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Nanofluids: preparation, stability, properties, and thermal performance in terms of thermo-hydraulic, thermodynamics and thermo-economic analysis

Duygu Yılmaz Aydın[1] · **Metin Gürü**[2]

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Abstract
In recent years, with the adaptation of nanotechnological engineering applications to complex systems, the use of nanofluids with better thermo-physical properties compared to conventional fluids has become widespread. In addition, studies on the preparation techniques of nanofluids, improving their thermal properties and evaluating their thermal performance are increasing. This study presents a review about preparation, evaluating and enhancement of the stability and thermal properties of nanofluids. Furthermore, the recent advances about the thermo-hydraulic, thermodynamic and thermo-economic performances of nanofluids in different types of thermal systems are summarized as well. The stability of nanofluid is a significant factor affecting its applicability. Various techniques have been used in the literature to enhance the stability of nanofluids such as surfactant addition, ultrasonic mixing and pH control. By using nanofluids, the desired thermo-physical properties can be obtained in order to improve the heat transfer property in the system. Some researchers recommend to hybrid nanofluids because of the hybrid effect of two or more particle types they contain. The reviewed literature also indicates that the use of nanofluids instead of conventional working fluids is an effective way to increase the thermo-hydraulic performance of thermal systems. In addition, according to the literature review, minimum entropy generation is an effective way to increase the energy efficiency and improve thermodynamic performance of the thermal system and the use of nanofluids provide a significant reduction in entropy production.

Keywords Nanofluid · Thermal conductivity · Heat transfer · Thermo-hydraulic performance · Thermodynamic performance

Abbreviations

DI	Deionized
EG	Ethylene glycol
DEG	Diethylene glycol
DW	Distilled water
HE	Heat exchanger
CTAB	Cetyltrimethylammonium bromide
SDBS	Sodium dodecylbenzenesulfonate
SDS	Sodium dodecyl sulfate
vol	Volume
PG	Polyglycol
DLS	Dynamic light scattering
CNT	Carbon nanotube
MWCNT	Multi-walled carbon nanotube
FMWCNT	Functionalized multi-walled carbon nanotube
SWCNT	Single-walled carbon nanotube
ISSRC	Integrated solar regenerative Rankine cycle
TEM	Transmission electron microscopy
FESEM	Field emission scanning electron microscopy
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
F	Friction factor
D	Inner diameter of microchannel, m
k_{nf}	Thermal conductivity of nanofluid
k_{bf}	Thermal conductivity of base fluid
μ	Viscosity (kg m^{-1} s)
ρ	Density (kg m^{-3})
$\dot{m}$	Mass flow rate, kg s^{-1}

✉ Duygu Yılmaz Aydın
duygu.aydin@ozal.edu.tr

[1] Bioengineering Department, Engineering and Natural Sciences Faculty, Malatya Turgut Özal University, Malatya, Turkey

[2] Chemical Engineering Department, Engineering Faculty, Gazi University, Ankara, Turkey

Δp	Pressure drop (Pa)
λ_m	Thermal conductivity of nanofluid ($W\ m^{-1}\ K^{-1}$)
λ_f	Thermal conductivity of liquid metal ($W\ m^{-1}\ K^{-1}$)
h	Forced convection heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)

Introduction

The need for energy is increasing day by day with the rapid development in technology. Especially in today's world where fossil energy resources are about to be exhausted, the importance of studies to research new energy resources has increased. Energy has become an important cost item in daily life, especially in industrial enterprises. This problem shows that the existing energy resources should be used more effectively and efficiently. It has become a necessity to increase efficiency at every stage from the production to the use of energy, which is an important need in all areas of life. The concept of efficiency becomes more significant in heating systems, especially in industrial facilities. Heat pipes, heat exchangers and heat plates are used in many different thermal systems to transfer heat from one place to another in industrial applications. In these systems, conventional fluids are generally used such as water, ethylene glycol and oil. The most important parameter affecting the thermal performance of the fluid used in heating and cooling systems is its thermo-physical properties. The poor thermal characteristics of conventional working fluids led to the search for new working fluids. Therefore, the thermal performance of the systems is increased by adding particles with superior thermo-physical properties into the base fluid [1]. Millimeter- and micrometer-sized particles added to the base fluid cause many problems in heat transfer devices such as particle clogging, low specific surface area, high pumping power and low dispersion stability. In recent years, nanofluids have been used in heat transfer devices to overcome these problems. The occurrence of heat transfer on the surface of the particle causes the thermal properties of nanofluids to be more developed than the colloidal suspensions of microparticles [2]. New generation nanofluids that can be used in heat transfer devices have been prepared by adding high thermal conductivity nanoparticles to industrial heat transfer fluids. Nanofluids are used in heat transfer systems to ensure stability and higher heat transfer. In addition, they can significantly reduce erosion and clogging because nanoparticles are so small [3]. Other benefits foreseen for nanofluids are reduction in pump power demand and significant energy savings [4].

Nanofluids also enhance the convective heat transfer coefficient so they increase Re and Nu Number [5, 6]. Many researchers are actively working on nanofluid systems to study their capabilities for use in heat transfer applications. Nanofluids has been used in many applications such as automobile, solar energy, mechanics, heat exchangers in reactors, optics, detergents, biomedical and electronic cooling [7]. With the use of high-tech nanofluids in the world of science, contributing to the development of more compact and high-efficiency heat exchanger designs from a different perspective has increased. Many researchers [8–15] used different nanofluids as working fluid in heat pipe and heat exchangers and they obtained enhancement in thermal performance of the systems. Nanofluids are also being used in solar collectors for heat transfer enhancement [16–18].

In the literature, there have been many valuable studies about preparation, stability and thermal properties of nanofluids and their applications in thermal systems. However, none of the previous research has presented a summary of the thermo-hydraulic, thermodynamic and thermo-economic performance of nanofluids in thermal systems, along with the properties of other nanofluids. This study aims to present a comprehensive review of the preparation, stability, thermo-physical properties of nanofluids, as well as a summary of the thermo-hydraulic, thermodynamic and thermo-economic performance studies of nanofluids in different thermal systems (Fig. 1).

Nanofluid types and base fluids

Nanoparticle and base fluid are the main components of a nanofluid. A wide variety of nanoparticles has been used in studies in the literature. Metals such as Ag, Cu [19, 20], ceramics compounds such as Al_2O_3, Fe_3O_4, CuO, TiO_2, SiO_2, CeO_2, ZnO [21–27], carbon-based nanoparticles such as carbon nanotubes [28] and hybrid nanoparticles such as Cu–CNT, TiO_2–Ag, Al_2O_3–Ag [29–31] are used as nanoparticle in nanofluids. Since nanosized particles will be needed first in the preparation of nanofluid, the material to be used must be reduced to nanosize. There are two widely used methods for this process, namely the top-down method and the bottom-up method. Top-down method, which is based on the principle of reducing the material size to nanoscale by giving mechanical energy, is a method that requires high energy. Mechanical grinding can be given as examples of this method. The bottom-up method is based on the principle of enlarging particles in atomic or molecular form through chemical reactions and bringing them to the nanoscale. Sol–gel, chemical vapor condensation and gas condensation techniques can be given as examples of this method [32]. Generally, water, ethylene glycol, mixture of water and ethylene glycol, oil, acetone, toluene, glycerol, etc. are used as base fluid in nanofluids. Studies have shown that thermal performance changes with the use of different

