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Review article

Thermophysical properties of nanofluids and their potential applications in heat transfer enhancement: A review

Sujata Kalsi [a], Sunil Kumar [a,*], Anil Kumar [b], Tabish Alam [c], Dan Dobrotă [d,*]

[a] Yogananda School of AI, Computers and Data Science, Shoolini University, Solan, India
[b] Department of Mechanical Engineering, UPES, Dehradun 248007, Uttarakhand, India
[c] CSIR-Central Building Research Institute, Roorkee 247667, Uttarakhand, India
[d] Faculty of Engineering, Department of Industrial Engineering and Management, Lucian Blaga University of Sibiu, 550024 Sibiu, Romania

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ABSTRACT

Colloidal suspensions of nanoparticles in a base fluid, known as nanofluids, have become increasingly popular in recent years due to their unique thermophysical features and promising heat transfer applications. This article provides an in-depth look at the latest developments in the field of nanofluids, covering everything from their synthesis techniques to their thermophysical characteristics. The advantages and disadvantages of nanofluids and their prospective uses in heat exchangers were also discussed. Study reveals that hybrid nanofluids are good alternatives in different heat exchangers as compared to simple fluids because of their better thermal performance. The stability of the thermal system not only influences the system's thermophysical parameters but also influences the system's performance. It has also been compared to how well nanofluids and conventional fluids function in heat exchangers. In conclusion, this article is a great reference for scientists and engineers who want to learn more about the use of nanofluids in heat transfer.

1. Introduction

Nanofluid is an attractive heat transfer fluid for use in better heat transfer (HT) applications due to its excellent thermal conductivity and rheological properties (Mikkola et al. 2018). When these millimeter or micrometer-sized particles are added to the base fluid, the base fluid's thermophysical properties change, making heat transfer better (Sundar et al. 2017). The unique properties of nanofluids, such as improved heat transfer performance, and increased stability, have led to their application in various fields. Adding nanoparticles to the base fluid alter its properties, resulting in improved performance compared to traditional fluids (Salman et al. 2020). The heat transfer rate and efficiency improved thermal performance of heat sinks for cooling electronic processors by using nanofluids (Afshari & Muratçobanoğlu, 2023). The application of nanofluids is broadly classified into two categories: heat transfer and non-heat transfer applications. In HT applications, nanofluids are used as coolants in industries such as automotive, aerospace, and electronics (Saidina et al. 2020). The enhanced thermal conductivity of nanofluids results in improved HT performance and reduced energy consumption (Kumar et al. 2022b). Overall, the application of nanofluids is a rapidly growing area that could have many different uses in various industries. The unique properties of nanofluids make them promising alternatives to traditional fluids, and ongoing research is focused on optimizing their performance for different applications in heat exchangers. The stability of the nanofluids and sedimentation of particles are operated in the field of heat exchanger by nanofluids (Afshari et al. 2022). Over the past ten years, the significance of Nanofluid research has become more apparent, as shown in Fig. 1, which lists the number of articles published since 2012 that mention nanofluids. These studies cover those that deal with their preparation, thermophysical properties measurement, and use in several applications. The information in Fig. 1 was discovered by looking through titles, abstracts, and keywords in Google Scholar for the terms "Nanofluids" and "Nanofluids in Heat Exchanger" over the time displayed. The search

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* Corresponding authors.
E-mail addresses: sunilthakur@shooliniuniversity.com (S. Kumar), k.anil@ddn.upes.ac.in (A. Kumar), tabish.iitr@gmail.com (T. Alam), dan.dobrota@ulbsibiu.ro (D. Dobrotă).

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Nomenclature

Symbols	**Units**
Nu	Nusselt number, Dimensionless
Re	Reynolds number, Dimensionless
C_p	Specific Heat Capacity, J/Kg.K
K_{nf}	Thermal conductivity of Nanofluid, W/mK
K_p	Thermal conductivity of the particles, W/mK
K_{bf}	Thermal conductivity of base fluid, W/mK
T	Temperature, K

Greek Symbols

μ_{bf}	Base fluid Viscosity, Ns/m^2
φ_m	Maximum particles packing fraction, Dimensionless
μ_{nf}	Nanofluid Viscosity, Pa/s
φ	Volume fraction of particles, Dimensionless
μ	Viscosity, Pa/s
T_{nf}	Temperature of Nanofluid, K

Abbreviations:

Bf	Base fluid
CNT	Carbon Nano Tube
HE	Heat Exchanger
HT	Heat Transfer
HTC	Heat Transfer Coefficient
HNF	Hybrid Nanofluid
MWCNT	Multi-walled carbon nanotube
NFs	Nanofluids
NPs	Nanoparticles
PEG	Polyethylene-glycol
PAS	Primary alkyl sulphate
SDS	Sodium Dodecyl Sulphate
SDBS	Sodium Dodecyl Benzene Sulphonate

revealed that 26,000 papers were circulated in 2022 alone, and this trend is expected to continue in the years to come.

The novelty of this review paper would lie in its focus on the latest development in the synthesis, characterization, and application of developing applications for nanofluids in areas including energy storage and desalination and biomedical engineering, highlighting the potential for these materials to enable new technologies and solutions for important social challenges.

This review article aims to provide a comprehensive summary of the current state of the art in the subject of nanofluids and their potential to enhance heat transfer in heat exchangers. In section 2 included an overview of NFs and their preparation. Section 3 outlined nanofluids' discussed most important properties such as thermal conductivity, viscosity, density, and specific heat capacity are all vital thermophysical qualities. Section 4 reviewed various nanofluids' applications related to heat exchangers, desalination, and bio-medical applications. The 5th section showed the challenges in nanofluid applications. Lastly, the section shows some concluding remarks and suggestions for future research.

2. Nanofluid, preparation and stabilization

Nanofluids are a type of fluid that has been engineered to have nanoparticles suspended in them. This suspension gives the nanofluid enhanced properties, such as increased heat transfer (HT) efficiency and thermal conductivity. NFs can be used to improve the performance of heating and cooling systems, increase the efficiency of solar cells, and even enhance the delivery of drugs to specific targets in the body (Nobrega et al. 2022). NFs are promising new technology that could revolutionize many industries in the future.

There are many nanofluids which are prepared by the mixture of nanoparticles and base fluids (BFs), like Copper oxide (CuO), Alumina (Al_2O_3), Silver (Ag), Zinc Oxide (ZnO), Titanium Dioxide

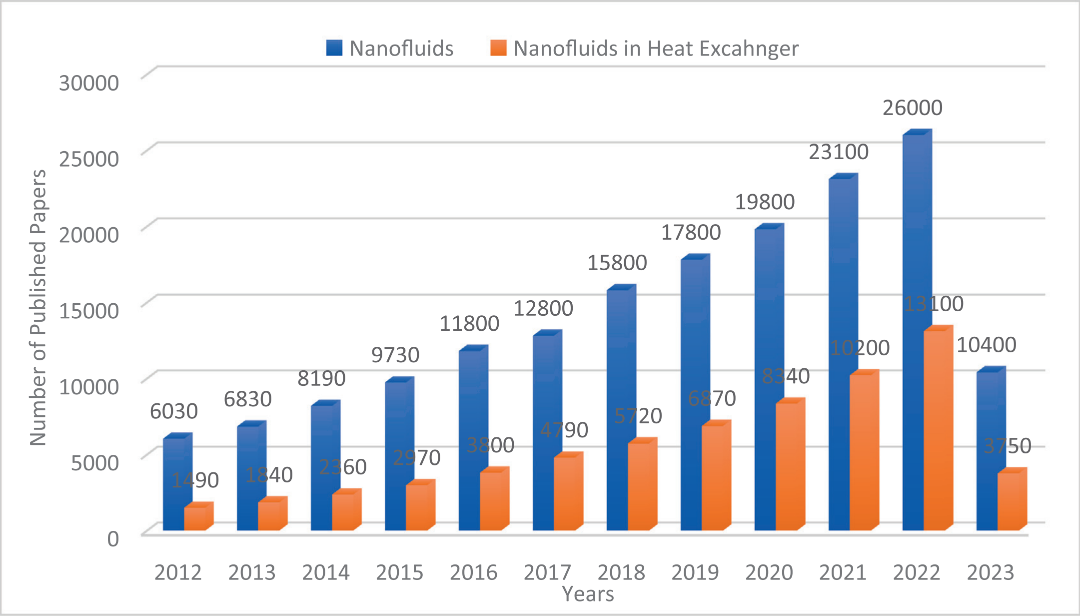


Fig. 1. The popularity of Nanofluids in last ten years. (Google Scholar for the search of Nanofluids, April 2023).

(TiO_2) Carbon Nanotube (CNT), Iron Oxide (Fe_2O_3), Magnesium Oxide (MgO), Cerium Oxide (CeO_2), Gold Nanoparticle (AU). Whereas common BFs may include, H_2O, ethylene–glycol and other coolants and lubricants, Bio-fluids etc. Mapping of some BFs and NPs shown in Fig. 2 the summarizing published articles related to NFs (Sharma & Mital 2016; Kumar & Arasu 2018),(Ali et al. 2018) Important reviews cover nanoparticle and nanofluid synthesis, characterisation, stability, aggregation, characteristics, and applications.

2.1. Preparations of nanofluids

The preparation of nanofluid is essential because it determines their stability. In general, researchers created nanofluids using the one-step and two-step method. The one-step method makes and disperses nanoparticles in BFs. This method avoids nanoparticle drying, storage, transportation, and dispersion. NFs have better thermal conductivity, diffusivity, convective HTC and viscosity than water or oil (Bakthavatchalam et al. 2020). NFs combine carbon, metal, oxide, and ceramic NPs with BFs, including, H_2O, ethylene, etc. Method for synthesizing nanoparticles is shown in Fig. 3. Nanoparticles (NPs) can be synthesised chemically, physically, physiochemically, or biologically (Asadi et al. 2019).

2.1.1. One step method

In a one-step method, the -size particles are made and dispersed into BFs simultaneously, which usually leads to less agglomeration (Chakraborty & Panigrahi 2020). Fig. 4 demonstrates the synthesis and dispersion of nanoparticles through this method. The one-step process had good dispersion stability compared to the two-step method (Aberoumand & Jafarimoghaddam 2018). The benefits and drawbacks of the one-step approach are laid out in Table 1. The most popular one-step method includes microwave radiation, laser ablation in liquid (LAL) etc. Microwave radiation includes microwave irradiating of microwave radiation includes microwave irradiating the initial solution utilizing the presence of a reducer. Energy for heating the fluid and driving the nucleation process comes from microwave irradiation(Zhu et al. 2004).

