances, technological progress and regulations for health and safety," 2024. doi: 10.1080/23311916.2024.2434623.
[29] G. Huminic, A. Huminic, Application of nanofluids in heat exchangers: a review, Renew. Sustain. Energy Rev. 16 (8) (2012) 5625–5638, https://doi.org/10.1016/j.rser.2012.05.023.

[30] T. Rehman, C.W. Park, Advances in nanofluids for tubular heat exchangers: thermal performance, environmental effects, economics and outlook, Energy 308 (2024) 132732, https://doi.org/10.1016/j.energy.2024.132732.
[31] Q. Tao, F. Zhong, Y. Deng, Y. Wang, C. Su, A review of nanofluids as coolants for thermal management systems in fuel cell vehicles, Nanomaterials 13 (21) (2023) 1–32, https://doi.org/10.3390/nano13212861.
[32] M.L.G. Ho, C.S. Oon, L.L. Tan, Y. Wang, Y.M. Hung, A review on nanofluids coupled with extended surfaces for heat transfer enhancement, Results Eng. 17 (2023) 1–27.
[33] A.H. Alami, et al., A critical insight on nanofluids for heat transfer enhancement, Sci. Rep. 13 (1) (2023) 1–14.
[34] W. Ajeeb, S.M.S. Murshed, Nanofluids in compact heat exchangers for thermal applications: a state-of-the-art review, Therm. Sci. Eng. Prog. 30 (3) (2022) 1–19.
[35] P. Abhilash, U. Raghupati, R. Nanda, Design and CFD analysis of hair pin heat exchanger using aluminium and titanium carbide nanofluids, Mater. Today Proc. 39 (23) (2021) 764–770.
[36] M. Tahmasebiboldaji, M. Afrand, A.A. Barzinjy, S.M. Hamad, P. Talebizadehsardari, Forced convection around horizontal tubes bundles of a heat exchanger using a two-phase mixture model: effects of nanofluid and tubes Configuration, Int. J. Mech. Sci. 161 (162) (2019) 1–15.
[37] S. Kamalnayan, D.P. Barai, S.S. Chawhan, B.A. Bhanvase, V.K. Saharan, Synthesis, characterization and heat transfer study of reduced graphene oxide-Al2O3 nanocomposite based nanofluids: investigation on thermal conductivity and rheology, Mater. Today Commun. 26 (2021) 1–14.
[38] S. Mohanty, O. Prakash, R. Arora, Analytical and comparative investigations on counter flow heat exchanger using computational fluid dynamics, J. Comput. Appl. Res. Mech. Eng. 10 (1) (2020) 139–152, https://doi.org/10.22061/jcarme.2019.4665.1564.
[39] B. Herrera, A. Gallego, K. Cacua, Experimental evaluation of a thermosyphon-based heat exchanger working with a graphene oxide (GO) nanofluid in a cogeneration system, Therm. Sci. Eng. Prog. 24 (18) (2021) 1–12.
[40] L.S. Sundar, V. Punnaiah, K.V. Sharma, A.J. Chamkha, A.C.M. Sousa, Thermal entropy and exergy efficiency analyses of nanodiamond / water nanofluid flow in a plate heat exchanger, Diam. Relat. Mater. 120 (34) (2021) 1–32.
[41] K. Apmann, R. Fulmer, B. Scherer, S. Good, J. Wohld, S. Vafaei, Nanofluid heat transfer: enhancement of the heat transfer coefficient inside microchannels, Nanomaterialsnomaterials 12 (615) (2022) 1–55.
[42] H. Ali, H. Babar, T.R. Shah, T. Multan, M.U. Sajid, Preparation techniques of TiO 2 nanofluids and challenges: a review, Appl. Sci. 5 (4) (2018) 78–89.
[43] M. Zolfalizadeh, S.Z. Heris, H. Pourpasha, M. Mohammadpourfard, J.P. Meyer, Experimental investigation of the effect of graphene/water nanofluid on the heat transfer of a shell-and-tube heat exchanger, Int. J. Energy Res. 4 (5) (2023) 1–16.
[44] S.H. Godasiaei, P. Talebizadehsardari, A hybrid machine learning-CFD method for the innovative analysis of Al2O3 nanoparticle deposition in shell-and-tubes heat exchangers, Therm. Sci. Eng. Prog. 54 (2024) 102807, https://doi.org/10.1016/j.tsep.2024.102807.
[45] S.K. Singh, J. Sarkar, Hydrothermal performance comparison of modified twisted tapes and wire coils in tubular heat exchanger using hybrid nanofluid, Int. J. Therm. Sci. 166 (23) (2021) 1–12.
[46] O. Yetik, T.H. Karakoc, Thermal management system with nanofluids for hybrid electric aircraft battery, Int. J. Energy Res. 45 (6) (2021) 8919–8931, https://doi.org/10.1002/er.6425.
[47] N.S. Pandya, H. Shah, M. Molana, A. Kumar, "Fluids, Heat transfer enhancement with nanofluids in plate heat exchangers: a comprehensive review, Eur. J. Mech. / B Fluids 81 (2020) 173–190.
[48] R. Syah, et al., Numerical investigation of nanofluid flow using CFD and fuzzy-based particle swarm optimization, Sci. Rep. 11 (1) (2021) 20973, https://doi.org/10.1038/s41598-021-00279-6.
[49] C. Liu, G. Zhou, W. Shyy, K. Xu, Limitation principle for computational fluid dynamics, Shock Waves 29 (8) (2019) 1083–1102, https://doi.org/10.1007/s00193-018-0881-6.
[50] A. Toptan, W. Jiang, J.D. Hales, B.W. Spencer, A. Casagranda, S.R. Novascone, FEA-aided investigation of the effective thermal conductivity in a medium with embedded spheres, Nucl. Eng. Des. 381 (2021) 111355, https://doi.org/10.1016/j.nucengdes.2021.111355.
[51] S. Čanić, M.L. Delle Monache, B. Piccoli, J.-M. Qiu, J. Tambača, Chapter 16 - Numerical methods for hyperbolic nets and networks, in: R. Abgrall, C.-W.B.T.-H. of N.A. Shu (Eds.), Handbook of Numerical Methods for Hyperbolic Problems, 18, Elsevier, 2017, pp. 435–463, https://doi.org/10.1016/bs.hna.2016.11.007.
[52] O. Kolditz, Finite volume Method BT - computational methods in environmental fluid mechanics, in: O. Kolditz (Ed.), Finite Volume Method BT, Springer Berlin Heidelberg, Berlin, Heidelberg, 2002, pp. 173–190, https://doi.org/10.1007/978-3-662-04761-3_8.
[53] M. Mouellef, F.L. Vetter, J. Strube, Benefits and limitations of artificial neural networks in process chromatography design and operation, Processes 11 (4) (2023), https://doi.org/10.3390/pr11041115.
[54] M. M. Mijwil, Artificial neural networks advantages and disadvantages, Mesop. J. Big Data 2021 (2021) 29–31, https://doi.org/10.58496/mjbd/2021/006.
[55] B. Du, P. Lund, J. Wang, Combining CFD and artificial neural network techniques to predict the thermal performance of all-glass straight evacuated tube solar collector, Energy 220 (Dec. 2020) 119713, https://doi.org/10.1016/j.energy.2020.119713.
[56] D.J. Armaghani, P.G. Asteris, A comparative study of ANN and ANFIS models for the prediction of cement-based mortar materials compressive strength 33 (9) (2021).