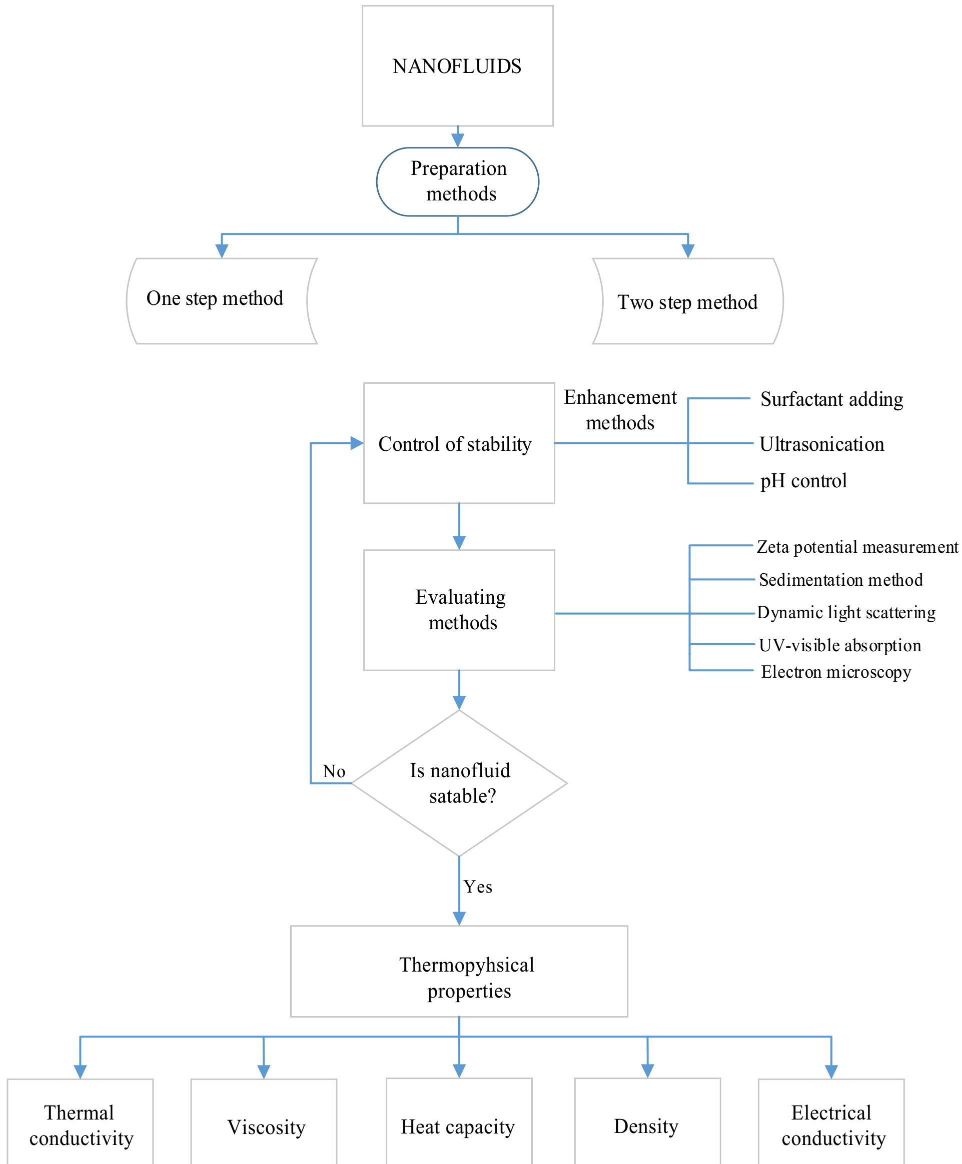

Fig. 1 Overview of preparation, stability and thermo-physical properties of nanofluids

base fluids. In a study, a nanofluid was prepared using water and mixture of ethylene glycol and water as the base fluids and 4 vol% SiC nanoparticles. Authors observed that SiC/EG–water nanofluid has approximately 5% higher thermal conductivity under the same conditions than when water is used as the base fluid [33]. Nikkam et al. [34] demonstrated that EG-based nanofluids show better thermal performance than DEG-based nanofluids.

Metal-based nanofluids

Metal nanofluid can be defined as the suspension of pure metal in a base fluid. Due to the high thermal conductivity of metals, the thermal conductivity of metal nanofluids is higher than other nanofluids (Table 1). Shahril et al. [35] conducted experiments on the heat transfer performance of Cu–H_2O nanofluids in concentric tube. They revealed that the thermal conductivity enhanced by 60% when the volume fraction of nanoparticles was 2%. Kumar et al. [36] produced Zn–oil and Cu–oil nanofluids by using two-step approach. They investigated thermo-physcial properties of the nanofluids. The results showed that Cu–oil nanofluid provided bigger thermal conductivity and viscosity enhancement than Zn–oil nanofluid. Chen et al. [37] prepared silver nanofluid by using ascorbic acid as a reductant and were used as the working fluid in the solar collector to enhance collector efficiency.

Ceramic-based nanofluid

Ceramic nanofluids are suspensions of low-density and high-stability ceramic particles formed with base fluids. Since

Table 1 Thermal conductivities of some nanoparticle material and base fluids

Material	Thermal conductivity (W/mK)	Reference
Silver	424	Perry and Green [230]
Copper	398	Perry and Green [230]
Aluminum	273	Perry and Green [230]
Iron	80	Perry and Green [230]
Steel	46	Alghoul et al. [231]
Al_2O_3	40	Shackelford and Alexander [232]
CuO	77	Hwang et al. [233]
TiO_2	8.37	Xuan et al. [234]
ZnO	29	Kim et al. [235]
SiO_2	1.2	Vajjha et al. [236]
Diamond	3300	Sundar et al. [237]
Carbon nanotubes	2000	Choi et al. [43]
Graphite	2000	Balandin [238]
Water	0.608	Wessel [239]
Ethylene glycol	0.257	Perry and Green [230]
40:60% EG/W	0.404	Sundar et al. [240]

ceramic particles are more economical and accessible, they have been used in many studies in the literature. The ceramic particles increase the heat capacity of the base fluid. Mohamed et al. [38] used ZnO–water nanofluid in flat-plate solar collector to investigate performance of energy storage system using nanofluid. They achieved stored energy increment of 7.78% for volume fraction of 0.1% compared to fluid without nanoparticles. Noghrehabadi et al. [39] tested SiO_2/water nanofluid with a mass fraction of 1% as a coolant in a symmetric, square flat-plate solar collector. They revealed that SiO_2/water nanofluid increased the efficiency of the square flat-plate solar collector compared with pure water. Choudhary et al. [40] investigated effect of MgO/EG–DW nanofluid on the thermal performance of flat-plate solar collector. They observed 16.36% maximum thermal efficiency enhancement at the conditions of 2.5 Lit/min and 0.2% volume fraction instead of EG/DW. Zhong et al. [41] used TiO_2 nanofluid inside a multiport mini-channel. They observed that thermal conductivity enhanced by 4.2% averagely for the 1% nanofluid. They also observed that the heat transfer performance increased when using the nanofluid compared to base water.

Carbon-based nanofluid

Carbon-based nanofluids like carbon nanotube [42–44], graphite [45, 46] and graphene oxide [47, 48] nanofluids have the nanoparticle percolation networks. These materials have anisotropic thermal conductivity, which provides abnormal increase in thermal conductivities of base fluids (Table 1). Carbon-based nanofluids provide improved heat transfer and higher stability with lower pressure drop compared to conventional fluids.

Sadeghinezhad et al. [49] made thermal performance analysis on graphene–water nanofluid with varying mass ratios in the range of 0.025–0.1%. They found that the thermal conductivity enhanced in the range of 7.96–25% compared to water with the use of graphene nanoparticles. Akhavan-Zanjani et al. [50] researched on the change in heat transfer by using graphene nanoparticles in a horizontal circular tube with constant heat flux on its surface. They studied at different nanoparticle concentrations in the range of 0.005–0.02% by volume. They revealed that heat transfer coefficient improved by 6.04% at the nanoparticle concentration of 0.02%. Akhavan-Zanjani et al. [51] took measurements about the improvement of thermal conductivity coefficient and heat transfer in their experimental research using graphene–water nanofluid in laminar flow conditions in a pipe. According to the results, the using graphene–water fluid at a concentration of 0.005, 0.01, 0.02% provide 17.9, 22.5, 26% heat transfer enhancement compared to base fluid, respectively. Arzani et al. [52] researched how the use of graphene nanofluid affects heat transfer and pressure drop. It has been stated that the Nu number enhances with the increasing of graphene concentration and therefore the friction value increases.

Hybrid nanofluid

Hybrid nanofluids are advanced varieties of nanofluids obtained by suspending a combination of multiple nanoparticles in different base fluids. Hybrid nanoparticles can form a nanocomposite structure in the base fluid, resulting in superior thermo-physical properties that are much higher than either type of nanoparticle. The thermal conductivity and viscosity of nanoparticles change with the combination of nanoparticles. The aim of the synthesis of hybrid nanofluids is to provide higher thermal conductivity than nanofluids containing a single type of nanoparticle due to the synergistic effect. The thermal conductivity of the base fluid increases by raising the concentration of hybrid nanoparticles to optimum point. This phenomenon is possibly related to an increase in the number of particles dispersed in the base fluid, thereby increasing the collision under the Brownian motion. Viscosity increases as a result of the presence of hybrid nanostructure in the base fluid, interactions between nanoparticles and liquid molecules. Viscosity is formed due to the shear stress between them. Therefore, as the particle concentration increases, viscous stress becomes significant and increases the viscosity of the nanofluid. An increase in the viscosity of the hybrid nanofluid is observed because the nanoparticles in the fluids can easily form a cluster and undergo surface adsorption [53]. The increment of thermal conductivity and dynamic viscosity of the base fluid with the hybrid nanoparticles concentration are known as desirable and undesirable results, respectively. Thus, using nanofluids for thermal enhancement requires careful attention and design [54]. Hybrid nanofluids provide effective results in heat transfer applications and they have the potential to make a significant contribution to reducing the cost of heat transfer equipment by making them smaller and lighter. Sundar et al. [55] determined that hybrid nanofluids have higher thermal conductivity and viscosity than single-nanoparticle-type suspensions. Nine et al. [56] observed that Al_2O_3–MWCNT nanofluid provides 8% enhancement in thermal conductivity compared to Al_2O_3 nanofluid. Madhesh et al. [57] conducted a study about heat transfer characteristics of Cu–TiO_2 hybrid nanofluid. They observed that convective heat transfer coefficient, Nu number and overall heat transfer coefficient enhanced by 52, 49 and 68%, respectively, when they used hybrid nanofluid in a heat exchanger according to base fluid. Yarmand et al. [58] investigated heat transfer performance of graphene-Pt nanofluid. They studied at the range of 5000–17,500 Reynolds number and different concentrations by mass of 0.02%, 0.06% and 0.1%. They obtained more effective heat transfer when using graphene-Pt nanofluid compared to using single-type particle of graphene (Table 2).