2.1.2. Double-Step method

The double-step method involves the dispersion of these nanoparticles in the BFs using various techniques like ultrasonication, high shear mixing and mechanical or magnetic stirring. The NPs are produced first and subsequently dispersed into BFs (Chakraborty & Panigrahi 2020). This method is highly effective in achieving better performance than the one-step method. However, when preparing nanofluid using the double-step method, it tends to result in high, agglomeration, leading to reduced stability compared to the One-step method (Mohammadpoor et al. 2019). Then, the dry powder nanoparticles are merged into the BFs using ultrasonic agitation and mixing, as shown in Fig. 5. There are some advantages and disadvantages of the double-step method which are shown in Table 1.

2.2. Stabilization of nanofluids

To prevent this undesirable behaviour and enhance the stability of nanofluids, surfactant are often used. Surfactants help prevent the agglomeration of NPs by reducing the surface tension between the NPs and the BFs (Gülmüş et al. 2023). Surfactants are containing both hydrophilic and hydrophobic region in their molecular structure. They absorb at the liquid–gas or liquid–liquid interfaces, reducing surface tension and improving the dispersion and stability of nanofluids. The stability of nanofluids is directly connected to their properties (Mukherjee et al. 2018). There are different types of surfactants to stabilize nanofluids like cationic, anionic, amphoteric and non-ionic. They also function as wetting agents, preventing the formation of droplets on the surface of solid particles suspended in a liquid. Other standard methods of stabilization include the use of shear thinning agents, the addition of electrolytes, and high-frequency ultrasound. There are some important aspects of stability shown in Fig. 6.

There are some drawbacks of using surfactants. Surfactants may exhibit significantly changes in their properties, particularly at elevated temperature. These changes can impact their effectiveness in stabilizing nanofluids potentially leading to reduced stability (Anggraini et al. 2020).

3. Thermophysical properties of nanofluids

To predict the HT behaviour of NFs, knowledge of their thermophysical properties is crucial. There is no contention that the addition of NPs, which have distinct thermophysical properties, alters the thermophysical properties of typical working fluids. There are some thermophysical properties of nanofluids like thermal con-

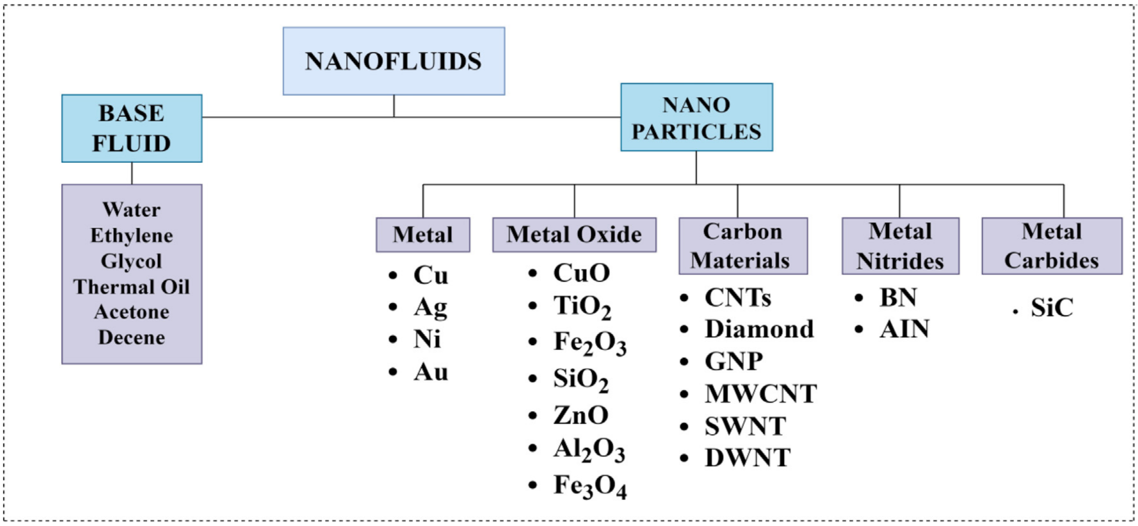


Fig. 2. Illustration of Various Base Fluids and Nanoparticles (Sajid & Ali, 2019).

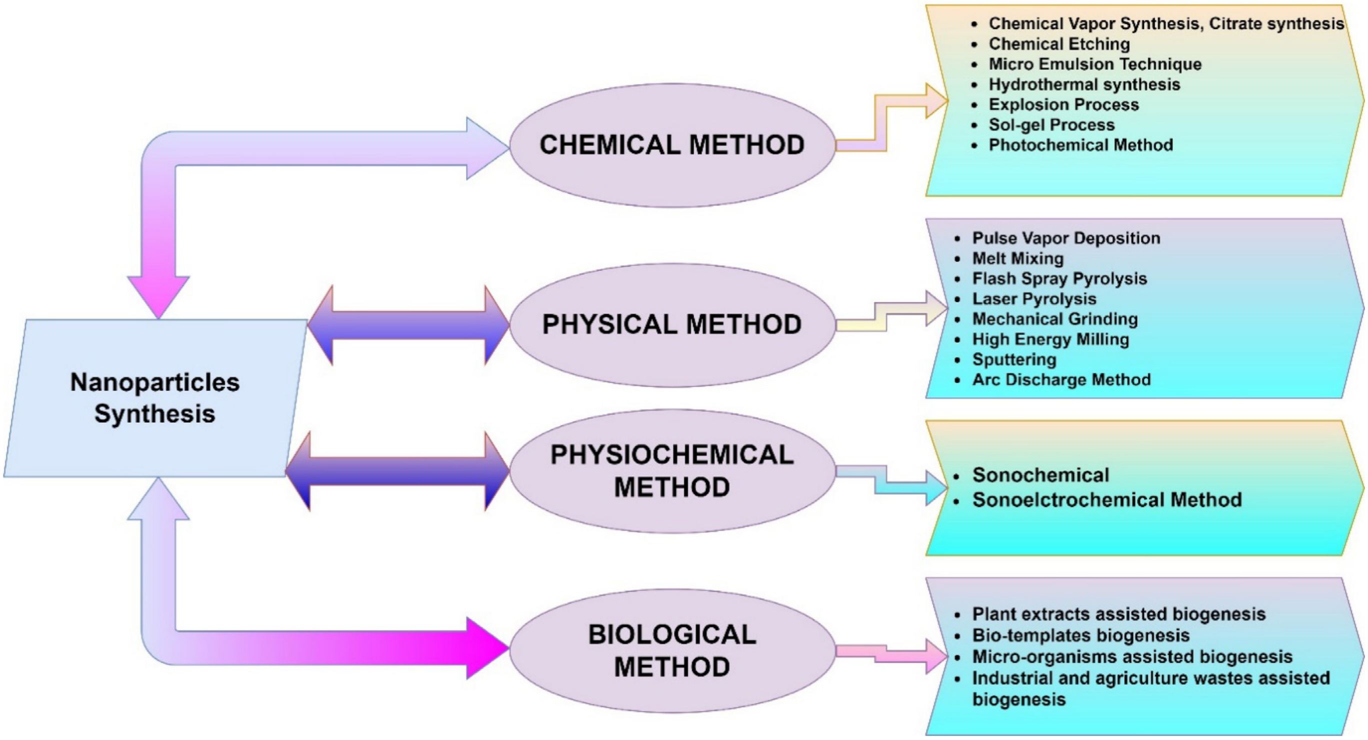


Fig. 3. Different methods of synthesizing nanoparticles (Bakthavatchalam et al. 2020).

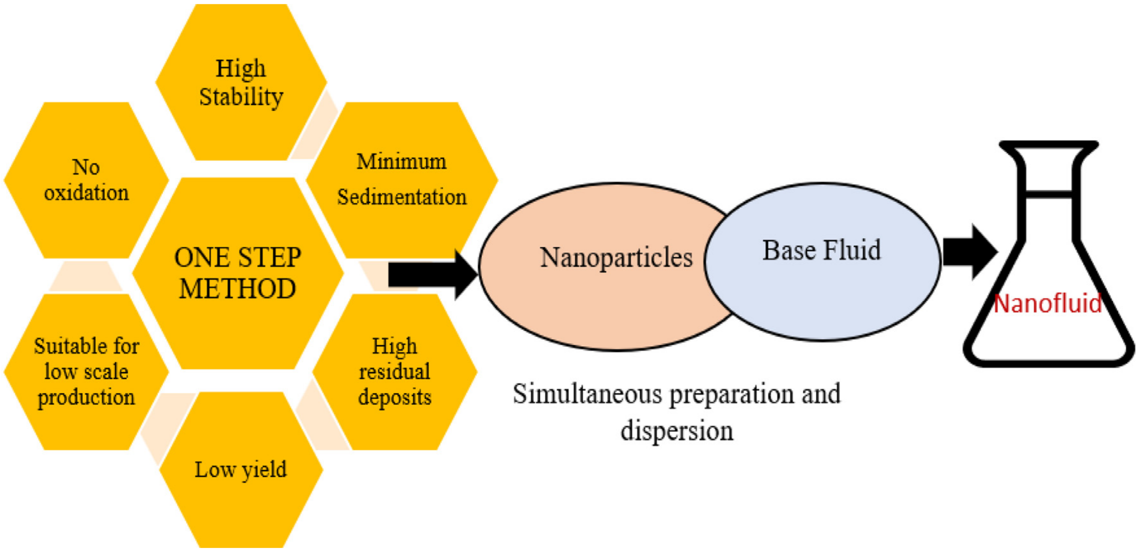


Fig. 4. One-Step Method (Bakthavatchalam et al. 2020).

ductivity, viscosity, specific heat capacity and density. By including nanoparticles into the BF, its thermal conductivity, viscosity, density, and specific heat can be considerably improved, all of which have an impact on the convective HT. The size, shape, concentration, and type of NPs as well as the qualities of the Bf all have an impact on the thermophysical parameters of NFs. This section gives a comprehensive and up-to-date review of the thermophysical characteristics and influencing factors of various BFs and nanoparticles (Said et al. 2021).

3.1. Thermal conductivity

The variation in nanofluids' thermal conductivity has been the subject of extensive theoretical and experimental study. As can be shown in Fig. 7, the thermal conductivity of NFs is affected by a wide range of parameters, including particle (size, shape, and material) and Bf, additives, and temperature. The thermal conductivity of NFs appears to be the most researched attribute in the existing literature. NFs are distinct from regular BFs because of

Table 1
Advantages and disadvantages of one-step and double-step methods.