[57] W. Yaici, E. Entchev, Coupled Computational Fluid Dynamics (CFD) and Artificial Neural Networks (ANNs) for prediction of thermal-hydraulic performance of plate-fin-tube heat exchangers, Comsol Conf. 2016 Bost (2016) 3–6.
[58] Y. Dai, et al., Life cycle environmental impact assessment of titanium dioxide production in China, Environ. Impact Assess. Rev. 105 (2024) 107412, https://doi.org/10.1016/j.eiar.2023.107412.
[59] N.V. Kuzmenkov, M.S. Frantcuzov, A.P. Koroleva, Performance of CFD and ANN modeling of heat transfer enhancement in a circular tube with artificial roughness, J. Phys. Conf. Ser. 1891 (1) (2021), https://doi.org/10.1088/1742-6596/1891/1/012063.
[60] E. Onyiriuka, Predictive modelling of thermal conductivity in single - material nanofluids: a novel approach ([Online]. Available), Bull. Natl. Res. Cent. 47 (140) (2023) 1–15, https://doi.org/10.1186/s42269-023-01115-9.
[61] B. Ruhani, et al., Statistical modeling and investigation of thermal characteristics of a new nano fl uid containing cerium oxide powder, Heliyon 8 (2022).
[62] S.L. Ghashim, A mathematical analysis of nanoparticles on heat transfer in a circular pipe, Case Stud. Therm. Eng. 28 (2021) 1–10.
[63] E. Lee, Chapter 16 - Diffusiophoresis of Rigid Particles, Interface Science and Technology, vol. 26, in: E. Lee (Ed.), Theory of Electrophoresis and Diffusiophoresis of Highly Charged Colloidal Particles, 26, Elsevier, 2019, pp. 323–358, https://doi.org/10.1016/B978-0-08-100865-2.00016-3. in Interface Science and Technology, vol. 26.
[64] X. Li, et al., Heat transfer enhancement of nanofluids with non-spherical nanoparticles: a review, Appl. Sci. 12 (9) (2022), https://doi.org/10.3390/app12094767.
[65] H.A. Mohammed, A.A. Al-aswadi, N.H. Shuaib, R. Saidur, Convective heat transfer and fluid flow study over a step using nanofluids: A review, Renew. Sustain. Energy Rev. 15 (6) (2011) 2921–2939, https://doi.org/10.1016/j.rser.2011.02.019.
[66] A. Ganguly, B.M. Alessio, A. Gupta, Diffusiophoresis: a novel transport mechanism - fundamentals, applications, and future opportunities (no. November), Front. Sens. 4 (2023) 1–8, https://doi.org/10.3389/fsens.2023.1322906.
[67] G.G. Pooja, "Performance Analysis of Heat Exchanger Using Nanofluid," in Biennial International Conference on Future Learning Aspects of Mechanical Engineering: Recent Advances in Mechanical Engineering, 2023, pp. 107–121.
[68] F. Afshari, et al., Experimental and numerical study on air-to-nanofluid thermoelectric cooling system using novel surface-modified Fe3O4 nanoparticles, Microfluid. Nanofluidics 27 (4) (2023) 26, https://doi.org/10.1007/s10404-023-02637-4.
[69] J. Li, X. Zhang, B. Xu, M. Yuan, Nanofluid research and applications: a review, Int. Commun. Heat. Mass Transf. 127 (2021) 1–23.
[70] H. Zhang, et al., A review of flame aerosol synthesis technology for the synthesis of nanoparticles and functional energy materials, J. Solid State Chem. 336 (2024) 124774, https://doi.org/10.1016/j.jssc.2024.124774.
[71] M. Muneeshwaran, G. Srinivasan, P. Muthukumar, C.-C. Wang, Role of hybrid-nanofluid in heat transfer enhancement – a review, Int. Commun. Heat. Mass Transf. 125 (2021) 105341, https://doi.org/10.1016/j.icheatmasstransfer.2021.105341.
[72] K. Khanafer, K. Vafai, Analysis of turbulent two-phase flow and heat transfer using nanofluid, Int. Commun. Heat. Mass Transf. 124 (2021) 105219, https://doi.org/10.1016/j.icheatmasstransfer.2021.105219.
[73] I. Khoswan, H. Nassar, M. Assali, A. AbuSafa, S. Sawalha, and H.S. Hilal, "Why Carbon Nanotubes Improve Aqueous Nanofluid Thermal Conductivity: A Qualitative Model Critical Review," 2024. doi: 10.3390/pr12040834.
[74] M.S. Khan, S. Ahmad, Z. Shah, N. Vrinceanu, M.H. Alshehri, Natural convection heat transfer of a hybrid nanofluid in a permeable quadrantal enclosure with heat generation, Case Stud. Therm. Eng. 56 (2024) 104207, https://doi.org/10.1016/j.csite.2024.104207.
[75] D.K. Mandal, et al., Convective heat transport in a porous wavy enclosure: nonuniform multi-frequency heating with hybrid nanofluid and magnetic field, Heliyon 10 (9) (2024) e29846, https://doi.org/10.1016/j.heliyon.2024.e29846.
[76] Y. Khan, et al., Classification, synthestic and chracterization approaches to nanoparticles, and their applications in various fields of nanotechnology: a review, Catalysts 12 (11) (2022) 1386.
[77] B.A. Miu, A. Dinischiotu, New green approaches in nanoparticles synthesis: an overview, Molecules 27 (19) (Oct. 2022), https://doi.org/10.3390/molecules27196472.
[78] A. Faraz, M. Eyuphan, R. Shabnam, S. Bayram, M. Burak, T.-M. Reza, A review study on factors affecting the stability of nanofluids, Heat. Transf. Res. 53 (18) (2022) 15, https://doi.org/10.1615/HEATTRANSRES.2022041979.
[79] K.A. Altammar, A review on nanoparticles: characteristics, synthesis, applications, and challenges, Front. Microbiol 14 (2023) 1–20.
[80] H.M. Abuzeid, C.M. Julien, L. Zhu, A.M. Hashem, Green synthesis of nanoparticles and their energy storage, environmental, and biomedical applications, Crystals 13 (11) (2023), https://doi.org/10.3390/cryst13111576.
[81] N. Maurya, S. Saha, M. Ghosh, Chapter 1 - Recent advances in the designs and development of functionalized nanoparticles, in: S. ul Islam, C.M. Hussain, S.K. B. T.-A, A.C.B. on F.N. Shukla (Eds.), Antiviral and Antimicrobial Coatings Based on Functionalized Nanomaterials, Elsevier, 2023, pp. 3–31, https://doi.org/10.1016/B978-0-323-91783-4.00010-3.
[82] J. Ferdous, F. Bensebaa, K. Hewage, P. Bhowmik, N. Pelletier, Use of process simulation to obtain life cycle inventory data for LCA: a systematic review (no. March), Clean. Environ. Syst. 14 (2024) 100215, https://doi.org/10.1016/j.cesys.2024.100215.

[83] F. Grimaldi, M. Pucciarelli, A. Gavriilidis, P. Dobson, P. Lettieri, Anticipatory life cycle assessment of gold nanoparticles production: comparison of milli-continuous flow and batch synthesis, J. Clean. Prod. 269 (2020) 122335, https://doi.org/10.1016/j.jclepro.2020.122335.