Table 2 Some hybrid nanofluids used in the literature

Researchers	Nanoparticles	Base fluid
Suresh et al. [53]	Al_2O_3–Cu	Water
Esfe et al. [241]	MWCNT–ZnO	Oil
Esfe et al. [242]	Cu–TiO_2	Water/EG
Abbasi et al. [243]	Al_2O_3/MWCNT	Water
Afrand [244]	fMWCNT–MgO	EG
Gürbüz et al. [245]	CuO–Al_2O_3	Water
Ahammed [246]	Al_2O_3–graphene	Water
Chen et al. [247]	Fe_2O_3/MWCNT	Water
Esfe et al. [248]	Ag–MgO	Water
Chopkar et al. [249]	Al_2Cu/Ag_2Al	Water/EG
Martin et al. [250]	Fe–CuO	Water
Minea [251]	SiO_2/TiO_2/Al_2O_3	Water
Asadi and Asadi [252]	MWCNT–ZnO	Oil
Gürbüz et al. [253]	ZnO–Al_2O_3	Ammonia/water
Nine et al. [254]	Cu–CuO_2	Water
Jana et al. [255]	CNT–Au	Water
Baghbanzadeh et al. [256]	Silicon–MWCNT	Water
Paul et al. [257]	Al–Zn	EG
Munkhbayar et al. [258]	Ag–MWCNT	Water
Batmunkh et al. [259]	Ag–TiO_2	Water
Arani and Pourmoghadam [260]	Al_2O_3/MWCNT	EG
Farajzadeh et al. [261]	Al_2O_3/TiO_2	Water
Esfe et al. [262]	MgO–SWCNT	EG
Giwa et al. [263]	γ-Al_2O_3/MWCNT	Water
Giwa et al. [264]	MgO–ZnO	Water

Preparation methods of nanofluids

The homogeneous distribution of the particles in the nanofluid mainly depends on the preparation method used. Thermo-physical properties and agglomeration tendencies of two similar nanofluids prepared by different methods may differ from each other. One-step method and two-step method are used in the preparation of nanofluids.

Two-step method

In this method, the desired nanoparticles are obtained and then the nanoparticles are dispersed into the basic fluid at a certain volume or mass concentration with or without. The two-step method is the most commonly used method due to its low production cost and the easy accessibility of nanoparticles [59]. This method has a higher commercialization potential, since it is possible to produce large quantities of nanofluids. Magnetic stirrers [60, 61] homogenizers [62], sonication [63–65] are used to ensure homogeneous distribution. In the two-step method, surfactants are used to increase stability and prevent agglomeration. In some studies, no surfactant or polymer was used while preparing a stable nanofluid with a two-step method (Fig. 2).

Mohammadpoor et al. [66] synthesized Cu/EG nanofluid using different methods. They compared the stability and heat transfer properties of nanofluids prepared by one-step method and two-step method. They observed that one-step nanofluid was more stable without any stabilizer. They also found that single method nanofluid increased thermal conductivity by 21%, while two-step nanofluid increased it by 39.4% at a concentration of 0.01%. In general, the two-step method is preferred for oxide nanoparticles, while the one-step method is preferred for metal nanoparticles [67] (Fig. 3).

One-step method

The one-step approach is based on combining the production and dispersion processes of nanoparticles in a nanofluid in a single step. For this method, chemical precipitation, chemical vapor deposition, physical vapor deposition (PVD) technique, inert gas condensation, microemulsion, sonochemical method, spray pyrolysis method are widely used. The one-step method is generally preferred for metal materials with high heat conduction coefficient and rapidly oxidizing. This is because when metal nanoparticles are synthesized with the fluid, their contact with air is prevented. However, this

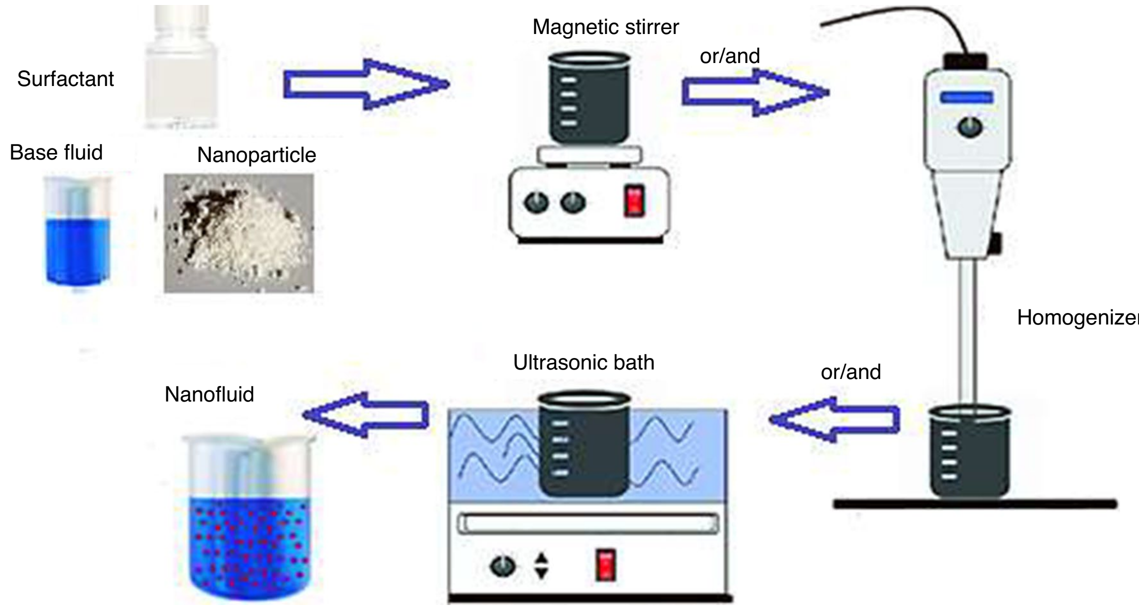

Fig. 2 Preparation of nanofluid by using two-step method

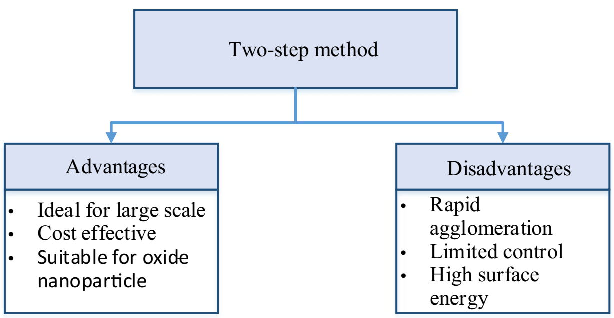

Fig. 3 Advantages and disadvantages of two-step method

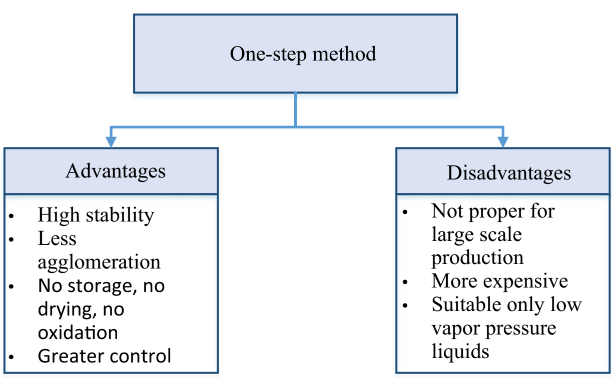

Fig. 4 Advantages and disadvantages of one-step method

method is suitable only low-vapor-pressure liquids, which limits the use of the method [68] (Fig. 4).