One-Step Method		Double-Step Method	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
No StorageNo Drying	High deposit of residual reactants	Most simple and economical	Need surfactant or functionalisation
No oxidationNo transportation	Suitable for low-pressure base liquids	Ideal for large scale	Increase of self-weight
No Re-dispersionrequirement	Not scaled up for large-scale production	Suitable for oxide nanoparticles	Rapid sedimentation, Quick agglomeration
Less agglomerationHigh Stability	The synthesis method is expensive	Cost-effective production	High surface energy

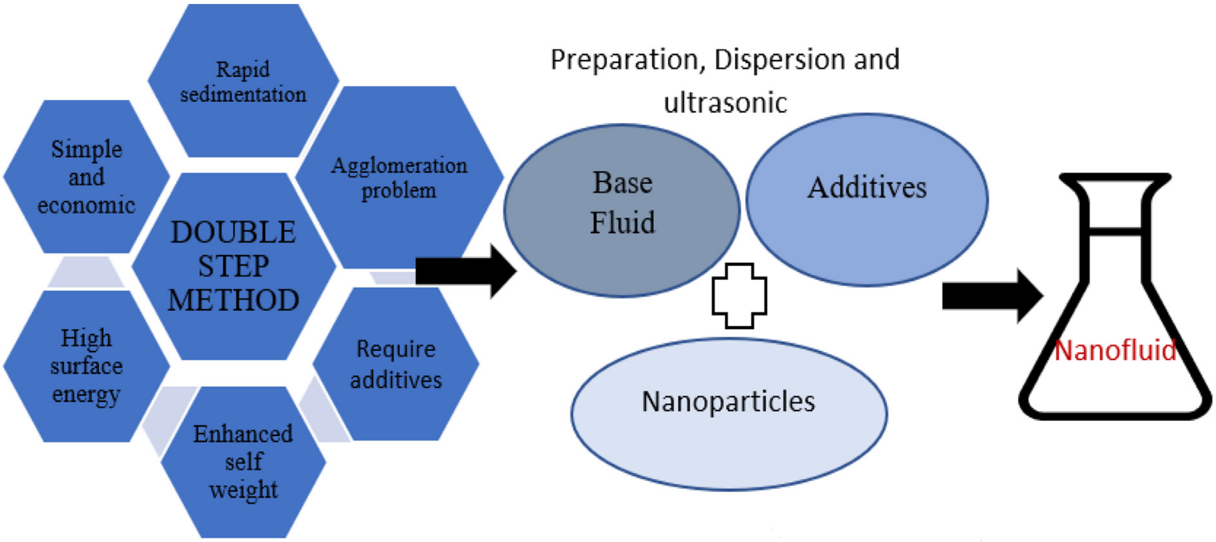


Fig. 5. Double-Step Method (Bakthavatchalam et al. 2020).

their improved thermal conductivity and other novel thermophysical features (Okonkwo et al. 2021). For the thermal conductivity of nanofluid, extensive experimental research was carried out utilizing various methodologies, which are discussed below.

3.2. Previous studies on thermal conductivity of nanofluids

Besides the numerical studies, there are so many experimental studies which different researchers have taken out to investigate the thermal conductivity of NFs using different types of BFs. How dispersant concentration and other parameters such as mass fraction, temperature, and standing time influenced CNT-nanofluid thermal conductivity. They discussed and observed the 20–60 °C range for temperature and φ is 0–7%, respectively. At increasing temperature and φ, the NF thermal conductivity increased Zhang et al. (2021) and Shahsavar et al. (2022).

Other various researchers have shown numerous theoretical studies to study the changes in the thermal conductivity of NFs (Yu and Choi (2003); Khdher et al. (2016); Yang et al. (2017); Pare & Ghosh (2021)). Maxwell (1873) presented the first correlation to compute suspension thermal conductivity of constituent phases and solid phase volume fraction. However, the correlation was only applicable to spherical particles. Hamiliton and Crosser (1962) suggested a modified Maxwell model with an empirical shape factor to extend the correlation to non-spherical particles. Xue (2005) calculated effective thermal conductivity using the very large axial ratio and spatial distribution of CNTs. Alawi et al. (2018) investigated the thermal conductivity of metallic oxide NFs for various NPs shapes and concentrations to enhance thermal system performance. Different researchers have created different theoretical and experimental models for determining the thermal conductivity of NFs, and a summary of these approaches is provided in Table 2.

3.3. Viscosity

The viscosity (μ) of nanofluids has been studied a great deal in recent decades because it could be useful in many industrial and medical fields. The accumulation of nanoparticles to the BF can increase its viscosity due to high surface area and interparticle solid forces (Girard et al. 2021). The viscosity of NFs is affected by several factors such as type, concentration, size, and surface characteristics of NPs, as well as the type of BFs. Moreover, the temperature also affects the viscosity of NFs, with increasing temperature resulting in decreasing viscosity (Suresh et al. 2011). Several experimental studies have been shown on the viscosity of NFs, which are further discussed in the following section.

3.4. Previous studies on viscosity of nanofluids

There are numerous experimental studies in addition to the numerical ones that different researchers have carried out to investigate the μ_{nf} discussed. Saeedinia & Razi (2012) investigated CuO-oil based NF and tested (0.2–2%) particle weight concentrations at temperature 293–343 K and μ increases with nanoparticle concentration, particularly at lower nanofluid temperature. Esfe et al. (2014) studied the turbulent flow of COOH-functionalised MWCNT/Water in double-tube heat exchanger at temperature and volume concentration (0.05%-1%). The result revealed that the HTC and thermal performance factor increased at the concentration (0.05%-1%). Sundar et al. (2014) showed that 60:40% EG/W-based NFs had a higher viscosity than 40:60% and 20:80% at

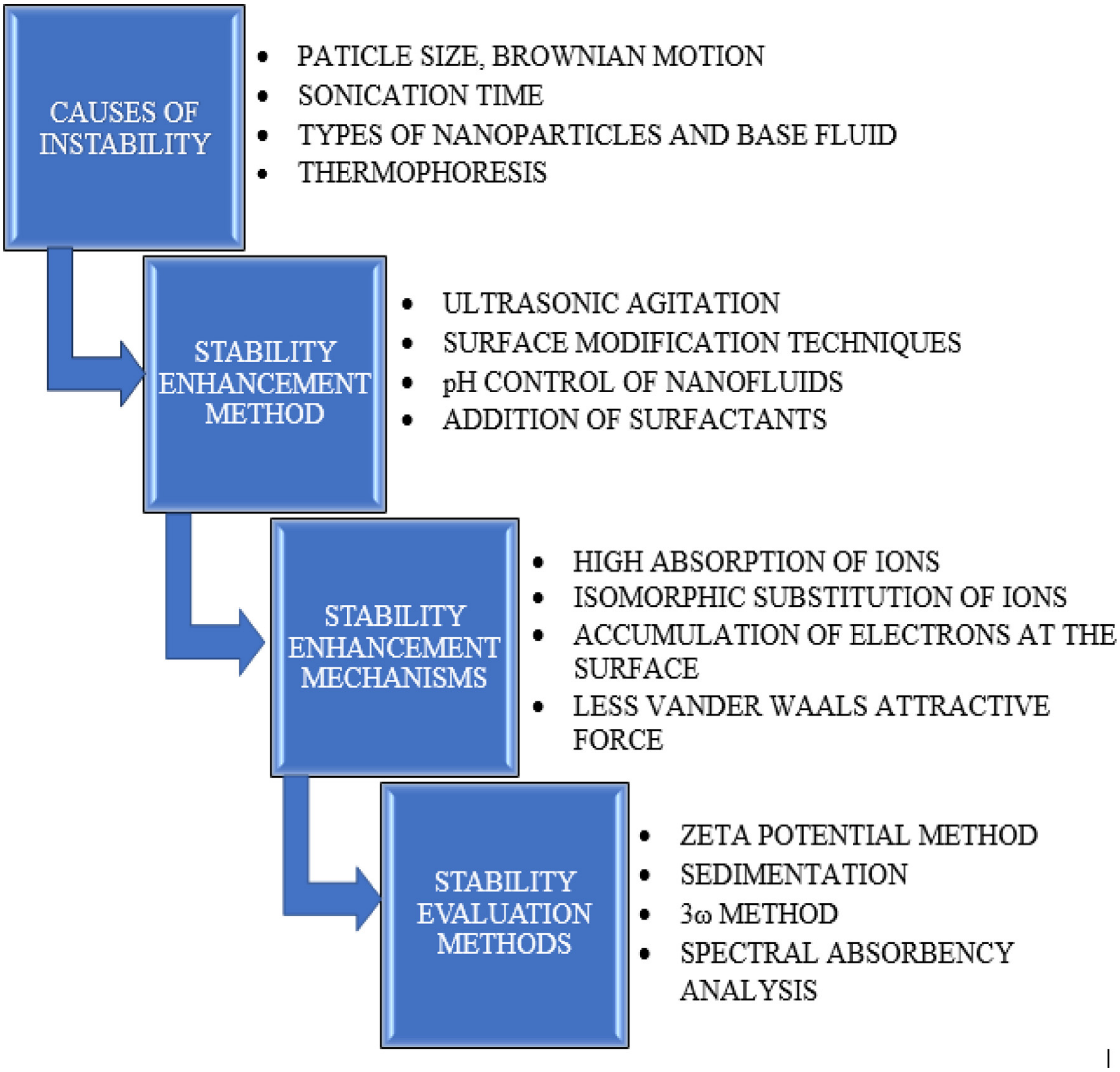


Fig. 6. Important aspects for the stability of NFs (Bakthavatchalam et al. 2020).

the measured particle loadings and temperatures. Li & Zou (2016) deliberate a combination of 60% water and 40% EG to determine the energy system's performance benefits from usings two conventional HT fluids. The μ_{nf} decreases with temperature and behaves like Newtonian fluid. Liu et al. (2022) discovered the NPs are highly disaggregated, the viscosity of the modified Fe_3O_4 nanofluid agrees with the Einstein equation. Along with experimental studies, different researchers have done theoretical work to study how the μ_{nf} changes. There are some equations for estimating the μ_{nf} shown in Table 3. Einstein (1905) Einstein's equation was the first to describe the rheology of NF with volume percentage (0–2%). The NF's viscosity may be affected by particle interaction at greater volume fractions. Brinkman (1952) extended the Einstein relation. This formula works only for particle volume fractions (0–4%). Krieger & Dougherty (2014) developed a semi-empirical viscosity relation for all particle volume fractions. Klazly & Bogn (2022) simplified the 1981 Frankel-Acrivos formula. Wang & Xu (1999) predicted nanofluid μ with correlation. In 2008, Brinkman and Batchelor's formulas grossly underestimated the viscosity of NF, particularly for very small particles $\varphi < 1\%$ (Nguyen et al. 2008). Ibrahim et al. (2019) utilized HNFs which are made by suspending various nanoparticles in mixed form. The hybrid nanofluid trades off the benefits and drawbacks of each suspension to improve heat transmission and pressure drop. Klazly & Bogn, (2022) proposed a correlation standardized to the BFs dynamic viscosity.