[84] B. Salieri, D.A. Turner, B. Nowack, R. Hischier, Life cycle assessment of manufactured nanomaterials: where are we? NanoImpact 10 (2018) 108–120, https://doi.org/10.1016/j.impact.2017.12.003.
[85] N.U.M. Nizam, M.M. Hanafiah, K.S. Woon, A content review of life cycle assessment of nanomaterials: current practices, challenges, and future prospects, Nanomaterials 11 (12) (2021), https://doi.org/10.3390/nano11123324.
[86] P.K. Nagarajan, J. Subramani, S. Suyambazhahan, R. Sathyamurthy, Nanofluids for solar collector applications: a review, Energy Procedia 61 (2014) 2416–2434, https://doi.org/10.1016/j.egypro.2014.12.017.
[87] Q. Tao, F. Zhong, Y. Deng, Y. Wang, and C. Su, "A Review of Nanofluids as Coolants for Thermal Management Systems in Fuel Cell Vehicles," 2023. doi: 10.3390/nano13212861.
[88] Nanomaterials, "The global market for nanomaetrials 2010-2030," Future Markets. [Online]. Available: 〈https://www.futuremarketsinc.com/the-global-market-for-nanomaterials-2010-2030/〉.
[89] V.I. Singla, P.M. Sutton, T.J. Woodruff, The environmental protection agency toxic substances control act systematic review method may curtail science used to inform policies, with profound implications for public health, Am. J. Public Health 109 (7) (2019) 982–984, https://doi.org/10.2105/AJPH.2019.305068.
[90] S.D.G. Rayasam, P.D. Koman, D.A. Axelrad, T.J. Woodruff, N. Chartres, Toxic Substances Control Act (TSCA) Implementation: how the amended law has failed to protect vulnerable populations from toxic chemicals in the United States, Environ. Sci. Technol. 56 (17) (Sep. 2022) 11969–11982, https://doi.org/10.1021/acs.est.2c02079.
[91] O. Journal, M.E. Ondokuzmay, Regulatory policies for safety of nanomaterials nanomalzemelerin Güvenliği ile İlgili Düzenleyici Politikalar, Open J. Nano 5 (1) (2020) 1–16.
[92] A. Gissi, G.F. Mangiatordi, T. Sobański, T. Netzeva, O. Nicolotti, 1.16 - Nontest Methods for REACH Legislation, in: S. Chackalamannil, D. Rotella, S.E.B.T.-C.M. C.I.I.I. Ward (Eds.), Comprehensive Medicinal CHemistry III, Elsevier, Oxford, 2017, pp. 472–490, https://doi.org/10.1016/B978-0-12-409547-2.12300-5.
[93] B. Madé, Canadian environmental protection act, pp. 37–37, Umweltwiss. und Schadst. Forsch. 1 (1) (1989), https://doi.org/10.1007/bf02937017.
[94] J. Allan, et al., Regulatory landscape of nanotechnology and nanoplastics from a global perspective, Regul. Toxicol. Pharm. 122 (2021) 104885, https://doi.org/10.1016/j.yrtph.2021.104885.
[95] A.T. Irewale, C.O. Dimkpa, F.O. Agunbiade, O.A. Oyetunde, E.E. Elemike, E. E. Oguzie, Unlocking sustainable agricultural development in Africa via bio-nanofertilizer application - challenges, opportunities and prospects, Sci. Afr. 25 (2024) e02276, https://doi.org/10.1016/j.sciaf.2024.e02276.
[96] OSHA, "Fact Sheet: Working Safely with Nanomaterials," OSHA - Fact sheet, pp. 1–2, 2014.
[97] C. Martin, A. Nourian, M. Babaie, G.G. Nasr, Environmental, health and safety assessment of nanoparticle application in drilling mud – review, Geoenergy Sci. Eng. 226 (2023) 211767, https://doi.org/10.1016/j.geoen.2023.211767.
[98] I. Kokkinopoulos, P. Karayannis, S. Saliakas, S. Damilos, and E.P. Koumoulos, "Employing Nanosafety Standards in a Nanomaterial Research Environment: Lessons Learned and Refinement Potential," 2022. doi: 10.3390/standards2040034.
[99] W.A. Khan, K. Shaikh, R. Nawaz, S.N. Kazi, M.N. Mohd Zubir, Enhancement of heat transfer with nanofluids and its applications in heat exchangers, Advances in Heat Transfer, vol. 57, in: J.P. Abraham, J.M. Gorman, W.J. Minkowycz (Eds.), Advances in Heat Transfer, 57, Elsevier, 2024, pp. 101–128, https://doi.org/10.1016/bs.aiht.2024.05.001. in Advances in Heat Transfer, vol. 57.
[100] P. Kumar, R.M. Sarviya, Recent developments in preparation of nanofluid for heat transfer enhancement in heat exchangers: a review, Mater. Today Proc. 44 (17) (2021) 2356–2361.
[101] K. Prashant, R.M. Sarviya, Recent developments in preparation of nanofluid for heat transfer enhancement in heat exchangers: a review, Mater. Today Proc. 44 (2021) 2356–2361.
[102] S.K. Das, S.U.S. Choi, H.E. Patel, Heat transfer in nanofluids — a review, Heat. Transf. Eng. 27 (10) (2016) 3–19.
[103] I. Bashtani, J. Abolfazli, K. Chun, Effects of water-aluminum oxide nano fl uid on double pipe heat exchanger with gear disc turbulators: a numerical investigation, J. Taiwan Inst. Chem. Eng. 124 (4) (2021) 63–74.
[104] N. Azwadi, C. Sidik, I.M. Adamu, M.M. Jamil, Preparation methods and thermal performance of hybrid nanofluids, J. Adv. Res. Mater. Sci. 56 (1) (2019) 1–10.
[105] A.O. Borode, N.A. Ahmed, P.A. Olubambi, A review of heat transfer application of carbon-based nanofluid in heat exchangers, NanoStruct. NanoObjects 20 (3) (2019) 1–20.
[106] J. Traciak, G. Żyła, Surface Tension of Ethylene Glycol-Based Nanofluids Containing Three Types of Oxides: Zinc Oxide (ZnO), Magnesium Oxide (MgO) and Indium Oxide (In 2 O 3), Int. J. Thermophys. 44 (3) (Mar. 2023) 3144.
[107] S.K. Gupta, S. Gupta, R. Singh, A comprehensive review of energy saving in shell & tube heat exchanger by utilization of nanofluids, Mater. Today Proc. 50 (2022) 1818–1826.
[108] J. Yang, X. Yang, J. Wang, H. Chin, B. Sunden, Review on thermal performance of nanofluids with and without magnetic fields in heat exchange devices, Front. Energy Res. 10 (Apr. 2022) 822776, https://doi.org/10.3389/fenrg.2022.822776.
[109] N. Ali, J.A. Teixeira, A. Addali, A review on nanofluids: fabrication, stability, and thermophysical properties, Hindawi J. Nanomater 4 (6) (2018) 33–65.
[110] E.C. Okonkwo, I. Wole-Osho, I.W. Almanassra, Y.M. Abdullatif, T. Al-Ansari, An updated review of nanofluids in various heat transfer devices, J. Therm. Anal. Calor. 145 (6) (2021) 2817–2872, https://doi.org/10.1007/s10973-020-09760-2.
[111] A.H. Alami, et al., A critical insight on nanofluids for heat transfer enhancement, Sci. Rep. 13 (1) (Sep. 2023) 1–14.