Stability of nanofluids

The stability of nanofluid is a significant factor affecting its applicability. Poor stability due to particle–particle and particle–liquid interactions is an important problem for nanofluids. Additionally, temperature and magnetic field can adversely affect the stability of the nanofluid [69]. Magnetic field intensity is very important for nanofluids. Hong et al. [70] investigated the effect of magnetic field strength and duration of action on the thermal conductivity of the nanofluid. Under the influence of the magnetic field, the magnetic particles (Fe_2O_3) form interconnected networks and also tend to take the one oriented toward the field direction, the nanotubes also move nearby, causing more physical contact, thereby increasing the thermal conductivity. They achieved a maximum increase of 35% using the magnetic field-free nanofluid. They also observed that as the residence time in the magnetic field increased, larger particle clusters formed and the thermal conductivity decreased. The strong magnetic field causes the repulsive force of the static electric charge between the suspension particles to decrease, thus making them agglomerate. Bigger clump of particles also form with a longer time in magnetic field; thus, the thermal conductivity decreases. Chang et al. [71] investigated the effect of magnetic field on the stability of CuO nanofluid. The CuO nanofluid loses stability at a faster rate in the presence of magnetic field. The repulsive potential acting between two suspended particles diminishes leading to higher nanoparticle aggregation. Formation of coarse particle takes place under the effect of magnetic field. Average particle size increases whereas zeta potential value decreases under the influence of strong magnetic field, which is a clear indication of clustering tendency and poor stability. Zhang et al. [72] investigated effect of particle concentration on the stability of water-based SiO_2 nanofluid. They found that the initial stability of the nanofluid was worse with increasing concentration. Large amounts of agglomeration in unstable nanofluids can cause precipitation and adsorption on the inner surface of the system; this can lead to decreased heat transfer efficiency, increased pumping power and even blockage in system pipe blocks [73]. Such behavior can be attributed to two opposing forces: (1) The van der Waals force causes agglomeration and then the particles separate from the nanofluid and sink to the bottom by the force of gravity. (2) Electrical double-layer repulsion tends to separate particles from each other by steric and electrostatic repulsion mechanisms [7475, 76]. The electrical double-layer repulsion force must be dominant over the van der Waals pull force for a stable nanofluid otherwise, particles tend to agglomerate and even cause sedimentation. In other words, to provide the stability of nanofluids, it is necessary to reduce the interaction between particles and activate their repulsive forces.

Methods of evaluating nanofluid stability

There are different methods used to evaluate the stability of nanofluids. These are zeta potential measurement, sedimentation method, ultraviolet–visible absorption spectroscopy method, electron microscopy method and dynamic light scattering method.

Zeta potential measurement

The electrical potential value of the repulsive force between nanoparticles is called zeta potential. It is measured in millivolts. Zeta potential value can take negative or positive values according to the particle surface charge. High zeta potential nanofluids are electrically stable. For nanofluids, when the zeta potential value is between 15 and 30 mV, precipitate formation is observed in a short time, stability is achieved at 30 mV, but it can be said that the stability is very good when the zeta potential is 45 mV and above. Kim et al. [77] prepared gold/water nanofluid without adding any surfactant. They determined the stability of nanofluid by measuring the zeta potential. The zeta potential of the nanofluid containing 0.018% and 0.0025% nanoparticles by volume was found as − 32.1 mV and − 38.5, respectively. Mondragon et al. [265] researched the effect of silica nanoparticle concentration on the stability of silica nanofluid. When the mass concentration of nanoparticles is 2%, the zeta potential value was −48.63 mV, while when the concentration was 20%, the zeta potential value was found to be −16 mV. They observed that the nanofluid containing 20% nanoparticles by mass showed a minimum stability of 48 h (Table 3).

Sedimentation method

The method of analyzing the stability of nanoparticles in nanofluids by observing their precipitation is called sedimentation method. The sedimentation method is one of the simplest nanofluidic stability determination methods. This method is based on the principle of measuring the sedimentation volume or amount over time by filling it from a prepared nanofluid into a transparent graduated glass tube [79]. Nanofluid is considered stable when the nanoparticles in it are homogeneously dispersed and there is no precipitation over time. When the particle size is getting smaller, sedimentation rate decreases. Therefore, the deposition rate of nanoparticles will be slower compared to large-sized particles in the base fluid. Sedimentation is a simple method compared to other techniques. Sedimentation can be analyzed by photographing the fluid and taking images. Figure 5 schematically shows the sedimentation-based stability evaluation method.

Table 3 Zeta potential values of some different nanofluids

Researchers	Nanofluid	Surfactant	Zeta potential value
Chakraborty et al. [266]	Cu–Zn–Al/water	None	38.6 mV
Wang et al. [96]	Al_2O_3/water	SDBS	− 40.1 mV
Sandhu et al. [267]	Al_2O_3/water–EG	None	57 mV
Sandhu et al. [267]	CuO/water–EG	SDS	47 mV
Ahammed et al. [268]	Graphene/water	SDBS	− 63.7 mV
Srinivas et al. [269]	CNT/water	None	20.5 mV
Hwang et al. [270]	Carbon Black/water	SDS	− 26.9 mV
Mostafizur et al. [271]	SiO_2/methanol	None	− 40 mV
Ghadimi et al. [272]	TiO_2/water	None	− 33.3 mV
Gupta and Sharma [29]	Cu–CNT/water	None	− 46.6 mV
Xian et al. [78]	TiO_2/water–EG	SDBS	−60 mV

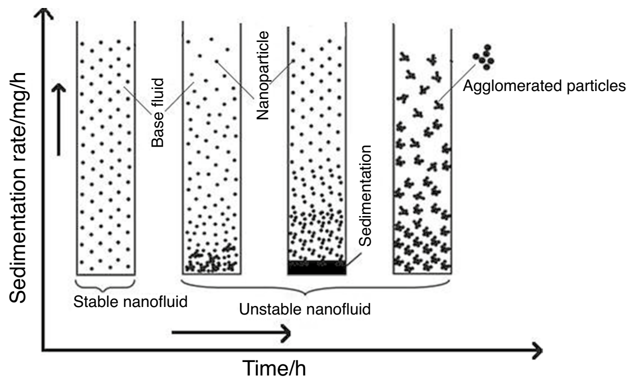

Fig. 5 Sedimentation measurement method for nanofluid stability evaluation

UV–visible absorption spectroscopy method

UV–visible absorption spectroscopy is another useful and effective method to observe the stability of nanofluids. Firstly, Jiang et al. [80] applied the UV–Vis spectrophotometer to evaluate the stability of nanofluids. If the characteristic aborption band of a nanofluid is at a wavelength of 190–1100 nm, the spectral absorbance method is appropriate for evaluating the stability of nanofluids [81]. UV–visible absorption spectroscopy method is based on the Beer–Lambert law. UV–visible absorption spectroscopy method is beneficial for obtaining quantitative results [82]. This method is not suitable for highly concentrated or dark colored nanofluids because high-concentration nanofluids cause high absorption of light and reduce the intensity of the scattered light, which degrades data quality [83].

Electron microscopy method

Electron microscopy is another alternative method to evaluate the stability of nanofluids by observing particle agglomeration and the distribution of nanoparticles using TEM and SEM devices. TEM provides a very high resolution in lattice images that can reach about 0.1 nm [84]. Duangthongsuk and Wongwises [85] used TEM to determine the size of TiO_2 nanoparticles in the TiO_2/water nanofluid. The nanoparticles were found to have an average diameter of about 21 nm and a spherical shape. Li et al. [86] used TEM images of Cu/water nanofluid, they observed that nanoparticles have a spherical or near-spherical shape and are well dispersed in the fluid. Seob et al. [273] prepared Cu/ethanol, Ni/ethanol, Cu/ethylene glycol and Ni/ethylene glycol nanofluids with the one-step method. Using TEM images, they determined that the particles are spherical and smaller than 100 nm. They also observed from the high-resolution images that EG shows better dispersion as base fluid compared to ethanol. Cu/EG nanofluid with the finest particle size showed the highest stability.

Stability enhancement methods

Various techniques have been used in the literature to enhance the stability of nanofluids. The most used of these are surfactant addition, ultrasonic mixing and pH control.

Surfactant addition

A nanofluid generally consists of two components. These are nanoparticles and base fluid. The stability of the nanofluid depends on the type of nanoparticles and the base fluid. Nanoparticles can be hydrophobic or hydrophilic, and base fluids can be polar or nonpolar. Hydrophilic nanoparticles such as oxide nanoparticles are easily dispersible in polar base fluids such as water, and hydrophobic nanoparticles such as carbon nanotubes can be dispersed in nonpolar basic fluids such as oils without requiring a third component. However, surfactants need to be added to stabilize the nanofluids if hydrophobic nanoparticles are dispersed in polar base fluids and hydrophilic nanoparticles in nonpolar base fluids. There are four different classes of surfactants. These are anionic, cationic, nonionic and amphoteric surfactants. Amphoteric surfactants contain both cationic and anionic hydrophilic groups. These surfactants can form cations and anions depending on the pH of the medium. They have antibacterial properties, resistance to water hardness and low toxicity [69] (Fig. 6).