3.5. Specific heat capacity (Cp)

To a large extent, the NFs heat transfer rate is determined by its specific heat capacity (Cp). That fluid are suspensions containing NPs dispersed into BF. Several factors influence the Cp of NPs, including their type and concentration of NPs, their size and shape, and the properties of BFs. One notable effect of incorporating NPs into BF is increased thermal conductivity of NFs, which can lead to higher Cp values compared to BFs alone.

3.5.1. Previous studies on the specific heat of nanofluids

There have been a lot of earlier investigations on the specific heat capacity of nanofluids Xi & Pan (2017). Table 4 presents theoretical equations for nanofluid-specific heat capacity that have been studied both experimentally and theoretically. Benigno Barbe et al. (2012) derived equation from the data of Cp measurements of Al_2O_3 NFs and dispersed in water and ethylene glycol. Sekhar & Sharma (2015) conducted equation from water-based nanofluid data (Al_2O_3, CuO, Si O_2 and Ti O_2). Due to thermal diffusivity, nanofluid Cp decreased with particle concentration.

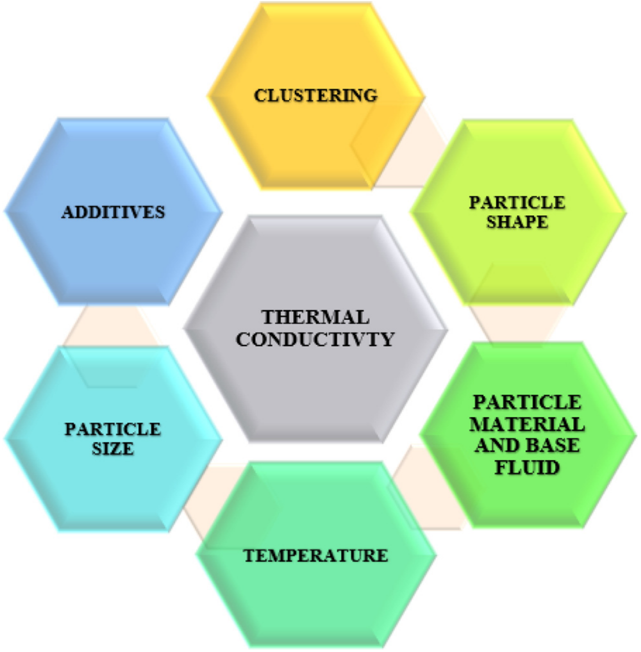


Fig. 7. Factors affecting the thermal conductivity of NFs (Gupta et al. 2017).

Cabaleiro et al. (2015) provided a new fitting equation to associate nanofluid specific heat with BF and concentration. Alklaibi et al. (2021) investigated the nanodiamond NFs in flat plate solar collector improves thermal efficiency (1.0 vol%) and reduces entropy generation compared to using pure water as the working fluid.

3.6. Density

Density is a thermophysical properties that affects nanofluid heat transfer performance. It impacts Re, friction factor, pressure loss, and Nu. Researchers have previously focused only k_{nf} and μ_{nf} and most of the studies are also available.

3.6.1. Previous studies on density of Nanofluids

Density affects flow parameter and friction factor, hence it must be evaluated and used in HT. The increase in density of NFs is primarily due to the additional mass of the nanoparticles. NPs have a much higher density than most BFs, and their addition can significantly increase the overall density of the nanofluid (Said et al. 2021). As may be seen, earlier equations on the density of NFs are displayed in Table 5.

4. Applications of nanofluids

Nanofluids, which are liquids containing nanoparticles of metals, oxides, or other materials, have established much interest in recent years because of their potential to improve HT capabilities. Here are some of the applications of nanofluids.

4.1. Application in different heat exchangers

Transferring thermal energy from one fluid to another is the primary function of heat exchangers. HT devices, such as heat exchangers, typically use NFs as working fluids. Classifying HEs according to the HT method used is seen in Fig. 8. When it comes to heat exchangers, there are two main types: direct contact and indirect contact. Nonetheless, the HT technique can be utilised to further categorise these tools. Vallejo et al. (2022) performed independently on mono or HNF for single and two-phase convective HT applications. The usage of NFs in various types of HE has been researched and described further below.

4.1.1. In Double–Tube heat exchanger (DTHE)

The DTHE is a popular choice for many commercial and industrial processes, such as those involved in the manufacture of chemicals and beverages. A greater overall heat transfer coefficient (HTC) and more efficient HE can be achieved by incorporating NPs into the BFs in order to improve their thermal conductivity (J. Zhao et al. 2022). In addition, the use of NFs can reduce the size and weight of the HE, which can be particularly beneficial in applications where space is limited. The thermal performance of TiO_2-H_2O nanofluids in DTHE were examined. The results show that NFs can improve HT rates by (10.8–14.8%), and pressure drop increased 51.9% (Qi et al. 2019) where, Moradi et al. (2019) explored MWCNT aqueous nanofluid HT in porous medium counter current double-pipe heat exchanger. MWCNT-water nanofluids increased HTC by 35%. Ozdemir & Ergun, (2019), Zheng et al. (2020) examined HT performance in counterflow DTHE using Al_2O_3/water NF with mean diameter 50 nm. The Nu increases with NP volume

Table 2
Previously developed models for thermal conductivity of NFs.

Researchers	Model	Remarks
(Maxwell, 1873)	$K_{nf} = \frac{(2K_{bf}+K_p)-2\varphi(K_p-K_{bf})}{(2K_{bf}+K_p)+\varphi(K_p-K_{bf})}K_{bf}$	The effective thermal conductivity of NFs is a function of the particle size distribution, BF content, and volume concentration.
(Hamiliton and Crosser, 1962)	$K_{nf} = \frac{(K_p)+(n-1)\times K_{bf}-(n-1)\phi(K_{bf}-K_p)}{(K_p)+(n-1)\times K_{bf}+\phi(K_{bf}-K_p)}K_{bf}$	The proposed combined liquid–solid mixture of various non-spherical particles has a thermal conductivity rate of the particles and BFs greater than 100.
(Xue, 2005)	$\frac{K_{nf}}{K_{bf}} = \frac{1-\phi+2\phi\frac{K_p}{K_p-K_{bf}}IN\frac{K_p+K_{bf}}{2K_{bf}}}{1-\phi+2\phi\frac{K_{bf}}{K_p-K_{bf}}IN\frac{K_p+K_{bf}}{2K_{bf}}}$	They discussed for the important properties of carbon-nano tube (CNT)
(Yu and Choi, 2003)	$\frac{K_{eff}}{K_f} = \frac{K_{pe}+2K_f-2\phi(K_{pe}-K_f)(1+\beta)^3}{K_{pe}+2K_f-\phi(K_{pe}-K_f)(1+\beta)^3}$	The influence of ordered nanolayers on NFs is accounted for in the revised important nanofluid Maxwell equation for effective thermal conductivity.
(Khdher et al. 2016)	$\frac{K_{nf}}{K_{bf}} = 1.268 \times \left(\frac{T}{80}\right)^{-0.0074} \times \left(\frac{\varphi}{100}\right)^{0.036}$	The thermal conductivity of BFs was shown to be a linear function of concentration, temperature, and the newly developed correlation.
(Yang et al. 2017)	$k_{eff} = \frac{(H-2T)k_{eff\_x}+(r+t)k_{eff\_z}}{H+R+3t}$	New thermal conductivity model for nanorod-based NFs.
(Yang & Xu, 2017)	$\frac{k_{nf}}{k_{bf}} = \frac{\bar{k}_{pe}+k_{bf}(n-1)+(n-1)\left(\bar{k}_{pe}-k_{bf}\right)\varphi_e}{\bar{k}_{pe}+k_{bf}(n-1)-\left(\bar{k}_{pe}-k_{bf}\right)\varphi_e}$	Modified Hamilton–Crosser model predicts effective thermal conductivity of CNT-based NFs.
(Alawi et al. 2018)	$\frac{k_{nf}}{k_{bf}} = \left[\frac{k_p+2k_{bf}-2\varphi\left(k_{bf}-k_p\right)}{k_s+2k_{bf}-\varphi(k_{bf}-k_s)}\right] + 5 \times 10^4\beta\emptyset\rho_f\left(C_p\right)\sqrt{\frac{k_BT}{d_p\rho_p}f(T,\emptyset)}$	Metallic oxide nanofluid thermal conductivity ratio increases with temperature and NPs volume%, but intensity increases as NPs size reduces.
(Pare & Ghosh, 2021)	$\frac{k_{nf}}{k_{bf}} = a + bT + c\varphi + dT^2 + e\varphi^2 + fT_{\varphi}$	They discussed and implemented artificial neural network model to predict thermal conductivity of NFs were measured between 20 °C and 90 °C

Table 3
Previously developed models for the viscosity of NFs:

Researchers	Model	Remarks
(Einstein, 1906)	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5\varphi$	This expression was assumed to be a spherical particle of very low volume fraction $\varphi < 2\%$.
(Brinkman, 1952)	$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{(1-\varphi)^{2.5}}$	This formula is only applicable for low particle concentration (φ = 0–4%).
(Krieger & Dougherty, 2014)	$\frac{\mu_{nf}}{\mu_{bf}} = \left(1 - \left(\frac{\varphi}{\varphi_m}\right)\right)^{-[\mu]\varphi_m}$	Semi-empirical viscosity relation for particle φ up to maximum fraction (φ_m = 0.495…0.54) and μ is 2.5.
(Wang & Xu, 1999)	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 7.3\varphi + 123\varphi^2$	Predict the viscosity of NFs.
(Nguyen et al. 2008)	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 0.025\varphi + 0.015\varphi^2$	Together the Brinkman and Batchelor formulas strictly underestimate the NFs viscosity unless the particle $\varphi < 1\%$.
(Avsec & Oblak, 2007)	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5\varphi_e + 2.5{\varphi_e}^2 + 2.5\varphi_e^3 + 2.5\varphi_e^4$	Using the exponential formula to calculate the viscosity of NFs.
(Masoumi et al. 2009)	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + \frac{\rho_p V_B d_p^2}{72\delta C}$	Predicting the viscosity of NFs.
(Klazly & Bogn, 2022)	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 9.4974\mu_e + 77.811{\varphi_e}^2 + 0.9514{\varphi_e}^3 + \frac{\sqrt{\frac{18K_b T\rho_p}{\pi\rho_p d_p}}}{39.6231\sqrt{\frac{\pi}{\varphi}}C\sqrt{d_p}}$	New correlation standardized to BF dynamic viscosity.

Table 4
Previously developed models for specific heat capacity of NFs.