[112] S. Kumari, et al., A comprehensive review on various techniques used for synthesizing nanoparticles, J. Mater. Res. Technol. 27 (2023) 1739–1763.
[113] S. Deb Majumder, A. Das, A short review of organic nanofluids: preparation, surfactants, and applications, Front. Mater. 8 (4,) (2021) 1–8.
[114] S. Chakraborty, P.K. Panigrahi, Stability of nanofluid: a review, Appl. Therm. Eng. 174 (2020) 115259, https://doi.org/10.1016/j.applthermaleng.2020.115259.
[115] A. Kapıcıoğlu, H. Esen, Experimental investigation on using Al2O3/ethylene glycol-water nano-fluid in different types of horizontal ground heat exchangers, Appl. Therm. Eng. 165 (11) (2020) 1–40.
[116] K. Sumesh, K. Kanthavel, Green synthesis of aluminium oxide nanoparticles and its applications in mechanical and thermal stability of hybrid natural composites, J. Polym. Environ. 27 (2019) 2189–2200.
[117] A. Bhattad, B.N. Rao, V. Atgur, I. Veza, M.F.M.A. Zamri, I.M.R. Fattah, Thermal performance evaluation of plate-type heat exchanger with alumina–titania hybrid suspensions, Fluids 8 (4) (2023) 1–16.
[118] A.M. Alklaibi, L.S. Sundar, K.V.V. Chandra, Experimental investigation on the performance of hybrid Fe 3 O 4 coated MWCNT / Water nanofluid as a coolant of a Plate heat exchanger, Int. J. Therm. Sci. 171 (56) (2022) 1–16.
[119] K.R. Chaturvedi, R. Narukulla, T. Sharma, CO2 capturing evaluation of single-step silica nanofluid through rheological investigation for nanofluid use in carbon utilization applications, J. Mol. Liq. 304 (2020) 112765.
[120] P.A.D. Cruz, E.E. Yamat, J.P.E. Nuqui, A.N. Soriano, Computational fluid dynamics (CFD) analysis of the heat transfer and fluid flow of copper (II) oxide-water nanofluid in a shell and tube heat exchanger, Digit. Chem. Eng. 78 (2) (2022) 1–34.
[121] A.M. Hassaan, An investigation for the performance of the using of nanofluids in shell and tube heat exchanger, Int. J. Therm. Sci. 177 (2022) 1–9.
[122] N.S. Rajput, D.D. Shukla, L. Ishan, K.S. Madhav, Enhancement of nusselt number by using CNT and CuO nanofluids in heat exchangers, Mater. Today Proc. 47 (2021) 1–7.
[123] N. Singh, D. Dilipbhai, L. Ishan, Enhancement of nusselt number by using Al 2 O 3 and TiO 2 nanofluids in heat exchangers, Mater. Today Proc. 47 (9) (2021) 1–7.
[124] E.A. Sattar, A.A. Ouda, M.D. Salam, Enhancement heat transfer in shell and tube heat exchanger by used hybrid and nanofluid, AIP Conf. Proc. (2023) 2787.
[125] S. Perumal, V. Venkatraman, R. Sivanraju, A. Mekonnen, S. Thanikodi, R. Chinnappan, Effects of nanofluids on heat transfer characteristics in shell and tube heat exchanger, Therm. Sci. 26 (2) (2022) 835–841.
[126] A. Talipova, O. Soloveva, S. Solovev, L. Belousova, J. Sabirova, Numerical simulation of heat transfer in a tube bundle of a shell-and-tube heat exchanger used in transport, Transp. Res. Procedia 63 (2022) 1294–1300, https://doi.org/10.1016/J.TRPRO.2022.06.138.
[127] R. Suprabha, C.R. Mahesha, C.E. Nanjundappa, Influence of process parameters and convective heat transfer on thermophysical properties of SiO2 nanofluids by multiobjective function analysis (DFA), J. Nanomater (2023) 1–10.
[128] K. Yacine, H.M. Abo-Dief, A.K. Alanazi, S.S. Mohammad, S. Suvanjan, Optimization of heat transfer in shell-and-tube heat exchangers using MOGA algorithm: adding nanofluid and changing the tube arrangement, Chem. Eng. Commun. 210 (6) (2023) 893–907.
[129] E. Onyiriuka, Predictive modelling of thermal conductivity in single-material nanofluids: a novel approach, Bull. Natl. Res. Cent. 2023 471 47 (1) (2023) 1–15, https://doi.org/10.1186/S42269-023-01115-9.
[130] R.J. Issa, A review on thermophysical properties and nusselt number behavior of Al2O3 nanofluids in heat exchangers, J. Therm. Sci. 30 (2) (2021) 418–431.
[131] M. Bahiraei, N. Mazaheri, M. Hanooni, Performance enhancement of a triple-tube heat exchanger through heat transfer intensification using novel crimped-spiral ribs and nanofluid: a two-phase analysis, Chem. Eng. Process. Process. Intensif. 160 (34) (2021) 1–13.
[132] A. Bose, S. Chakraborty, S.S. Mukhopadhayay, Thermo-hydraulic performance enhancement of liquid he based cryogenic nanofluid flow in laminar region through rectangular plate fin heat exchangers-a numerical Study, IOP Conf. Series Mater. Sci. Eng. (2020) 1–8, https://doi.org/10.1088/1757-899X/998/1/012001.
[133] B. Saleh, L.S. Sundar, Experimental study on heat transfer, friction factor, entropy and exergy efficiency analyses of a corrugated plate heat exchanger using Ni / water nanofluids, Int. J. Therm. Sci. 165 (17) (2021) 1–20.
[134] B. Saleh, L.S. Sundar, Thermal performance, embodied energy and environmental CO2 emissions analyses for double pipe U-bend heat exchanger working with MWCNT / water nanofluid, Int. J. Therm. Sci. 169 (43) (2021) 107094.
[135] E. Tavousi, N. Perera, D. Flynn, R. Hasan, Heat transfer and fluid flow characteristics of the passive method in double tube heat exchangers: a critical review, Int. J. Thermofluids 17 (2023) 1–18.
[136] R. Kavitha, Y. Methkal, A. Algani, K. Kulkarni, M.K. Gupta, Heat transfer enhancement in a double pipe heat exchanger with copper oxide nanofluid: an experimental study, Mater. Today Proc. 56 (6) (2022) 3446–3449.
[137] T. Rasheed, et al., Hybrid nanofluids as renewable and sustainable colloidal suspensions for potential photovoltaic/thermal and solar energy applications, Front. Chem. 9 (2021). 〈https://www.frontiersin.org/journals/chemistry/articles/10.3389/fchem.2021.737033〉 (Online]. Available).
[138] Z. Said, et al., Sustainable thermal solutions: enhancing heat transfer with turbulators and nanofluids, Adv. Energy Sustain. Res. 6 (2025) 1–45, https://doi.org/10.1002/aesr.202400335.

[139] A. Jafarzad, M.M. Heyhat, Thermal and exergy analysis of air- nano fl uid bubbly fl ow in a double-pipe heat exchanger 372 (47) (2020) 563–577.
[140] A. Karimi, A.A.A.A. Al-rashed, M. Afrand, O. Mahian, S. Wongwises, A. Shahsavar, The effects of tape insert material on the flow and heat transfer in a nanofluid-based double tube heat exchanger: two-phase mixture model, Int. J. Mech. Sci. 156 (2019) 397–409.