The foam formation is the disadvantage of surfactants, which affects the thermal properties of the fluid. The addition of surfactant to the nanofluid can increase the stability but the high-temperature applications cause negative effect for surfactant (Table 4).

Ultrasonication

Ultrasonic mixing process, which is a physical method based on the use of ultrasonic waves in a fluid, is used to enhance the stability of the nanofluid by breaking the gravitational force for the nanoparticles. Sonication time is an important parameter. So it should be optimized. Long-term sonication can damage surfactants in nanofluids. In addition, nanoparticle size may decrease as sonication time increases. Chen and Wen [88] prepared the gold/water nanofluid with a sonication time ranging from 10 to 60 min. They observed that as the sonication time increased, the amount of agglomerated particles decreased. However, after 45 min., they found no change in particle size. Mahbubul et al. [89] applied ultrasonication for 30, 60, 90, 120, 150, 180 min. for TiO_2/water nanofluid.

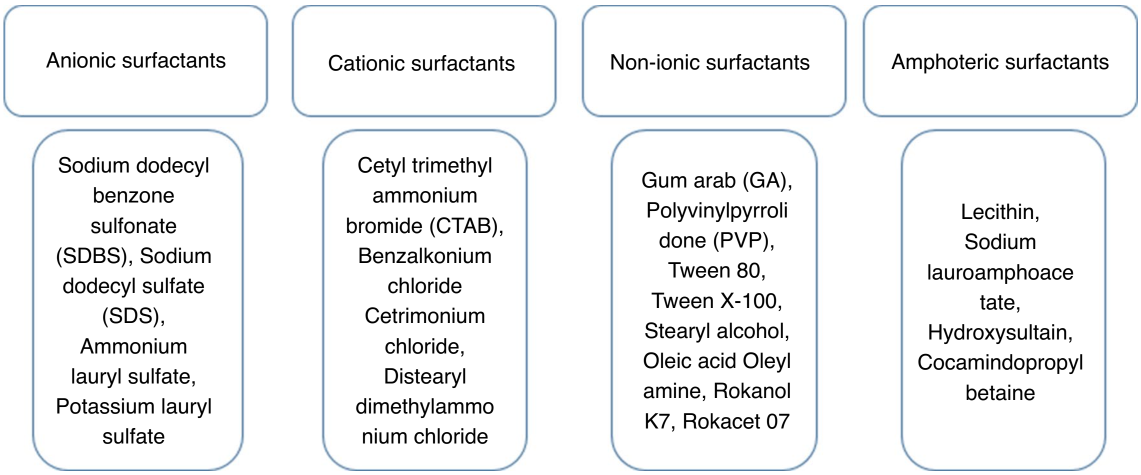

Fig. 6 Examples of surfactant types

Table 4 Effect of different surfactants on stability

Researchers	Nanofluid	Surfactant	Zeta potential values
Li et al. [86]	Cu–water	CTAB SDBS TX-10	28.1 mV −43.8 mV −8.3 Mv
Khairul et al. [274]	CuO/water	None SDBS	28 mV −85.1 mV 30 mV
Cacua et al. [275]	Al_2O_3–water	None SDBS CTAB	20 mv 32 mV
Choudhury et al. [276]	Al_2O_3–water	None SDS	14 mV −30 mV
Song et al. [277]	Stainless steel–water	SDBS CTAB	−70 mV 60.1 mV
Chakraborty et al. [278]	Cu–Zn–Al–water	SDS Tween 20	−50.6 mV 24.3 mV
Ghadimi et al. [272]	TiO_2–water	None SDS	−33.3 mV −55 mV
Jiang et al. [279]	CNT/water	None SDS	−30 mV −40 mV
Yılmaz Aydın et al. [87]	Dolomite–water	SDBS Triton X-100	30 mV 26 mV

According to the experimental results, they determined that the optimum ultrasonication time is 150 min. to provide the longest stability. More than 150 min. of sonication time caused the nanoparticles to re-agglomerate. Azmi et al. [90] kept TiO_2/water–ethylene glycol (60:40) nanofluid in magnetic stirrer for 30 min. and then in ultrasonic bath for 2 h. They conducted stability analysis using FESEM and TEM. They observed that the nanofluid was stable for more than 7 months. Mahbubul et al. [91] provided the distribution of 0.5% Al_2O_3 nanoparticles by ultrasonication in distilled water for different periods in the range of 0–5 h. They examined the distribution of nanoparticles by electron microscopy. The researchers found that higher ultrasonication time was required to achieve better stability as well as lower viscosity. According to the TEM analysis results, they observed better particle distribution after 2 h of ultrasonication. In addition, an external force such as ultracentrifugation can be used to separate and purify nanoparticles. This technique relies on particle deposition via centrifugal force caused by the rotation of the ultracentrifuge [92].

pH control

The pH value of nanofluids correlates with the surface tension of nanoparticles, and the pH change can be useful in the case of unstable nanoparticles. pH control of nanofluid is an approved technique for dispersing the aggregated nanoparticles in liquid and finally preparing of a stable nanofluid. pH is an effective parameter on stability of nanofluids [93]. pH value of a nanofluid can be enhanced or reduced by adding a suitable non-reactive alkaline or acidic solution [94]. Flow pattern change with pH variation of the nanofluids. In addition, this is not only change caused by PH variation of nanofluids. During the last decade, some studies showed that the variation of pH in nanofluid is an important parameter for enhancing of stability, thermal conductivity and viscosity of nanofluids. Lee et al. [95] revealed that as the pH of the water-based CuO nanofluids varied far from the isoelectric point of particles, the colloidal particles become more stable and finally alter the thermal conductivity of the fluid. Wang et al. [96] studied the thermal conductivity of Cu and Al_2O_3 nanoparticles in water under different pH values. Results showed that at lower pH values, the thermal conductivity ratio enhances with pH for different weight fractions of nanoparticles, whereas at higher pH values, this ratio decreases. They resulted that there is an optimal pH value for the highest thermal conductivity of the nanofluids. Wamkam et al. [97] investigated aggregation, precipitation and enhancement in thermo-physical properties (viscosity and thermal conductivity) of water-based nanofluids of ZrO2 and TiO2 at pH of isoelectric point (IEP). When the pH value of ZrO_2–water nanofluid was modified from the isoelectric point, the nanofluid viscosity enhancement was reduced by 46% because the aggregate size decreased and the nanofluid samples became stable.

Li et al. [86] investigated the effect of pH on the stability of SDBS doped copper/water nanofluid. They observed that the stability of the nanofluid is quite good at pH 9.5. Ju et al. [98] investigated the pH effect on carbon nanotube (CNT) nanofluids. They prepared nanofluid using deionized water as the base fluid and SDBS as a surfactant. They found that the agglomeration kinetic of CNTs depends on pH. The agglomeration of the CNT particles decreased significantly, as the pH increased from 3 to 10.

Comparing the above-mentioned approaches for preparing stable nanofluids, it can be found that the efficacy of these techniques may vary according to the type of nanoparticles, type of base fluids, nanoparticle concentrations and sonication time [99]. When the sonication time and power increase, cluster size reduces and the stability of suspension improves. However, this statement is not true for very high power of sonication and for large time intervals [100]. An ultrasonic device increases the temperature of the nanofluid but ambient temperature also affect, so various locations or different weather conditions can be result in producing a diverse nanofluid. Thus, it should be necessary to find out optimum period and power up to which sonication shows results assisting stability of nanofluids. Meanwhile, surface modification techniques are relatively difficult and expensive, which is not suitable for industrial applications. It is easy and economical to obtain stable nanofluids with pH control [93]. However, very low or high pH can cause acidity or alkalinity in nanofluids that damage the heat transferring equipment and restrict the use of nanofluids in practical applications [100]. Surfactant act as bridge between nanoparticles and base fluids to form the continuity between them by decreasing the surface tension of base fluids and by improving the dispersion process of nanoparticle. However, at high temperatures, surfactant-containing nanofluids cause foaming and clogging occurs on the inner walls of the pipes. Therefore, prolonged use of surfactant-containing nanofluids at high temperatures can cause thermal devices to fail [100].

Thermo-physical properties of nanofluids

In recent years, new kind of working fluids which contain nanosized material particles doped into a base fluid (ethylene glycol, deionized water, etc.) have been preferred for heat transfer applications due to the fact that they have outstanding effects on the thermo-physical properties of the base fluid. The various nanomaterials affect the thermo-physical properties of the base fluids differently. The concentration, shape and size of the nanoparticles are some of the major parameters that remarkably change the thermo-physical properties.