Researchers	**Model**	**Remarks**
(Barbe et al. 2012)	$C_{p,nf} = \frac{(1-\emptyset)\cdot\rho_{bf}\cdot C_{p,bf} + \emptyset\cdot\rho_p\cdot C_{p,p}}{\emptyset\cdot\rho_p + (1-\emptyset)\cdot\rho_{bf}}$	The first law of thermodynamics accurately justifies nanofluid Cp.
(Sekhar & Sharma, 2015)	$C_{p,nf} = 0.8429\left(1 + \frac{T_{nf}}{50}\right)^{-0.3037}\left(1 + \frac{r_p}{50}\right)^{0.4167}\left(1 + \frac{\emptyset_p}{100}\right)^{2.272}$	The Cp of the nanofluid reduced as particle concentration increased due to an increase in thermal diffusivity.
(Cabaleiro et al. 2015)	$\frac{C_{p,bf}(T) - C_{p,nf}(T)}{C_{p,bf}(T)} = \frac{\emptyset_p + A\frac{C_{p,p}(T)}{C_{p,bf}(T)}}{B + \emptyset_P}$	New correlation was found of specific heat capacity
(Alklaibi et al. 2021)	$C_{p,nf} = C_{p,bf}(1 + \emptyset)^{-0.0143}\left(\frac{T}{60}\right)^{0.14\times10^{-4}}$	Specific heat correlation for nanodiamond/water NFs.
(Sundar et al. 2021)	$C_{p,nf} = C_{p,bf}(1 + \emptyset)^{-0.148\times10^{-1}}\left(\frac{T_{min}}{T_{max}}\right)^{-0.537\times10^{-4}}$	Specific heat connection for nanodiamond +Fe_3O_4/60:40% EG/W mixture based HNF.

Table 5
Previously developed models for the density of NFs.

Researchers	**Model**	**Remarks**
(Vsajjha et al. 2009)	$\rho_{nf} = \emptyset\rho_{np} + (1 - \emptyset)\rho_{bf}$	Determined the value of ρ (Density) of various nanofluids
(Alklaibi et al. 2021)	$\rho_{nf} = \rho_{bf}(1 + \emptyset)^{0.03279}\left[\frac{T}{60}\right]^{0.0003355}$	A density correlation for water nanofluids was developed.
(Sundar et al. 2021)	$\rho_{nf} = \rho_{bf}\left[(1 + \emptyset)^{0.427\times10^{-1}}\left(\frac{T_{min}}{T_{max}}\right)^{0.95\times10^{-4}}\right]$	Density relation for nanodiamond + Fe3O4/60:40% water and EG mixture created on the HNF.
(Saleh & Sundar, 2021a)	$\rho_{nf} = \rho_{bf}\left[(1 + \emptyset)^{0.414\times10^{-1}}\left(\frac{T_{min}}{T_{max}}\right)^{0.1106\times10^{-3}}\right]$	Density relation for nanodiamond + Fe3O4/water HNF.

concentration and Re, but decreases with cold side double-pipe HE with temperature inlet. Mansoury et al. (2019) examined, the DTHE has the highest HTC enhancement of 26%, while the PHE had only 7%. Jalili et al. (2022) studied turbulent flow convection HT in DTHE with different fins. The study showed that water/Al_2O_3 nanofluid have better convection HTC than water/TiO_2 and pure water. Karimi et al. (2019) simulating NF flow in twisted tape DTHE. The result showed that Nu increased by 22%, and alumina particles in water enhanced HT by 30% and pressure decrease by 40%.

4.1.2. In plate heat exchanger (PHE)

PHE are widely used in various industries for heat transmission applications, and the use of nanofluids in these HE can enhance their performance. Many research have been conducted to study the use of NFs in PHE and the outcomes revealed significant increases in HT rates. Alklaibi et al. (2022) investigated MWCNT-Fe_2O_4/water nanofluids as PHE coolants for innumerable particle volume concentrations and coolant flow rates. The results showed that the HNF is more efficient than de-ionized (DI) water at 10.5% and 0.3%vol. particle concentration. Saleh & Sundar (2021a, 2021b) synthesised Ni/water NFs flow in PHE and prepared water-based nickel nanofluids at (0.1%-0.6%) particle volume concentrations and Re varies from (300–1000). The consequence demonstrations that the thermal conductivity and ρ improvements are 33.92% and 67.45% at 60 °C respectively. Kumar et al. (2022a) and Bahiraei & Monavari (2020) examined PHE performance utilising Al_2O_3-nanofluid and five particle morphologies at 90 °C inlet temperature and NP concentration 1%. Platelet-shaped NF has highest HTC. Few studies of single-phase convective HT in PHE have studied HNFs but just one of the mono NF. Shirzad et al. (2019), Bhattad et al. (2020a, 2020b) investigated the combination study for Al_2O_3–SiC, AlN, MgO, CuO, and MWCNT in 4:1 NP volume ratio and 100% Al_2O_3 with 0.1 vol% concentration in DI water and temperatures from (10–25 °C). They observed that Al_2O_3: MWCNT/water HNF had the highest enhancement 31.2%. Khanlari et al. (2019) analysed the HT characteristics in the PHE and TiO_2/water NF improved the overall HTC by average of 6%, with maximum improvement of 10%.

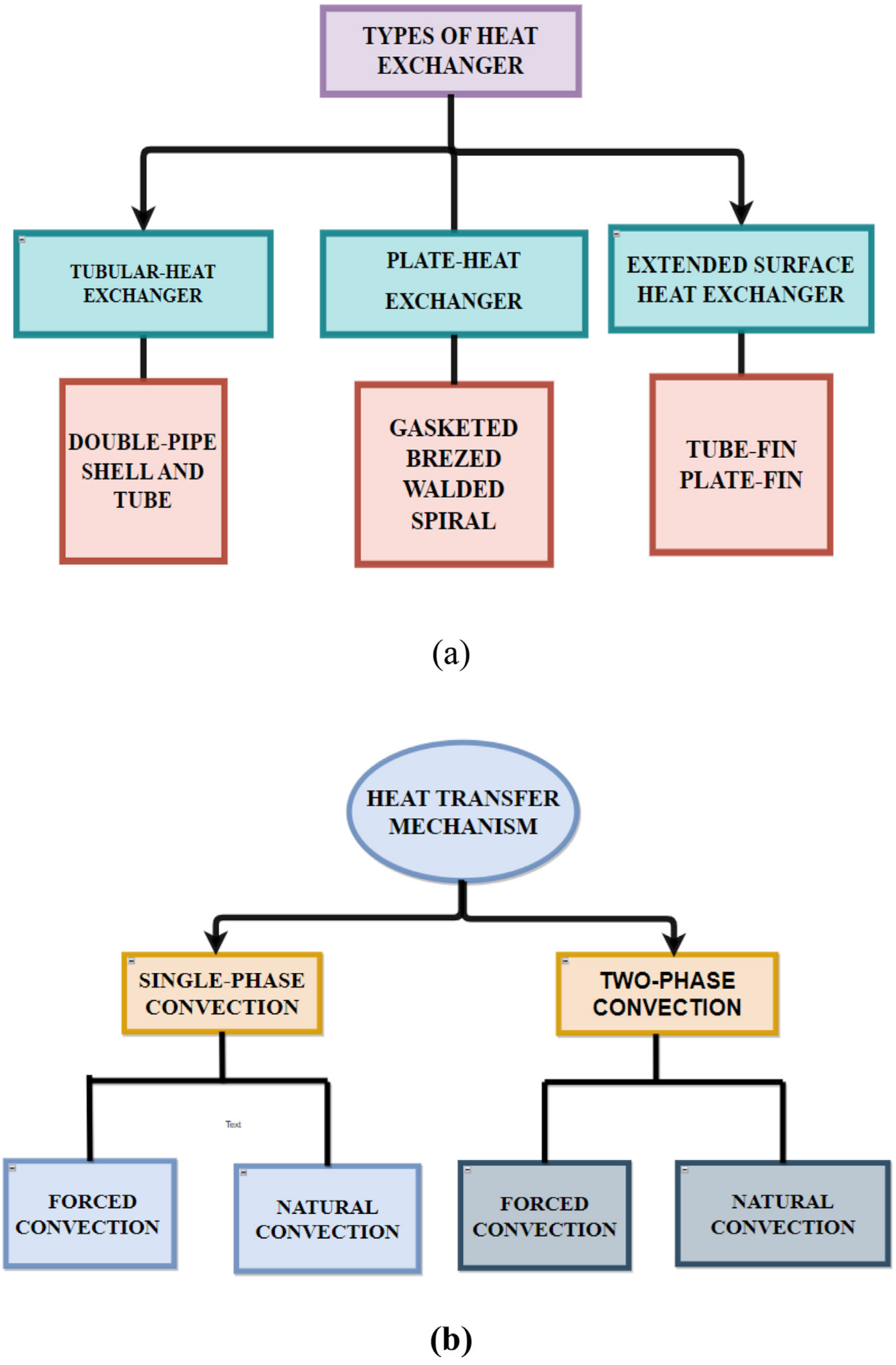


Fig. 8. (a) Types of heat exchanger and (b) classification of heat exchanger according to heat transfer mechanism (Vallejo et al. 2022).

4.1.3. In shell and tube heat exchanger

Heat exchangers (HEs) of the shell and tube variety feature a cylinder with a number of tubes inside it. Inside the shell, the tubes (often metal) are organised in a specific pattern. Barzegarian et al. (2017) deliberate the HT performance under laminar regime in horizontal shell-and-tube HE is with water-based Al_2O_3-gamma nanofluid. The results indicated that the Re raises then Nu and HTC of heat exchanger increase with NP volume concentration. Cruz et al. (2022) studied CuO-water based nanofluid flow behaviour in shell-and-tube HE beneath turbulent regions. Particle loading (0.1–1%vol), and Re increased HT and pressure drop. They observed maximum HT enhancement was 48%. Martínez et al. (2019) investigated the hydraulic and thermal effectiveness of heat sinks having microchannels using TiO_2/ water-based nanofluids. Compared to pure bf, the convective HTC increases by 19.66% and friction coefficient increases by 137.68% in the 1 wt% nanofluid. Priyanka et al. (2023) and Kumar & Sarkar (2020a, 2020b) examined Al_2O_3–MWCNT/water hybrid nanofluid with various NP mixture ratios. Re and temperature are observed using 0.01% volume concentration. MWCNT (5:0) hybrid nanofluid had 44.02% higher convective HT than water and pressure drop at 20 °C is 51.2% higher than bf's and increases HT. Table 6 shows various experimental studies of single-phase and double-phase convective HT using HNFs and corresponding mono-nanofluids.

Table 6
Overview of experimental studies of single-phase and double-phase convective heat transfer using hybrid and mono NFs.