[141] M. Zaboli, M. Nourbakhsh, S.S.M. Ajarostaghi, Numerical evaluation of the heat transfer and fluid flow in a corrugated coil tube with lobe-shaped cross-section and two types of spiral twisted tape as swirl generator, J. Therm. Anal. Calor. 147 (1) (2022) 999–1015, https://doi.org/10.1007/s10973-020-10219-7.
[142] B. Raei, S.M. Peyghambarzadeh, Measurement of local convective heat transfer coefficient of alumina-water nanofluids in a double tube heat exchanger, J. Chem. Pet. Eng. 53 (1) (2019) 25–36.
[143] M. Jamshidmofid, A. Abbassi, M. Bahiraei, Efficacy of a novel graphene quantum dots nanofluid in a microchannel heat exchanger, Appl. Therm. Eng. 189 (34) (2021) 1–15.
[144] M. Bahiraei, M. Naseri, A. Monavari, Thermal-hydraulic performance of a nano fluid in a shell-and-tube heat exchanger equipped with new trapezoidal inclined baffles: Nanoparticle shape effect, Powder Technol. 395 (4) (2022) 348–359.
[145] N. Mazaheri, M. Bahiraei, S. Razi, Second law performance of a novel four-layer microchannel heat exchanger operating with nano fl uid through a two-phase simulation, Powder Technol. 396 (33) (2022) 673–688.
[146] A.S. Alsagri, R. Moradi, Application of KKL model in studying of nanofluid heat transfer between two rotary tubes, Case Stud. Therm. Eng. 14 (2019) 461–478.
[147] H. Waqas, S.A. Khan, U. Farooq, T. Muhammad, A. Alshehri, S. Yasmin, Thermal transport analysis of six circular microchannel heat sink using nanofluid, Sci. Rep. 12 (1) (2022) 1–19.
[148] A.W. Al-Fatlawi, H. Niazmand, Thermal analysis of hybrid nanofluids inside a microchannel heat exchanger for electronic cooling, J. Therm. Anal. Calor. 149 (9) (2024) 4119–4131.
[149] S. Dayou, T. Wei, B. Vigolo, Comparison of heat transfer performance of water-based graphene nanoplatelet- and multi-walled carbon nanotube-nanofluids in a concentric tube heat exchanger, Diam. Relat. Mater. 125 (53) (2022) 1–9.
[150] M. Bahiraei, A. Monavari, Thermohydraulic performance and effectiveness of a mini shell and tube heat exchanger working with a nanofluid regarding effects of fins and nanoparticle shape, Adv. Powder Technol. 32 (2021) 1–13.
[151] F. Afshari, A.D. Tuncer, A. Sözen, H.I. Variyenli, A. Khanlari, E.Y. Gürbüz, A comprehensive survey on utilization of hybrid nanofluid in plate heat exchanger with various number of plates, Int. J. Numer. Methods Heat. Fluid Flow. 32 (1) (Jan. 2022) 241–264, https://doi.org/10.1108/HFF-11-2020-0743.
[152] D. Zhong, H. Zhong, T. Wen, Investigation on the thermal properties, heat transfer and flow performance of a highly self-dispersion TiO2 nanofluid in a multiport mini channel, Int. Commun. Heat. Mass Transf. 117 (2020) 1–14.
[153] S. Zeinali, E. Neshat, A. Sarrafzadeh, Comparison of the use of different nanofluids for heat transfer from the outer surface of spiral tubes: Energy, exergy, and exergoeconomic (3E) analysis, Case Stud. Therm. Eng. 52 (2023) 103693.
[154] A.Razak Kaladgi, K.C. Vishwanath, P. Madhu, A. Chandrashekar, B. V. Chaluvaraju, Effect of copper oxide nano fluids as coolant on thermal performance of spiral heat exchanger, IOP Conf. Ser. Mater. Sci. Eng. 1189 (1) (2021) 012037.
[155] D. Zheng, J. Wang, Z. Chen, J. Baleta, B. Sundén, Performance analysis of a plate heat exchanger using various nanofluids, Int. J. Heat. Mass Transf. 158 (76) (2020) 1–11.
[156] G. Peker, C. Yıldız, G. Çakmak, A. Yıldız, Investigation of the effect of nanofluids on heat transfer enhancement by using parallel and vertical springs in a plate heat exchanger, Heat. Mass Transf. 59 (7) (2023) 1167–1183.
[157] S. Thet, M. Than, K.A. Lin, M.S. Mon, Heat. Exch. Des. 2 (10) (2018).
[158] E. Edreis, A. Petrov, Types of heat exchangers in industry, their advantages and disadvantages, and the study of their parameters, IOP Conf. Ser. Mater. Sci. Eng. 963 (Nov. 2020) 12027, https://doi.org/10.1088/1757-899X/963/1/012027.
[159] S.-P. Yu, Y.-F. Lue, T.-P. Teng, H.-K. Hsieh, and C.-C. Huang, "Enhanced Heat Transfer Performance of the Tube Heat Exchangers Using Carbon-Based Nanofluids," 2021. doi: 10.3390/app11178139.
[160] R.A. Parisher, R.A. Rhea, Chapter 6 - Mechanical equipment, in: R.A. Parisher, R. A.B. T.-P. D., D. (Fourth E. Rhea (Eds.), Pipe Drafting and Design, Boston: Gulf Professional Publishing, 2022, pp. 119–153, https://doi.org/10.1016/B978-0-12-822047-4.00011-X.
[161] V.S. Devahdhanush, Y. Lei, Z. Chen, I. Mudawar, Assessing advantages and disadvantages of macro- and micro-channel flow boiling for high-heat-flux thermal management using computational and theoretical/empirical methods, Int. J. Heat. Mass Transf. 169 (2021) 120787, https://doi.org/10.1016/j.ijheatmasstransfer.2020.120787.
[162] S. Ghanami, M. Farhadi, Heat transfer enhancement in a single-pipe heat exchanger with fluidic oscillators, J. Therm. Anal. Calor. 140 (3) (2020) 1107–1119, https://doi.org/10.1007/s10973-019-08816-2.
[163] M. Behera, J. Nayak, S. Bal, Heat transfer analysis of CuO-ZnO/water hybrid nanofluid in a Shell and tube heat exchanger with various tube shapes, Int. J. Thermofluids (2024) 100972, https://doi.org/10.1016/j.ijft.2024.100972.
[164] R.K. Ajeel, W.-I.W. Salim, K. Hasnan, Numerical investigations of heat transfer enhancement in a house shaped-corrugated channel: combination of nanofluid and geometrical parameters, Therm. Sci. Eng. Prog. 17 (2020) 100376, https://doi.org/10.1016/j.tsep.2019.100376.
[165] S.A. Marzouk, A. Aljabr, F.A. Almehmadi, S. Alqaed, M.A. Sharaf, Numerical study of heat transfer, exergy efficiency, and friction factor with nanofluids in a plate heat exchanger, J. Therm. Anal. Calor. 148 (20) (2023) 11269–11281, https://doi.org/10.1007/s10973-023-12441-5.
[166] A. Bhattad, J. Sarkar, P. Ghosh, Hydrothermal performance of different alumina hybrid nanofluid types in plate heat exchanger, J. Therm. Anal. Calor. 139 (6) (2020) 3777–3787, https://doi.org/10.1007/s10973-019-08682-y.