Thermal conductivity

Thermal conductivity is the most significant property for heat transfer systems. Nanofluids provide excellent heat transfer efficiency because of their higher thermal conductivities compared to base fluids. One of the reasons why nanofluids have a better thermal conductivity than the base fluid is that nanoparticles move in a random direction when they collide with molecules in the fluid. This motion is described as Brownian motion, a key mechanism that controls the thermal behavior of nanoparticle–liquid suspensions [101]. Brownian motion efficiency increases as particle size decreases. Another reason is the nanolayer. Liquid molecules close to the solid particle surface form this layer. In addition, it is possible to say that the heat transfer coefficient of the base fluid is also effective on the thermal conductivity of the prepared nanofluid solution. The methods used to measure the thermal conductivity of nanofluids are as follows: hot wire method, transient plane welding method, temperature swing technique, steady-state parallel plate technique and optical method. Many parameters affect the thermal conductivity. Some of them are nanoparticle concentration, nanolayer, size of the nanoparticle, temperature and type of the basic fluid. Several models have since been developed for thermal conductivity of nanofluids. Some of thermal conductivity models for nanofluids are presented in Table 5. In the derivation of most of the analytical models, the classical Maxwell [102] and Hamilton and Crosser [103] models are used as the basis. The Maxwell model can accurately predict of the very dilute particle–liquid mixtures containing spherical shaped particles. Maxwell model is based on the conduction solution through a stationary random suspension of spheres. The Hamilton and Crosser model [103] is the extended version of the Maxwell model to take into account irregular particle geometries by introducing a shape factor for determination of particle–liquid mixtures containing non-spherical particles. Bruggeman model [280] is based on the differential effective medium (DEM) theory to estimate the effective thermal conductivity of composites at high particle concentrations. Patel model [283] takes into account the specific surface area of nanoparticles and nanoconvection induced by Brownian nanoparticles. In this model, kinetic theory-based microconvection is considered as well as liquid layering, in addition to particle concentration. The Evans et al. [106] was obtained by analyzing and simulating the effect of aggregation and interface thermal resistance on the effective thermal conductivity of nanofluids and nanocomposites. Singh model [107] is a modified Hamilton–Crosser model for spherical particles. Rea model [282] is based on experimental data of thermal conductivity of alumina and zirconia nanofluids at various temperatures (20–80 °C). Afrand correlation [109] is proposed to estimate the thermal conductivity ratio of magnetic nanofluid using experimental data. In experimental studies, the thermal conductivities of Fe_3O_4 nanofluids at different concentrations were measured at different temperatures (20–55 °C). Khdler

Table 5 Some thermal conductivity models of nanofluid

Researcher	Equation	Remarks
Maxwell [102]	$k_{nf} = \frac{k_p+2k_f+2\phi(k_p-k_f)}{k_p+2k_f-\phi(k_p-k_f)}k_f$	A theory developed for spherical particles dependent on volume concentration
Hamilton and Crosser [103]	$k_{nf} = \frac{k_p+(n-1)k_f+(n-1)\phi(k_p-k_f)}{k_p+(n-1)k_f-\phi(k_p-k_f)}$	A theory developed for spherical and cylindrical particles
Bruggeman [280]	$\frac{k_{nf}}{k_f} = \frac{(3\phi-1)\frac{k_p}{k_f}+[3(1-\phi)-1]+\sqrt{\Delta}}{4}$	A theory to estimate the effective thermal conductivity of mixed bodies from isotropic substances
Lu and Lin [281]	$\frac{k_{eff}}{k_f} = 1 + a\phi_p + b\phi_p^2$	The model is based on composites containing aligned spheroidal inclusions
Eastman et al.[105]	$\frac{k_{eff}}{k_f} = \left[1 + \frac{k_p\phi d_f}{k_f(1-\phi)d_p}\right]$	A generic model
Evans et al. [106]	$\frac{k}{k_f} = 1 + \varphi_p\frac{k_p}{3k_1}$	A model developed considering particle thermal conductivity
Singh et al. [107]	$k_{nf} = k_f(1 + 4\phi)$	This is a modified Hamilton–Crosser model
Rea et al. [282]	$k_{nf} = k_f(1 + 4.5503\phi)$	A model based on experimental data
Khanafer and Vafai [104]	$\frac{k_{nf}}{k_f} = 1 + 1.0112\phi + 2.4375\phi\left(\frac{47}{d_p(nm)}\right) - 0.0248\phi_p\left(\frac{k_p}{0.613}\right)$	A model based on experimental works
Wang et al. [45]	$\frac{k}{k_f} = 1 + \frac{3fq(p)/p_0}{1-fq(p)/p_0}$	A model considering nanoparticle size, volume faction shape, nanolayer and interaction between particles
Sundar et al. [237]	$k_{nf} = k_{bf}(1 + 10.5\phi)^{0.1051}s$	A model suitable for Fe_2O_3 with a specified range of volume fraction and temperature
Patel et al. [283]	$\frac{k_{eff}}{k_f} = 1 + \frac{k_p d_f\phi}{k_f d_p(1-\phi)}[1 + c\frac{2k_B T d_p}{\pi\alpha_f\mu_f d_p^2}]$	A microconvection model for thermal conductivity of nanofluids
Wang et al. [108]	$\frac{k_{eff}}{k_f} = \frac{(3\phi-1)k_p/k_f+[3(1-\phi-1]+\sqrt{\Delta_B}}{4}$	A fractal model for predicting the effective thermal conductivity of liquid with suspension of nanoparticles
Afrand et al. [109]	$\frac{k_{nf}}{k_{bf}} = 0.7575 + 0.3\varphi^{0.323}T^{0.245}$	A model developed by curve fitting of data and based on magnetic nanofluid
Khndher et al. [110]	$\frac{k_{nf}}{k_{bf}} = 1.268\times\left(\frac{T}{80}\right)^{-0.0074}\times\left(\frac{\varphi}{100}\right)^{0.036}$	A model developed based on temperature, particle volume concentration
Zaraki et al. [111]	$\frac{k_{nf}}{k_{bf}} = 1 + N_c\times\phi$	A model based on experimental data for low volume fractions of nanoparticles ($\phi < 5\%$)

model [110] is based on experimental data which include thermal conductivity of Al_2O_3 nanoparticles dispersed in bio glycol-based fluid. This correlation is function of concentration, temperature and the thermal conductivity of base fluid. Zaraki et al. [111] developed a model based on the results of the measured thermal conductivity of nanofluids reported by the previous studies. This relation is only appropriate for low volume fractions of nanoparticles ($\phi < 5\%$) where Nc denotes the number of thermal conductivity. The number of thermal conductivity (Nc) can be changed by altering various parameters, such as the size of the nanoparticles, the shape of the nanoparticles, the type of the nanoparticles and the type of the base fluid.

Effect of particle concentration on thermal conductivity of nanofluids

The addition of nanoparticles with optimal size improves the thermal performance of thermal systems. However, the thermal conductivity decreases when the particle agglomeration begins after a certain concentration value. The particles with higher volume fraction and size promote agglomeration and sedimentation, which increases the viscosity of the nanofluid and causes particle fouling on the heat transfer surfaces. The development of fouling behavior and the higher viscosity of the working fluid lead to an increased pressure drop and therefore a greater pumping power demand resulting in lower thermal–hydraulic performance and lower thermal performance than conventional fluid [112, 113114]. In order to achieve high heat transfer with low-pressure drop, it is necessary to determine the optimum volume fraction of nanoparticles with higher thermal conductivity. It is important to maintain the system in maximum heat transfer and minimum pumping power to design an energy-saving thermal system [49].

Goodarzi et al. [115] investigated thermal performance and pressure drop of double pipe heat exchanger by using nitrogen-doped graphene (NDG) nanofluids with various nanosheets at several concentrations (0.01, 0.02, 0.04, 0.06 mass%). They revealed adding nanosheets to water improve the heat transfer coefficient of the working fluid. They obtained 15.86% enhancement of the convective heat transfer coefficient in comparison with water for 0.06% concentration of ultrafine particles in NDG nanofluid. They also concluded an augmentation in Reynolds number and particle mass percentage could increase the friction factor, which then led to the pressure drop and pumping power rise. Akhavan-Behabadi et al. [116] investigated heat transfer characteristics and pressure drop performance of heat exchanger by using MWCNTs–water nanofluid as a working fluid with different particle mass concentrations of 0.05, 0.1 and 0.2%. They observed heat transfer coefficient of nanofluid is higher than that of the base fluid and increases with the particle concentrations. They observed 24.1 and 25.9% enhancement in Nu number for 0.5% concentration of nanofluid and 11,000 and 19,000 Re number while for 0.2% concentration of nanofluid the Nu number increased 33.3 and 34.9%, respectively. Similarly, minimum pressure drop (17%) was found for 0.1% weight concentration of nanofluid and maximum pressure drop was found (24.9%) for 0.2% concentration of nanofluid at Re number of 12,000.