Reference	NFs	Test section	Flow regime	Nano additives concentration	Remarks
(Naddaf et al. 2019)	OA-MWCNT/diesel oil	Tube	Laminar	0.05–0.5 wt%	0.5 wt% OA-MWCNT/diesel oil mono nanofluid increases ΔP by 9.9%.
(Hashemzadeh & Hormozi, 2020)	$\gamma-Al_2O_3$: SiO_2/H_2O $\gamma-Al_2O_3/H_2O$ SiO_2/H_2O	Minichannel heat sink	Laminar	0.05–0.2 vol%	$\gamma-Al_2O_3$: SiO_2/H_2O, HNF (75:25 ratio) and $\gamma-Al_2O_3$: SiO_2/H_2O HNF (75:25 ratio) enhances Nu 46% and 65.2% respectively at 0.5 wt% concentration.
(V. Kumar & Sarkar, 2020a)	Al_2O_3/H_2O $MWCNT/H_2O$	Minichannel heat sink	Laminar	0.01 vol%	$MWCNT/H_2O$ mono NF gets the best improvement of 44.0% for h and 41.0% for Nu.
(Bhattad et al. 2019)	Al_2O_3: MWCNT / H_2O Al_2O_3/H_2O $MWCNT/H_2O$	Plate heat exchanger	Laminar	0.01 vol%	$MWCNT/H_2O$ mono NF has the highest h increment 15.2%.With the nano additive, there is small increase in ΔP.
(Bhattad et al. 2020)	Al_2O_3: graphene/ H_2O Al_2O_3/H_2O	Plate heat exchanger	Laminar	0.01 vol%	Al_2O_3: graphene/water hybrid NF obtains the highest h enhancement 25.4%, with the lowest ΔP increase, 0.35%.
(Klazly et al. 2022)	Al_2O_3/H_2O	–	Laminar	1 vol%	Al_2O_3-water NF thermal performance at different Re using single and two-phase approaches.
(Esfe et al. 2022)	Al_2O_3/H_2O	Tube	Laminar	–	HT rate and average Nu were improved by increasing Al_2O_3 nanoparticle volume fraction.
(Omri et al. 2022)	CNT-H_2O	Microchannel heat exchanger	Laminar	0-5 vol%	CNT nanofluid and triangular fins significantly improve HE.
(Zhong et al. 2020)	DW/TiO_2	Multiport mini channel	Laminar and turbulent	0.5 – 1 vol%	HT performance is improved for Re 1500–2200.

4.2. Desalination application

Nanofluids offers a promising solution for improving HT rates in desalination expedient and freshwater manufacture rates. This process is critical to providing the proper freshwater quantities for humanity (Lee et al., 2011; Patel & Modi, 2020). Various researchers have proposed different techniques to enhance freshwater manufacture, but these often come with increased energy consumption. In contrast, researchers like (Masoud et al. 2020; Sha et al. 2020; Iqbal et al. 2021; He et al. 2022) have explored the use of solar energy-driven desalination system to produce clean water. Solar-powered desalination systems demonstrated significant improvement by employing NFs to enhance system performance. The design of the desalination system is displayed in Fig. 9.

4.3. Bio-medical application

The biomedical industry relies heavily on nanoparticles and nanofluids for a variety of important applications. The importance of NP suspension fluids in various medical industry areas like drug-delivery, disease diagnosis, antibacterial cases, bio-medical compo-

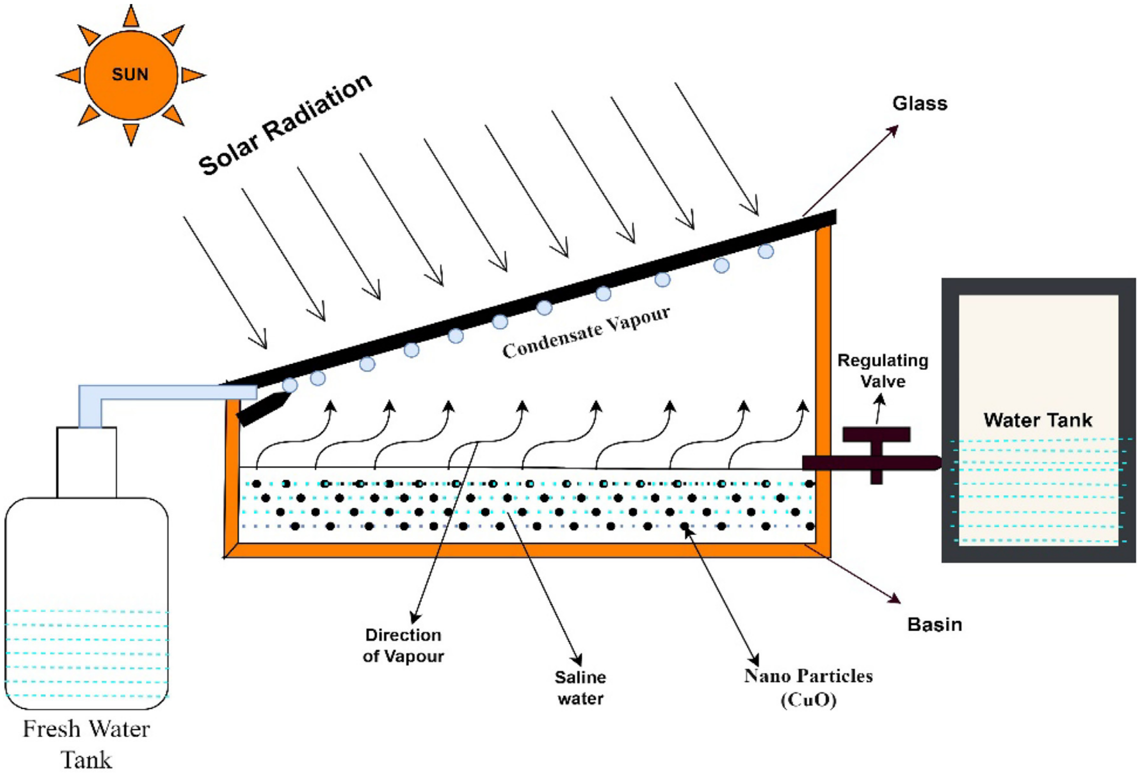


Fig. 9. Schematic illustration of the solar desalination system (Iqbal et al. 2021).

nent cooling, cryopreservation, sterilisation processes, and micropumping systems for drug and hormones has been reported in studies. However, NFs must be used securely by carefully examining parameters, including features, uniform suspension, shape, size, biocompatibility, and crystallinity (Mojgan Sheikhpour et al. 2020).

4.3.1. Drug delivery

In recent decades, drug delivery-based nanofluids have been studied to enhance effectiveness and specificity. Surface modification of MNP can improve its biological significance by improving cellular recognition, biocompatibility, and drug release of numerous treatments (Lucena et al. 2016). Jampilek and Kralova (2021) suggested using graphene-based nanofluids in anticancer medication delivery devices. Pin et al. (2020) examined the biological applications of Fe_3O_4 NPs for cancer treatment. After blood injection, an external magnetic field can guide these particles shown in Fig. 10. (Rashidy et al. 2023; Das et al. 2019) studied magnetic-fluid hyperthermia employing biocompatible magnetic NPs as heat mediators for cancer treatment because its efficiency and few adverse effects. They developed magnetic nanoparticle-based hyperthermia therapy and heat-mediated delivery of drugs for cancer treatment. (Prashant et al. 2022) looked at Magnetic nanoparticle-based biological platforms. Surface qualities make zinc oxide, CNTs, and magnetic NPs better for medicine delivery and cancer treatments. (TiO_2), ZnO, and silica were better antibacterial NPs. More research should be required to create new NPs and investigate their uses in the medical field.

4.3.2. Diagnosis

In recent decades, nanofluids have been investigated for diagnosis-based applications in the field of biomedical and molecular biology research. The diagnosis and treatment of COVID-19 caused by the SARS-CoV-2 virus have also been studied, with several novel management strategies being developed. Traditional nucleic acid extraction for COVID-19 diagnosis can be time-consuming, and several studies have explored the use of nanotechnology to make the process more efficient. Weiss et al. (2020), Torres et al. (2020) developed a method that uses magnetic nanoparticles to extract viral RNA, which can be used for diagnosis and treatment. For instance, Z. Zhao (2020) investigated the use of poly amino easter-coted Fe_2O_3 nanoparticles could extract nucleic acids from saliva swabs and offer results in just 20 min. Additionally, Prashant et al. (2022) used magnetic iron oxide nanoparticles for viral RNA extraction, highlighting their widespread investigation for quick extraction shown in Fig. 11. However, low extraction purity can lead to false negative in RT-PCR amplification, making it crucial to address this issue. Overall, these studies suggest that nanotechnology could offer promising solutions for diagnosing and treating COVID-19.

4.3.3. In solar collectors

To increase the collector's efficiency, nanofluids can be utilised to increase the HT rate from the heated plate to the working fluid. Several studies have focused on improving parabolic trough collector performance (PTC). PTC are installed more than other concentrated solar power technologies worldwide. The latest HT fluids utilised in PTC and nano-enhanced HT fluids with better characteristics are compared (Krishna et al. 2020) where Mashhadian et al. (2021) inspected the environmental performance of a direct absorption PTC using a water-dispersed mixture of Al_2O_3 and MWCNTs. The results show that HNFs reduce CO_2 emissions and water usage by 450.33 kg and 16.6 m^3 per collector. Priyanka et al. (2022), Priyanka et al. (2022) optimised different parameters of the receiver tube of a solar collector using the PSI method. Martínez-Merino et al. (2022) Concentrated solar power replaces polluting energy sources. Spherical MoS_2 nanoparticles increased specific isobaric heat by 13% and TC by 6% over thermal oil. Parabolic trough solar collectors were expected to gain 5% efficiency.

5. Comparative study

This section displays the comparison of previous published studies on Nanofluid and different types of HE. Fig. 12 (a) and (b) represents the comparison of Nu and Re from 1000 to 40,000 for different heat exchanger (Double-tube HE, Plate HE, Shell and Tube HE and these nanofluids are used in the heat exchangers TiO_2-H_2O nanofluids, ND-Fe_3O_4 Hybrid nanofluid, MWCNT/Water nanofluids, Al_2O_3/Water Nanofluid) and for various NFs (BF-Water/EG, ND-Fe_3O_4 HNF, MWCNT-Water Nanofluid, MgO-Water Nanofluid, MWCNT-Fe_3O_4 HNF) with Re ranging from 2000 to 10000. It is

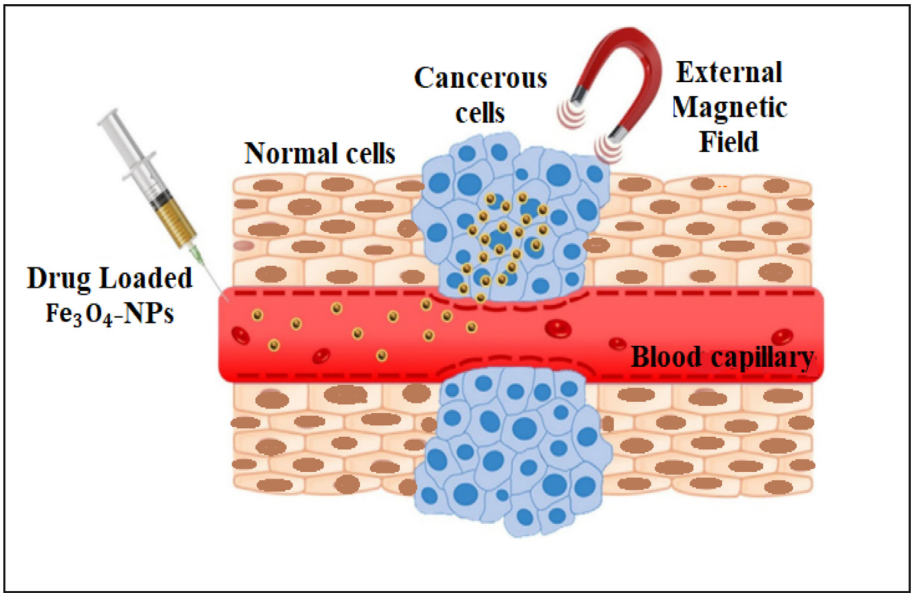


Fig. 10. Schematic depiction of the mechanism for delivering drugs to specific organs (Pin et al. 2020).