[167] S. Jaganathan, et al., Experimental investigation of the performance of silver nanofluid as a coolant in a helical shell and tube heat exchanger, J. Therm. Anal. Calor. 149 (1) (2024) 439–451, https://doi.org/10.1007/s10973-023-12722-z.
[168] G.S. Dhumal, S.N. Havaldar, Enhancing heat transfer performance in a double tube heat exchanger: experimental study with twisted and helical tapes, Case Stud. Therm. Eng. 51 (2023) 103613, https://doi.org/10.1016/j.csite.2023.103613.
[169] X. Li, U. Khaled, A. Al-Rashed, M. Goodarzi, M. Sarafraz, R. Meer, Heat transfer evaluation of a microchannel heat exchanger cooling with spherical carbon-acetone nanofluid, Int. J. Heat. Mass Transf. 149 (2020) 119124, https://doi.org/10.1016/j.ijheatmasstransfer.2019.119124.
[170] V.N.S.H. Nakhjavani, Thermal performance of a micro heat exchanger (MHE) working with zirconia - based nanofluids for industrial cooling, Int. J. Ind. Chem. 10 (2) (2019) 193–204, https://doi.org/10.1007/s40090-019-0183-6.
[171] J.H. Lee, S.G. Hwang, and G.H. Lee, "Efficiency Improvement of a Photovoltaic Thermal (PVT) System Using Nanofluids," 2019. doi: 10.3390/en12163063.
[172] M. Farhan, et al., Experimental performance evaluation of an auto-tracking parabolic trough solar collector with recirculation of nanofluids, J. Therm. Anal. Calor. (2025), https://doi.org/10.1007/s10973-025-14001-5.
[173] H. Ravi Kulkarni, C. Dhanasekaran, P. Rathnakumar, S. Sivaganesan, Experimental study on thermal analysis of helical coil heat exchanger using Green synthesis silver nanofluid, Mater. Today Proc. 42 (2021) 1037–1042, https://doi.org/10.1016/j.matpr.2020.12.087.
[174] M.A. Gabris, J. Ping, Carbon nanomaterial-based nanogenerators for harvesting energy from environment, Nano Energy 90 (2021) 106494, https://doi.org/10.1016/j.nanoen.2021.106494.
[175] M. Mehos et al., "Concentrating Solar Power Gen3 Demonstration Roadmap. Technical Report: NREL/TP-5500-67464," Natl. Renew. Energy Lab., no. January, pp. 1–140, 2017, [Online]. Available: https://www.nrel.gov/docs/fy17osti/67464.pdf%0Ahttp://www.nrel.gov/docs/fy17osti/67464.pdf.
[176] Cimetrics Analytika, "Revolutionary Nanotechnology for Energy Efficiency Gains," Revolutionary Nanotechnology for Energy Efficiency Gains. [Online]. Available: ⟨https://analytika.com/nanotechnology-in-energy-efficiency/⟩.
[177] M. Maisuria, M. Rathod, A. Parmar, Thermal performance augmentation of automobile radiator using water-based Al 2 O 3 and CuO nanofluid as a coolant, SEA MOBILUS 04 (14) (2020) 1340, https://doi.org/10.4271/2020-01-1340.
[178] S. Bright, "Nanotechnology and Semi-Transparent Solar Panels: Pioneers in Sustainable Agriculture," Sustainable Agriculture with Nanotechnology. [Online]. Available: ⟨https://www.britesolar.com/nanotechnology-and-semi-transparent-solar-panels-pioneers-in-sustainable-agriculture⟩.
[179] ThermoFisher, "Automated nanoparticle analysis workflow for large area, high resolution imaging and data acquisition at the nanoscale.," Nanoparticle Analysis. [Online]. Available: ⟨https://www.thermofisher.com/ng/en/home/materials-science/automated-nanoparticle-workflow.html⟩.
[180] M. Sulaiman, S. Kuye, S. Owolabi, Investigation of fouling effect on overall performance of shell and tube heat exchanger in a urea fertilizer production company in Nigeria, Niger. J. Technol. 35 (1) (2016) 129, https://doi.org/10.4314/njt.v35i1.20.
[181] R.A. Wahyuono and I.M. Arsana, "Nanofluid-Enhancing Shell and Tube Heat Exchanger Effectiveness with Modified Baffle Architecture," M. Araiz, Ed., Rijeka: IntechOpen, 2021. doi: 10.5772/intechopen.96996.
[182] A. Almertejy, M.M. Rashid, N. Ali, and S. Almurtaji, "Application of Nanofluids in Gas Turbine and Intercoolers—A Comprehensive Review," 2022. doi: 10.3390/nano12030338.
[183] TSMC, "The New Frontier in Advanced Logic Technology," TSMC N2 Nanosheet. [Online]. Available: ⟨https://n2.tsmc.com/english/dedicatedFoundry/technology/N2.htm⟩.
[184] Intel, "Terasic DE10-Nano Kit," Terasic DE10-Nano Kit. [Online]. Available: ⟨https://www.intel.com/content/www/us/en/developer/topic-technology/edge-5g/hardware/fpga-de10-nano.html#:~:text=Flexible and Adaptive. Run state-of-the-art applications with,adapt to evolving standards%2C algorithms %2C and threats⟩.
[185] K. Pramanand, B. Yadav, A. Kumar, C. Bora, A. Kumar, S. Das, An experimental study on heat transfer performance of GO and rGO-CuO nanofluids in a heat exchanger, FlatChem 27 (3) (2021) 1–11.
[186] I. Fazeli, M. Reza, S. Emami, A. Rashidi, Investigation and optimization of the behavior of heat transfer and flow of MWCNT-CuO hybrid nanofluid in a brazed plate heat exchanger using response surface methodology, Int. Commun. Heat. Mass Transf. 122 (34) (2021) 1–18.
[187] C. Thianpong, K. Wongcharee, H. Safikhani, S. Chokphoemphun, A. Saysroy, Multi objective optimization of TiO 2 / water nanofluid flow within a heat exchanger enhanced with loose-fit delta-wing twisted tape inserts, Int. J. Therm. Sci. 172 (13) (2022) 1–12.
[188] R.R. Riehl, S. Mancin, Estimation of thermophysical properties for accurate numerical simulation of nanofluid heat transfer applied to a loop heat pipe, Int. J. Thermofluids 14 (May 2022) 100158, https://doi.org/10.1016/J.IJFT.2022.100158.
[189] Y. Cao, et al., MHD natural convection nanofluid flow in a heat exchanger: effects of Brownian motion and thermophoresis for nanoparticles distribution, Case Stud. Therm. Eng. 28 (2021) 1–12, https://doi.org/10.1016/j.csite.2021.101394.
[190] D. Zheng, J. Wang, Z. Chen, J. Baleta, B. Sundén, Performance analysis of a plate heat exchanger using various nanofluids, Int. J. Heat. Mass Transf. 158 (2020) 1–13.

[191] A. Bhattad, J. Sarkar, P. Ghosh, Experimentation on e ff ect of particle ratio on hydrothermal performance of plate heat exchanger using hybrid nano fl uid, Appl. Therm. Eng. 162 (4) (2019) 1–10.
[192] S.K. Singh, J. Sarkar, Thermohydraulic behavior of concentric tube heat exchanger inserted with conical wire coil using mono / hybrid nanofluids, Int. Commun. Heat. Mass Transf. 122 (7) (2021) 105–134.