Ezekwem and Dare [117] prepared SiC/DW and SiC/EG nanofluids using a two-step method at volume concentrations of 0.5–5%. The thermal conductivities of nanofluids were analyzed. The thermal conductivity of nanofluid enhanced with an increase in the volume concentration of nanoparticles. They found that SiC/EG and SiC/DW nanofluids increased thermal conductivity by 25% and 16% at 5 vol. % concentration, respectively. Suresh et al. [118] investigated the thermal conductivity of Al_2O_3–Cu/water hybrid nanofluids with different nanoparticle concentrations (0.1–2% by volume). They concluded that the thermal conductivity is related to nanoparticle concentration. They observed that when 2% nanoparticles by volume are added to water, the thermal conductivity increases by 12.11%. Gandhi et al. [119] prepared graphene–water nanofluid at the range of 0.001–0.2% by volume concentration and measured thermal conductivity. They found that as the nanoparticle concentration increased, the thermal conductivity increased. The thermal conductivity increased by 27% compared to the base fluid when using 0.2% nanofluid. Saholi and Sabbaghi [120] prepared CuO/EG–W nanofluid at different concentrations ranging from 0.01 to 0.1% by mass fraction. They observed that as the amount of nanoparticles added to the base fluid increased, the thermal conductivity increased. However, after a certain time, the nanoparticles agglomerated and the nanofluid became unstable, so the thermal conductivity started to decrease as the amount of CuO nanoparticles in the nanofluid increased. They obtained 1.66% maximum thermal conductivity enhancement at 0.06% nanoparticle concentration at 70 °C. Increasing the nanoparticle concentration causes large shear stresses and requires high pumping power. Therefore, it is significant to choose the appropriate nanoparticle concentration in the prepared nanofluids [121].

Effect of particle size on thermal conductivity of nanofluids

The particle size is a significant parameter affecting the thermal conductivity of nanofluids. A lot of study presented that the thermal conductivity of nanofluid enhances with the decreasing of particle size. Chopkar et al. [122] used Al_2Cu–water nanofluid at 2% concentration. When the particle size was 101 nm, thermal conductivity increased by 61% compared to water, while when particle size was 31 nm, thermal conductivity increased by 96%. Maheshwary et al. [123] investigated particle size effect on thermal conductivity. They found that thermal conductivity increased with the reduction in particle size of TiO_2–water nanofluid. Some studies in the literature discussed that thermal conductivity decreases with the reduction of nanoparticle size. Sun et al. [124] prepared SiO_2–water nanofluid using SiO_2 with particle sizes of 10 nm and 60 nm to show the effect of nanoparticle size on thermal conductivity. They observed 11% and 13% enhancement in thermal conductivity, respectively. Although there is not a big difference, this study shows that sometimes there may be an enhancement in thermal conductivity with increasing nanoparticle size. Yashawantha et al. [125] investigated effect of particle size on thermal conductivity. Their results showed that 2 vol. % graphite–ethylene glycol nanofluid with nanoparticle size < 50 nm increased the thermal conductivity by 16.3% compared with nanoparticle size < 100 nm.

Effect of base fluid on thermal conductivity of nanofluids

Studies have shown that the base fluid is an effective parameter on the thermal conductivity of the nanofluid. Reddy and Rao [126] used TiO_2 nanofluid with three different base fluids to investigate base fluid effect. They used water, EG–water (40:60) and EG–water (50:50) as the base fluids. At 1% nanoparticle concentration by volume, they obtained the increase in thermal conductivity of 5.01, 14.38, 4.2%, when they use water, EG–water (40:60), EG–water (50:50), respectively. In their study, the most effective result was obtained when using EG–water (50:50) mixture as base fluid. Abdolbaqi et al. [127] measured the thermal conductivity of Al_2O_3 nanofluids prepared using different base fluids. When they used bioglycol–water (60:40) as the base fluid, the thermal conductivity increased by 13%, while the thermal conductivity increase was 24% when they used bioglycol–water (40:60) as the base fluid. According to these results, the maximum increase in thermal conductivity increased approximately 2 times with the use of bioglycol–water (40–60). Usri et al. [128] took thermal conductivity measurements of nanofluids prepared with water–ethylene glycol (60:40, 50:50 and 40:60) base fluids using the two-step method with 13-nm-sized Al_2O_3 nanoparticles. According to the experimental results, as the ratio of EG in the mixture increases, the increase in thermal conductivity decreases due to its properties. Dadwal and Joy [129] prepared nanofluids by using magnetite (Fe_3O_4) nanoparticles in two different base fluids. They investigated thermal conductivity of nanofluids and they found the kerosene-based nanofluid showed relatively larger enhancement in the thermal conductivity than the toluene-based fluids at similar concentrations.

Effect of temperature on thermal conductivity of nanofluids

Studies have shown that temperature has an effect on thermal conductivity and thermal conductivity increases with temperature increase. The effective viscosity of nanofluids consists of two parts, static and dynamic. The static part of the viscosity of the nanofluid is a combination of the Einstein model and the viscosity effect from the nanolayer. The nanolayer-dependent viscosity effect is enhanced in that a nanolayer is around a nanoparticle and its thickness is one nm. The dynamic part consists of the viscosity effect resulting from the Brownian motion of the nanoparticles [130]. The decrease in viscosity at high temperatures is due to the increase in intermolecular distance in the base fluid at high temperature. As the temperature increases, the intermolecular attraction between the nanoparticles and their base fluids weakens. The viscosity increase in nanofluids increases more with temperature compared to the base fluid. This effect is greater at higher concentrations. In a study, 2.96 times higher viscosity increase was observed with a 2.0% volume concentration at 60 °C compared to the base fluid [131]. In addition, the viscosity enhancement can change type of base fluid. The viscosity enhancement decreased with increment percentage of ethylene glycol in mixture [132]. Naik and Sundar [133] investigated effect of temperature on thermal conductivity of CuO nanofluid with a water/propylene glycol mixture (30:70%) as base fluid and they revealed thermal conductivity enhancements of 10.9% and 43.37% for 1.2 vol% and at 298.15 and 338.15 K, respectively. Buonomo et al. [134] measured thermal conductivity of Al_2O_3–water nanofluid at different temperatures and concentrations. They revealed that the increase in the thermal conductivity of nanofluid compared to pure water is higher as the temperature increases. They showed that the increase with 0.5% particle concentration at 25 °C increased from about 0.57% to about 8% at 65 °C. They also found that for 4% volume concentration, the increase in thermal conductivity enhanced from 7.6% to 14.4% as the temperature increased from 25 to 65 °C.

Viscosity

Viscosity of nanofluid is as important as thermal conductivity in heat transfer applications. The viscosity of the base fluid changes with adding nanoparticles. The enhancement in pressure drop due to viscosity increases the pump power. Many parameters affect the viscosity of nanofluids. These are temperature, nanoparticle concentration, nanoparticle size and shape, shear stress, surfactant addition, type of base fluid, agglomeration rate and type of nanoparticles [47]. As the temperature increases, the viscosity decreases due to influence on the intermolecular forces. Surfactants also increase the viscosity of the nanofluids [135]. Viscometer types most used in viscosity measurements of nanofluids are vibrating/oscillating viscometer, rotating viscometer, orifice-type viscosimeter, capillary viscometer and bubble viscometer [284]. Some of the important viscosity models are given in Table 6.

Effect of temperature on viscosity of nanofluids

Heating the liquids gives higher energy to the molecules of the liquid. This increase in energy contributes to the increase in random movements and the weakening of the intermolecular forces that hold the fluid molecules. These events cause a decrease in the resistance of the fluid to shear stress and as a result, a decrease in viscosity is seen. Anoop et al. [137] prepared Al_2O_3–water and Al_2O_3–EG nanofluids at different nanoparticle concentrations. They took viscosity measurements at different temperatures. They found that the viscosity increased as the temperature reduced. Kumerasan and Velraj [138] investigated the relationship between the temperature of MWCNT/EG–water nanofluid and viscosity in their study. They observed an increase in viscosity at temperatures above 25 °C. However, in the low-temperature range, the increase in viscosity was found to be lower compared to higher temperatures. Moldoveanu et al. [139] investigated the viscosities of Al_2O_3/water, SiO_2/water and Al_2O_3–SiO_2/water nanofluids at 25 °C. They presented that viscosity decreases with increasing of temperature. Aydın et al. [140] analyzed viscosity of bauxite/DI water nanofluid. They showed that the viscosity is decreasing with increase in the temperature (Fig. 7).