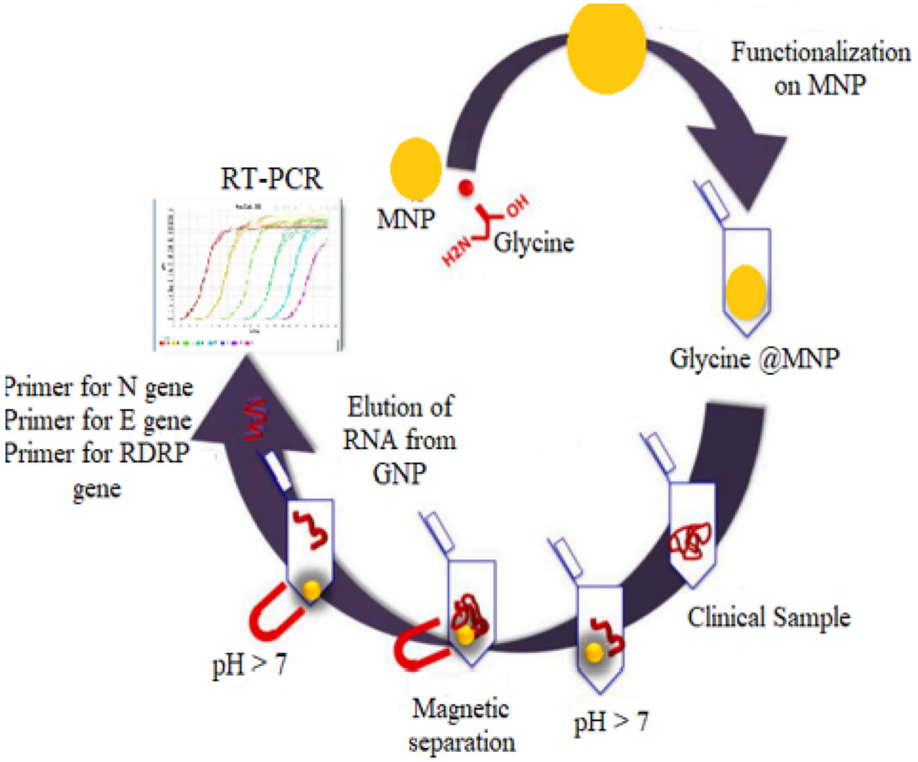


Fig. 11. Illustration of the Magnetic Nanoparticle-Based Approach for SARS-CoV-2 RNA Detection and Diagnosis of COVID-19 (Prashant et al. 2022).

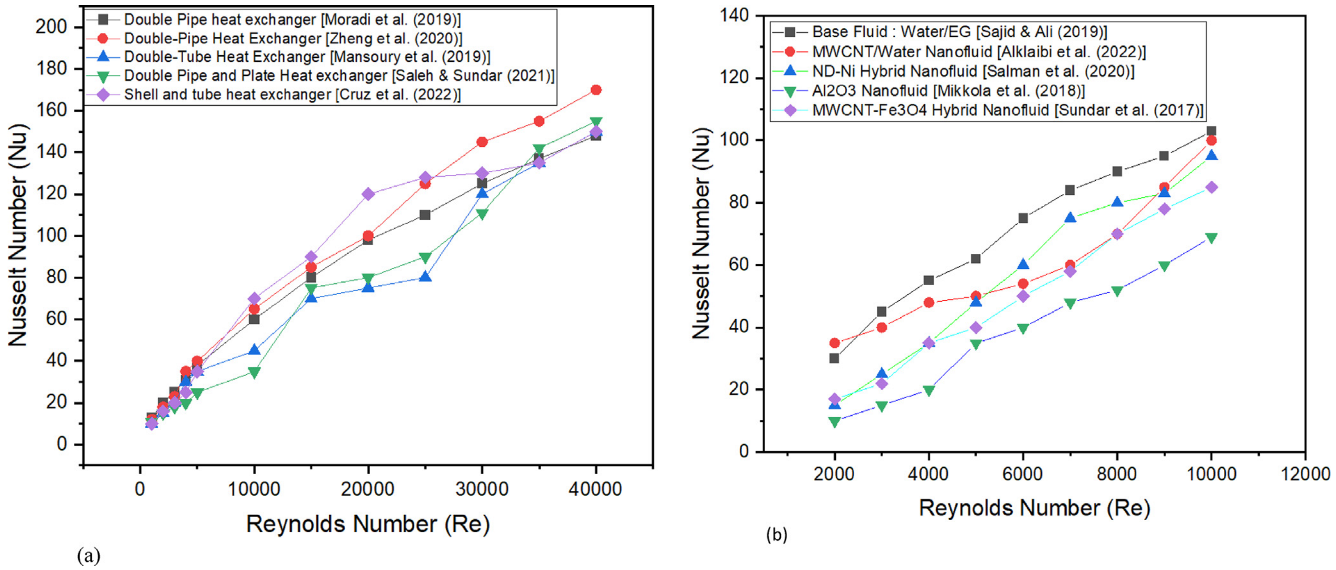
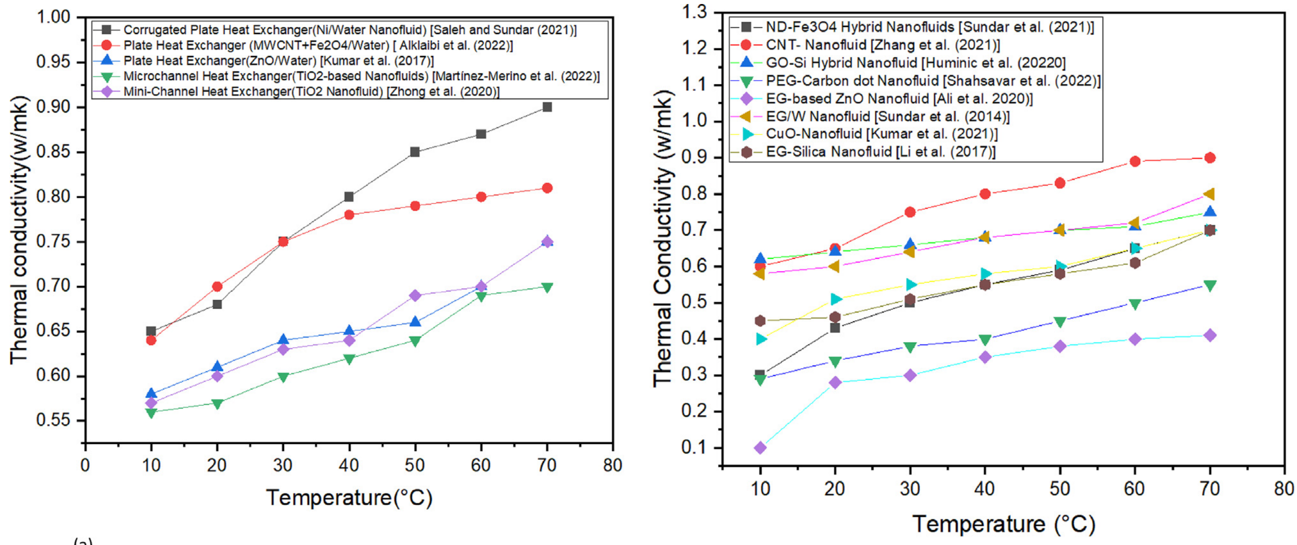


Fig. 12. Comparison of Nu and Re for (a) Different Heat Exchangers, (b) Different NFs.

clear from the Fig. 12 (a) and (b) that the value of Nu increases with increasing Re for every HEs and NFs.

Fig. 13(a) and (b) describe the comparison of Thermal conductivity with Temperature for different heat exchangers (corrugated plate heat exchanger, plate heat exchanger) and various NFs (ND-Fe_3O_4 Hybrid Nanofluid, CNT-Nanofluid, GO-Si Hybrid Nanofluid, PEG-Carbon dot Nanofluid, EG-based ZnO-Nanofluid, EG/W-Nanofluid, CuO-Nanofluid, EG-Silica Nanofluid), respectively. From the Fig. 13(a) and (b) the thermal conductivity and the temperature increasing with the rise in temperature. The corrugated PHE has attained the maximum thermal conductivity while in NFs the CNT nanofluids has attained maximum thermal conductivity.