[193] D. Purbia, A. Khandelwal, A. Kumar, A.K. Sharma, Graphene-water nanofluid in heat exchanger: mathematical modelling, simulation and economic evaluation, Int. Commun. Heat. Mass Transf. 108 (8) (2019) 1–12.
[194] I.M. Mahbubul, Thermophysical Properties of Nanofluids, in: I.M.B.T.-P. Mahbubul Characterization (Ed.), Micro and Nano Technologies, William Andrew Publishing, 2019, pp. 113–196, https://doi.org/10.1016/B978-0-12-813245-6.00004-6.
[195] N.B. Do, K. Imenes, K.E. Aasmundtveit, H.-V. Nguyen, and E. Andreassen, "Thermal Conductivity and Mechanical Properties of Polymer Composites with Hexagonal Boron Nitride—A Comparison of Three Processing Methods: Injection Moulding, Powder Bed Fusion and Casting," 2023. doi: 10.3390/polym15061552.
[196] M. Fernández-García, J.F. Sánchez-Pérez, F. del Cerro, and M. Conesa, "Mathematical Model to Calculate Heat Transfer in Cylindrical Vessels with Temperature-Dependent Materials," 2023. doi: 10.3390/axioms12040335.
[197] M. Everts, S. Bhattacharyya, A.I. Bashir, J.P. Meyer, Heat transfer characteristics of assisting and opposing laminar flow through a vertical circular tube at low Reynolds numbers, Appl. Therm. Eng. 179 (2020) 115696, https://doi.org/10.1016/j.applthermaleng.2020.115696.
[198] A.G. Caket, C. Wang, M.A. Nugroho, H. Celik, M. Mobedi, Recent studies on 3D lattice metal frame technique for enhancement of heat transfer: discovering trends and reasons, Renew. Sustain. Energy Rev. 167 (2022) 112697, https://doi.org/10.1016/j.rser.2022.112697.
[199] Fangfang Qi Chen, L. Xu, J. Yu, X. Chen, Effects of reynolds number on the overall characteristics of flow and heat transfer in the long micro-tube with dimples, Processes 10 (12) (2022), https://doi.org/10.3390/pr10122696.
[200] V. Kumar, R.R. Sahoo, 4 E ' s (Energy, Exergy, Economic, Environmental) performance analysis of air heat exchanger equipped with various twisted turbulator inserts utilizing ternary hybrid nanofluids, Alex. Eng. J. 61 (2022) 1–18.
[201] A. Mahammedi, H. Ameur, Y. Menni, D.M. Medjahed, Numerical study of turbulent flows and convective heat transfer of Al2 O 3 -water nanofluids in a circular tube, J. Adv. Res. Fluid Mech. Therm. Sci. 77 (2) (2021) 1–12.
[202] J. Jeevanandam, A. Barhoum, Y.S. Chan, A. Dufresne, M.K. Danquah, Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations, Beilstein J. Nanotechnol. 9 (4) (2019) 1–25.
[203] S. Mourdikoudis, R.M. Pallares, Characterization techniques for nanoparticles: comparison and complementarity upon studying, Nanoscale 10 (4) (2018) 1–64.
[204] T.R. Shah, et al., Potential evaluation of water-based ferric oxide (Fe2O3-water) nanocoolant: an experimental study, Energy 246 (2022) 123441, https://doi.org/10.1016/j.energy.2022.123441.
[205] M. Malika, R. Bhad, S.S. Sonawane, Journal of the Indian chemical society ANSYS simulation study of a low volume fraction CuO – ZnO / water hybrid nano fl uid in a shell and tube heat exchanger, J. Indian Chem. Soc. 98 (11) (2021) 1–16.
[206] G. Towler, R. Sinnott, Chapter 15 - Design of reactors and mixers (Third E. Sinnott, Eds.), in: G. Towler, R. B. T.-C. E. D (Eds.), Chemical Engineering Design, 3rd Edition, Butterworth-Heinemann, 2022, pp. 497–588, https://doi.org/10.1016/B978-0-12-821179-3.00015-7 (Third E. Sinnott, Eds.).
[207] F. Akashige, L. Theodore, Introduction to process heat transfer, Kern'S. Process Heat. Transf. (2019) 1–41, https://doi.org/10.1002/9781119364825.ch1.
[208] N.H. Abu-hamdeh, et al., The effects of incident solar radiation on the collector ef fi ciency using coolant hybrid nano fl uid via simulation of solar tower system with the parallel heat exchangers, J. Taiwan Inst. Chem. Eng. 124 (2021) 106–115.
[209] M. Bahiraei, M. Naseri, A. Monavari, A CFD study on thermohydraulic characteristics of a nanofluid in a shell-and-tube heat exchanger fitted with new unilateral ladder type helical baffles, Int. Commun. Heat. Mass Transf. 124 (5) (2021) 1–17.
[210] B.J. Jayesh P, Y. Mukkamala, Design and testing of energy-efficient heat exchangers for Newtonian and non-Newtonian fluids – a review, Sage J. Inst. Mech. Eng. 263 (3) (2021).
[211] M. Fares, M. Al-mayyahi, M. Al-saad, Heat transfer analysis of a shell and tube heat exchanger operated with graphene nanofluids, Case Stud. Therm. Eng. 18 (1) (2020) 1–8.
[212] H.A. Prince, A. Ghosh, M.M.H. Siam, M.A.H. Mamun, AI predicts MHD double-diffusive mixed convection and entropy generation in hybrid-nanofluids for different magnetic field inclination angles by ANN, Int. J. Thermofluids 19 (2023) 100383, https://doi.org/10.1016/j.ijft.2023.100383.
[213] A.G. Olabi, et al., Application of artificial intelligence for prediction, optimization, and control of thermal energy storage systems, Therm. Sci. Eng. Prog. 39 (2023) 101730, https://doi.org/10.1016/j.tsep.2023.101730.
[214] B. Ouyang, et al., Toxicity and environmental impact of multi-walled carbon nanotubes to nitrogen-fixing bacterium Azotobacter chroococcum, J. Environ. Chem. Eng. 9 (4) (2021) 105291, https://doi.org/10.1016/j.jece.2021.105291.
[215] M. Bahiraei, N. Mazaheri, A comprehensive analysis for second law attributes of spiral heat exchanger operating with nanofluid using two-phase mixture model: Exergy destruction minimization attitude, Adv. Powder Technol. 32 (1) (2021) 211–224.
[216] S.M.M. Rizvi, D. Shin, Specific heat capacity, viscosity, and thermal stability of carbonate-based molten salt nanofluids, J. Energy Storage 43 (2021) 103192, https://doi.org/10.1016/j.est.2021.103192.
[217] K. Yashawantha, V. Vinod, Heat trasnfer characterisitcs and entropy generation analysis in a plate heat exchanger using gycol and water mixture-based Al2O3 nanofluid, Heat. Transf. 51 (8) (2022) 296–322.
[218] M.S. Yılmaz, M. Ünverdi, H. Kücük, N. Akcakale, F. Halıcı, Enhancement of heat transfer in shell and tube heat exchanger using mini-channels and nanofluids: an experimental study, Int. J. Therm. Sci. 179 (2022) 107664, https://doi.org/10.1016/j.ijthermalsci.2022.107664.