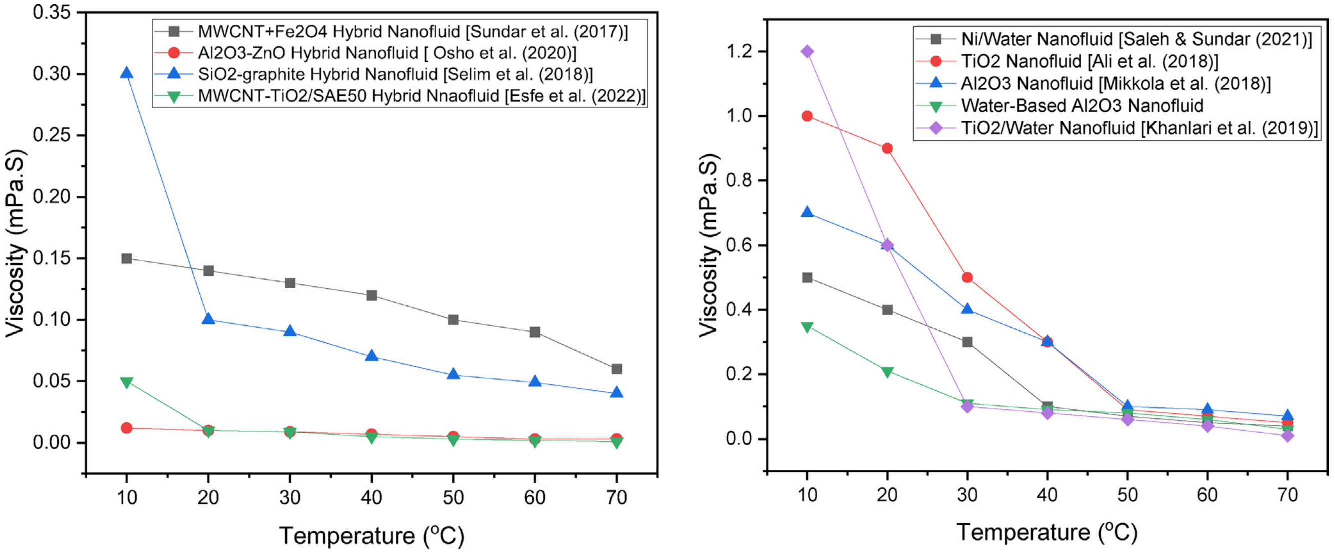
Fig. 14(a) and (b) characterised the comparison of viscosity with Temperature range (10 °C–70 °C) for different hybrid nanofluids (MWCNT-(TiO_2) /SAE50 hybrid nanofluid, SiO_2-graphite hybrid nanofluid, Al_2O_3-ZnO nanofluid, MWCNT-Fe_3O_4 hybrid nanofluid) and from (10 °C–80 °C) several NFs (Ni/Water Nanofluid, (TiO_2) Nanofluid, Al_2O_3 Nanofluid, Water-Based Al_2O_3 Nanofluid, (TiO_2)/



(a)

(b)

Fig. 13. Comparison of Thermal Conductivity and Temperature for (a) Different Heat Exchangers, (b) Different NFs.



(a)

(b)

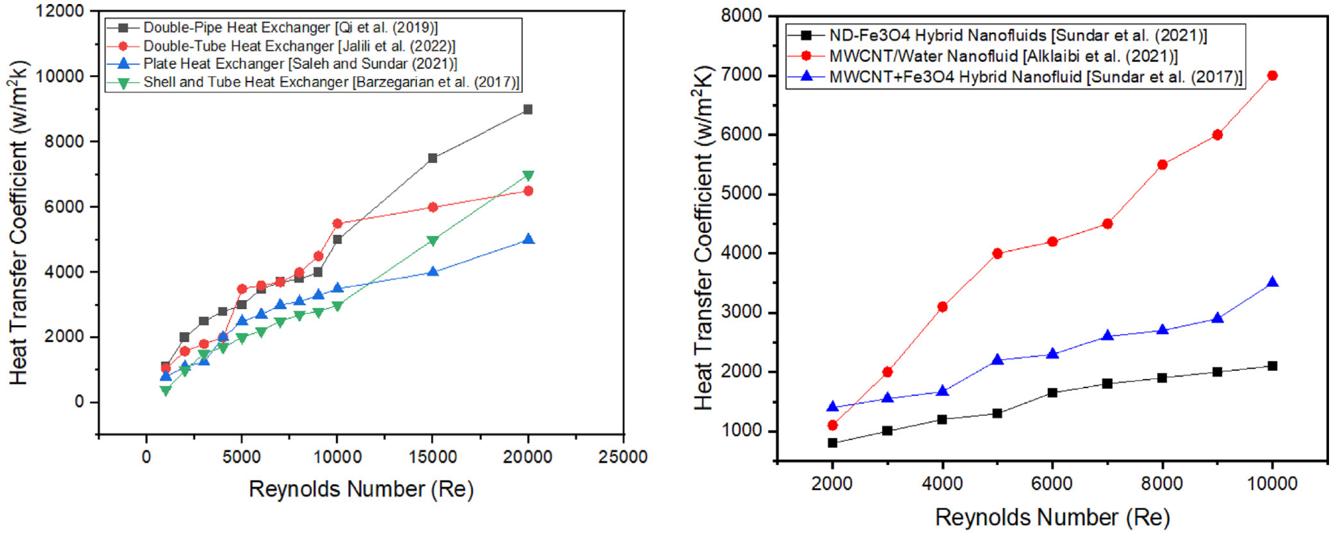
Fig. 14. Comparison of Viscosity and temperature for (a) Different Hybrid Nanofluids, (b) Different NFs.

Water Nanofluid) respectively. Fig. 14 (a) and (b) clear that the viscosity reductions as the temperature upsurges. Fig. 14 (b) indicates that (TiO_2)/Water Nanofluid produces the highest viscosity of 1.2 at 10 °C of temperature among nanofluids and from Fig. 15 (a) SiO_2-graphite hybrid nanofluid have highest viscosity of 0.30 at 10 °C of temperature among hybrid nanofluids. From the comparison of both Fig. 14 (a) and (b) we recognise the Nanofluids have highest viscosity as comparison to the hybrid nanofluids.

Fig. 15(a) and (b) represent the ratio of HTC to Re for various types of HE (and various NFs (ND-Fe_3O_4 hybrid nanofluid, MWCNT with combined water nanofluid, MWCNT-Fe_3O_4 Hybrid Nanofluid), respectively. It is clear from the Fig. 15 (a) and (b) that the value of HTC increases with increasing Re for every HE and NFs. However, the HE reached a higher value (9000) than that of NF's (7000) indicating that the heat exchanger is more effective.

6. Challenges in nanofluid applications

The goal of this review is to examine many challenges in nanofluid applications. The research on NFs has exposed that the implementation of nanofluids HT faces many difficulties. NFs technology has significant opportunities for developing further highly efficient and cost-effective cooling technology, particularly in the fields of defence, transportation, electronics, and manufacturing. The most significant issue for traditional nanofluid conduction, convection,



(a)

(b)

Fig. 15. Comparison of Heat Transfer Coefficient and Reynolds Number for (a) Different Heat Exchanger, (b) Different NFs.

and boiling models is that recorded experimental values always exceed the stated microscopic theories. The common difficulties in using NFs in real-world applications are covered in the following section. Challenges in NFs applications are shown in Fig. 16.

6.1. Stability factor of NFs

The ability of nanoparticles to agglomerate in a critical problem faced in the practical application of nanofluids. The Agglomeration

Fig. 16. Challenges in NFs Applications (Said et al. 2021).

affects nanofluid characteristics and heat transmission. Several factors, including time, can affect the size and shape of agglomerates. The factors that affect the stability of a NFs dispersion must be researched and analysed. Laboratory-scale research has difficulty producing stable nanofluids made up of monosized nanoparticles (Said et al. 2021). The exact merit of NFs has not been decided using various mechanical approaches and chemical stabilisers. More challenges associated with using nanofluids include corrosion, clogging, fouling, and compatibility.

6.2. High cost of NFs

The production of nanofluids in huge quantities at an affordable price will be the most challenging goal of any future direction. The cost of NFs is high due to the high cost of NPs. The cost of NPs is driven by the cost of raw materials used to make them, such as rare earth metals and other rare elements (Esfe et al. 2014). The cost of production is also high due to the specialized equipment and processes needed to create NFs. Additionally, NFs are relatively new technology, and the cost of research and development is still high, contributing to the entire cost. Because of their immense price, many consumers do not prefer NFs. Although if manufacturing processes allow for expanded production of NPs and ionic liquids, the cost will stay high.

6.3. Formation of foam

Foam formation in nanofluids is highly challenging because the presence of nanoparticles causes the surface tension of the fluid to increase to an extreme amount. The presence of NPs decreases foam formation because they raise the surface tension of the NF (Bakthavatchalam et al. 2020). The foam formation can be reduced by adding surfactants to the NF, which help to reduce the surface tension. The choice of BF and NPs type can also affect the foam formation.

6.4. Environmental concerns and safety

If nanoparticles are not handled properly, they can be toxic to the environment and have long-term effects if not disposed of properly. NPs can get into the lungs and, the skin, which can cause breathing problems, inflammation, and diseases that can lead to cancer. So, the right rules or parameters must be set up to make and work with NFs (Bakthavatchalam et al. 2020). In the future, nanofluid engineers will have to think about and create NFs by choosing nanoparticles that are not harmful to the environment, human health, or safety. This will allow NFs to be made in large quantities and used in many industries.

7. Conclusions

This article includes a review on the use of NFs for thermophysical properties and applications of NFs in various fields. The purpose is to gain an understanding of the thermophysical features that NFs possess, particularly the thermal conductivity, viscosity, and specific heat capacity of nanofluids. In addition, the paper's conclusion supplies point-by-point observations, which include the whole of the following content:

- The use of nanofluids in MRI (Magnetic Resonance Imaging), the most exciting imaging and diagnosis technique, has expanded in recent years. In the MRI, the role of the contrast agent is crucial, where some NFs such as Fe_2O_4-based fluids have been taken into consideration. To achieve the optimal contrasting behaviour of various agents in various diagnosis circumstances, it may be helpful to experiment with other NFs.
- The addition of NFs to the desalination system can raise the amount of freshwater produced by between 30 and 40%. The Al_2O_3 nanoparticle is the one that better represents the parameters of this investigation.
- Nanofluids comprising small number of nanoparticles have significantly higher thermal conductivity than those of BFs. The thermal conductivity enhancement of NFs depends on the particle volume fraction, size, type of base fluids and NPs, pH value of nanofluids.
- Nanofluids can improve heat transmission in base fluids. The concentration of nanoparticles impacts HT because of their higher heat capability from the hot fluid source and the increased enhancement when utilising a high concentration.
- The hydrothermal performance of HNFs is better than other fluids. It was found that hybrid nanofluids are good alternatives in plate heat exchangers as compared to simple fluids because of their better thermal performance.
- The stability of NFs continues to be the primary challenge that prevents the application of these fluids in a variety of different industries. The stability of the thermal system not only influences the system's thermophysical parameters but also influences the system's performance. As a result of their instability, NFs gradually lose their functional capabilities over time.

8. Future recommendation

These are some of the reasonable possibilities that investigators can work on nanofluids in the future to propagate their usage in a variety of applications, and these are some of the directions that are being discussed here.

- There have only been a few of research done on the thermal conductivity of nanofluids at high temperatures. Thus, additional research is required to characterise the thermal conductivity of nanofluids at high temperatures.
- To better anticipate thermal conductivity and the effect of other characteristics, further research is needed to develop new models and correlations. There is a need for further generalized correlations to be created in respect to the increase of heat transmission by NFs for practical applications.
- Several studies have used ionic liquid hybrid nanofluids, which could be explored further.
- Using nanofluids as solar collectors is becoming an increasingly attractive field of study. Several parabolic trough collectors (PTC) research with nanofluids have been published. However, they primarily consider nanofluids with a water and temperatures below 100 °C.

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.

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