[219] M. Ogbonnaya, et al., Rheological characteristics of aluminium oxide (AL2O3) based nanolubricant, Niger. J. Technol. 39 (2) (2020) 424–432.
[220] R. Pal, A novel method to determine the thermal conductivity of interfacial layers surrounding the nanoparticles of a nanofluid, Nanomaterials 4 (4) (2014) 844–855.
[221] A. Hajatzadeh, S. Aghakhani, M. Afrand, B. Mahmoudi, An updated review on application of nano fl uids in heat exchangers for saving energy, Energy Convers. Manag 198 (34) (2019) 1–13.
[222] M. Nadda, S.K. Shah, S. Roy, A. Yadav, CFD-based deep neural networks (DNN) model for predicting the hydrodynamics of fluidized beds, Digit. Chem. Eng. 8 (2023) 100113, https://doi.org/10.1016/j.dche.2023.100113.
[223] M. Shirzad, S. Soheil, M. Ajarostaghi, M. Aghajani, K. Sedighi, Improve the thermal performance of the pillow plate heat exchanger by using nanofluid: numerical simulation, Adv. Powder Technol. 30 (7) (2019) 1356–1365.
[224] A. Borode, T. Tshephe, P. Olubambi, A critical review of the thermophysical properties and applications of carbon-based hybrid nanofluids in solar thermal systems (no. January,), Front. Energy Res. 12 (2024) 1–31, https://doi.org/10.3389/fenrg.2024.1509437.
[225] D.K. Le, J.Y. Yoon, A hybrid CFD – Deep learning methodology for improving the accuracy of pressure drop prediction in cyclone separators, Chem. Eng. Res. Des. 190 (2023) 296–311, https://doi.org/10.1016/j.cherd.2022.12.035.
[226] U. Singh, N.K. Gupta, Stability issues and operating limitations of nanofluid filled heat pipe: a critical review, Mater. Today Proc. (2023), https://doi.org/10.1016/j.matpr.2023.01.309.
[227] M. Omri, H. Smaoui, L. Frechette, L. Kolsi, A new microchannel heat exchanger configuration using CNT-nanofluid and allowing uniform temperature on the active wall, Case Stud. Therm. Eng. 32 (4) (2022) 118–136.
[228] M.S. Graish, et al., Prediction of the viscosity of iron-CuO/water-ethylene glycol non-Newtonian hybrid nanofluids using different machine learning algorithms, Case Stud. Chem. Environ. Eng. 11 (2025) 101180, https://doi.org/10.1016/j.cscee.2025.101180.
[229] M. Oh *et al.*, "Transition of Carbon Nanotube Sheets from Hydrophobicity to Hydrophilicity by Facile Electrochemical Wetting," 2023. doi: 10.3390/nano13212834.
[230] H.Ben Bacha, N. Ullah, A. Hamid, N.A. Shah, A comprehensive review on nanofluids: Synthesis, cutting-edge applications, and future prospects (no. January), Int. J. Thermofluids 22 (2024) 100595, https://doi.org/10.1016/j.ijft.2024.100595.
[231] P.K. Das, et al., An extensive review of preparation, stabilization, and application of single and hybrid nanofluids, J. Therm. Anal. Calor. 149 (17) (2024) 9523–9557, https://doi.org/10.1007/s10973-024-13449-1.
[232] V. Ghazanfari, A. Taheri, Y. Amini, F. Mansourzade, Enhancing heat transfer in a heat exchanger: CFD study of twisted tube and nanofluid (Al2O3, Cu, CuO, and TiO2) effects, Case Stud. Therm. Eng. 53 (2024) 103864, https://doi.org/10.1016/j.csite.2023.103864.
[233] M. Bahiraei, S. Heshmatian, H. Moayedi, Artificial intelligence in the field of nanofluids: a review on applications and potential future directions, Powder Technol. 353 (2019) 276–301, https://doi.org/10.1016/j.powtec.2019.05.034.
[234] A. Basu, A. Saha, S. Banerjee, P.C. Roy, and B. Kundu, "A Review of Artificial Intelligence Methods in Predicting Thermophysical Properties of Nanofluids for Heat Transfer Applications," 2024. doi: 10.3390/en17061351.
[235] E.J. Onyiriuka, Predicting the accuracy of nanofluid heat transfer coefficient ' s computational fluid dynamics simulations using neural networks, HEAT Transf. 52 (4) (2023) 3389–3410.
[236] H. Adun, I. Wole-Osho, E.C. Okonkwo, O. Bamisile, M. Dagbasi, S. Abbasoglu, A neural network-based predictive model for the thermal conductivity of hybrid nanofluids, Int. Commun. Heat. Mass Transf. 119 (2020) 104930, https://doi.org/10.1016/j.icheatmasstransfer.2020.104930.
[237] M. Sadeghzadeh, et al., Prediction of thermo-physical properties of TiO2-Al2O3/water nanoparticles by using artificial neural network, Nanomater. 2020 Vol. 10 Page 697 10 (4) (Apr. 2020) 697.
[238] S.M. Mamand, Applied sciences thermal conductivity calculations for nanoparticles embedded in a base fluid, Appl. Sci. 11 (2021) 1459–1470.
[239] M.H. Esfe, S. Esfande, S.H. Rostamian, Experimental evaluation, new correlation proposing and ANN modeling of thermal conductivity of ZnO-DWCNT / EG hybrid nanofluid for internal combustion engines applications (Online]. Available), Appl. Therm. Eng. 133 (2018) 452–463, https://doi.org/10.1016/j.applthermaleng.2017.11.131.
[240] M. Sepehrnia, Majtaba Mohammadzadeh, Kazem Veyseh, M.Mohammad Agah, Emad Amani, Rheological behavior of engine oil based hybrid nanofluid containing MWCNTs and ZnO nanopowders: experimental analysis, developing a novel correlation, and neural network modeling, Power Technol. 404 (2022) 1–15.
[241] B. Yang, et al., Computer vision and machine learning methods for heat transfer and fluid flow in complex structural microchannels: a review, energies 16 (2023) 1500.
[242] A. Karthikeyen, W. Rapheal, J.R. Taveres, Nanofluids as heat transfer fluids: hurdles to industrial application and economic considerations, Can. J. Chem. Eng. 100 (11) (2021) 3311–3320.

[243] Z. Liu, R. Fu, Y. Yuying, Preparation and evaluation of stable nanofluids for heat transfer application, Adv. Nanolfuid Heat. Transf. (2022) 25–57.
[244] L. Zhang, P. Qu, Y. Ling, X. Yao, W. Wang, C. Shi, Mechanism analysis of the influence of nanoparticles on the convective heat transfer coefficient of traditional fluids, Mater. Commun. 32 (2022) 1–25.
[245] N. Czaplicka, A. Grzegoska, J. Wajs, J. Sobczak, A. Rogala, Promising nanoparticle-based heat transfer fluids—environmental and techno-economic analysis compared to conventional fluids, MDPI 22 (7) (2021) 9201–9221.
[246] A.H. Alami, et al., A critical insight on nanofuids for heat transfer enhancement, Sci. Rep. 13 15303 (2023) 1–14.
[247] Z. Said, E. Bellos, H. Muhammad Ali, S. Rahman, C. Tzivanidis, Nanofluids, turbulators, and novel working fluids for heat transfer processes and energy applications: current status and prospective, Appl. Therm. Eng. 258 (2025) 124478, https://doi.org/10.1016/j.applthermaleng.2024.124478.