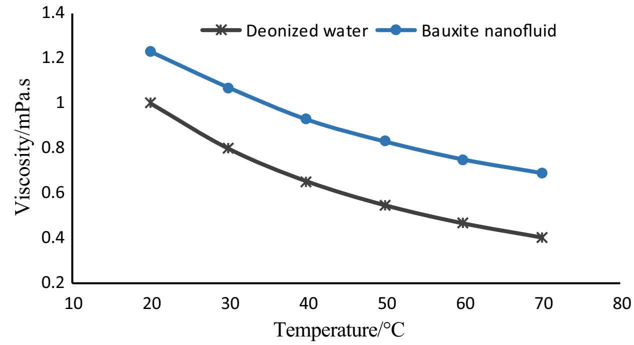

Fig. 7 Viscosity values of deionized water and bauxite nanofluid depending on temperature [140]

Effect of concentration on viscosity of nanofluids

The concentration of nanofluid is a significant parameter that affects viscosity. As the concentration of nanoparticles increases, the viscosity of the nanofluid increases because velocity and the convection reduce. The larger fractions of nanoparticles make the nanofluid more viscous as such the velocity and the convection decreases which leads to the rise of boundary layer thickness resulting in reduced temperature gradient and Nusselt number [67]. Baratpour et al. [141] prepared SWCNT/EG nanofluid and studied at various temperatures and concentration. They found that dynamic viscosity increased with increasing solid volume fraction and decreased with increasing temperature. Banisharif et al. [142] investigated thermo-physical properties of Fe_3O_4/EG–water nanofluid. They observed that the dynamic

Table 6 Some viscosity models of nanofluids

Researcher	Equation	Remarks
Einstein [285]	$\mu_{eff} = \mu(1 + 2.5\phi)\phi < 0.05$	A model valid for spherical particles of volume concentration less than or equal to 2%
Brinkman [286]	$\frac{\mu_{eff}}{\mu_f} = \frac{\mu_{eff}}{(1-\phi)^{2.5}}$	An extended Einstein model
Bruijn [287]	$\frac{\mu_{eff}}{\mu_f} = 1 + 2.5\phi + 4.698\phi^2$	A model valid for spherical particles
Batchelor [288]	$\mu_{eff} = \mu_0\left(1 + 2.5\phi + 6.5\phi^2\right)$	A model developed considering interaction between particles
Wang et al. [289]	$\frac{\mu_{eff}}{\mu_f} = 1 + 7.3\phi + 123\phi^2$	A generic model
Dávalos-Orozco et al. [290]	$\mu_{eff} = \mu_f\left(1 + 2.5\phi + 6.17\phi^2\right)$	A model based on volume concentration of nanoparticles
Nguyen et al. [291]	$\mu_{nf} = \mu_0\left(1 - 0.025\phi + 0.015\phi^2\right)$	A model based on curve fitting of experimental data
Abedian et al. [292]	$\mu_{nf} = \frac{\mu_{bf}}{(1-2.5\varphi)}$	A model developed for particle suspensions
Heyhat et al. [293]	$\mu_{nf} = \mu_0(T)Exp\left(\frac{5.989\phi}{0.278-\phi}\right)$	A model valid for a specified temperature range, particle size and concentration
Esfe et al. [294]	$\frac{\mu_{nf}}{\mu_{bf}} = 1 = \left(0.1008 \times \varphi^{0.69574} \times d_p^{0.44708}\right)$	A model developed considering effect of particle diameter of Fe–water nanofluid
Hamid et al. [136]	$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 1.42(1 + R)^{-0.1063}\left(\frac{T}{80}\right)^{0.2321}$	A model developed for a specified nanoparticle volume concentration and temperature range
Zaraki et al. [111]	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + N_\nu \times \phi$	A model developed for diluted nanofluids with where Nv denotes viscosity parameter

viscosity of nanofluid decreased with nanoparticle content in particular below 273.15 K, up to 40% at 0.1% in volume.

Effect of particle size on viscosity of nanofluids

The effect of the size of nanoparticles used in nanofluids on viscosity has been associated with different results in different studies. In some studies, viscosity of nanofluids increases with the increasing of particle size [143144] while in some studies, viscosity increases with the decreasing of nanoparticle size [145, 146]. He et al. [147] investigated viscosity of TiO_2–water nanofluid with different concentrations and different particle sizes. They found that when the particle size and particle concentration increases, relative viscosity of nanofluids increases. Nguyen et al. [148] used Al_2O_3 nanoparticles of 36 nm and 47 nm sizes while preparing Al_2O_3–water nanofluid. They observed that particle size effect became more important at high volumetric concentration (> 4%) and the viscosity of the nanofluid was found to be greater when using small nanoparticle size than when using large nanoparticles. According to this result, the viscosity of the nanofluid prepared with 47 nm-sized particles at high concentration was found to be higher than the viscosity of the nanofluid prepared with 36 nm particles. According to this result, they found that the viscosity of the nanofluid increased as the particle size increased at high concentrations. In an experimental study, Al_2O_3–water nanofluid was prepared using 45 nm and 150 nm nanoparticles by Anoop et al. [137]. According to the viscosity measurement results, the viscosity of the nanofluid prepared with nanoparticles with a particle size of 45 nm was found to be greater than the viscosity of the nanofluid prepared with nanoparticles with a particle size of 150 nm. In other words, they argued that smaller nanoparticles increased the viscosity more. Considering the researches, it can be inferred that viscosity of nanofluids is highly dependent on particle size.

Heat capacity

Specific heat is another important parameter affecting the heat transfer rate of nanofluids. It is directly linked to heat storage, transfer and the Prandtl number. Base fluid and nanoparticles, which are components of a nanofluid, both affect the specific heat capacity of the nanofluid.

Kumerasan and Velraj [138] investigated the specific heat of MWCT/EG–water nanofluid in their study. The addition of carbon nanotube particles to the base fluid increased the specific heat. However, as the nanoparticle concentration increased, the increase in the specific heat value decreased. Yarmand et al. [149] prepared carbon–graphene/EG nanofluid and investigated the specific heat capacity of the hybrid nanofluid. They found that the specific heat capacity of the hybrid nanofluid enhanced with increasing of temperature and nanoparticle concentration. Yiamsawasd et al. [150] prepared nanofluids using TiO_2 and Al_2O_3 nanoparticles and pure water and EG/water (20:80 mass%) as base fluid. The nanoparticle concentration and temperature range from 0 to 8% and 15–65 °C, respectively. They observed that the specific heat of nanofluids is lower than that of the base liquids. They also observed that the specific heat reduces with increasing of the particle concentration and the specific heat of nanofluid enhances with increasing temperature. Studies have shown that nanoparticle concentration and temperature are effective on specific heat.

The low heat capacity of the working fluid used is a disadvantage for thermal energy storage systems. The fluid used as a refrigerant should also have a high heat capacity [151]. Using a working fluid with a higher heat capacity is the most direct way to increase the efficiency of small heat exchangers [152] Therefore, increasing the heat capacity of nanofluids has become a current issue. One of these methods is the use of nanoencapsulated PCMs for the preparation of nanofluids. Nanoencapsulated phase change material (NEPCM) is a type of nanofluid in which the nanoparticle consists of a core and a shell. The core is made of a phase change material (PCM), which can undergo a solid–liquid phase change and absorb or release a significant amount of energy due to the latent heat of phase change. Ghalambaz et al. [153] investigated heat transfer performance of NEPCM particles in a cavity. They observed a higher heat transfer rate in the cavity due to the increase in the heat storage capacity of the NEPCM particles as a result of the increase in the latent heat of the PCM cores. The researchers also used nanoencapsulated phase change materials in different systems such as a minichannel heat sink, double pipe heat exchanger, an eccentric annulus, an inclined porous cavity [151, 152, 154, 155].

Density

Density is a significant property of nanofluid. Re number, friction factor, pressure loss and Nu number are affected by density change. When nanoparticles are dispersed in base fluids, the density of nanofluids increases. Although the researches on density are very limited, the most basic nanofluid density calculation method by Pak and Cho [156] is given in Eq. 1.

$$\rho_{\mathrm{nf}} = \varphi\rho_{\mathrm{p}} + (1 - \varphi)\rho_{\mathrm{bf}} \tag{1}$$

where ρ_{nf} is the density of the nanofluid, ρ_{p} is the density of the particle, φ is the particle volume concentration and ρ_{bf} is the density of the base fluid. Pak and Cho conducted the experiment at only one temperature (25 °C) for γ-Al_2O_3 and TiO_2 nanofluids up to 4.5% volume concentration to verify Eq. (1).

It has been concluded that the density of nanofluid enhances with the increase in the concentration of nanoparticles [157, 158]. Considering two solutions with and without nanoparticles added for unit volume of fluid, although the amount of fluid remains constant, there is an increase in the total mass, so the solution containing nanoparticles will be denser than the other. Density is an intensive property that varies depending on the amount of material. Al-Waeli et al. [159] prepared nanofluids with SiC nanoparticle (0.5 mass %) and different base fluid (water, water/EG, water/PG) and measured the density. They observed the increasing temperature results in density decrease. They found that density increase was 0.0015% at 25 °C, whereas increase rate decreased to 0.002% at 60 °C. EG has a much higher density than PG, but when added to water at 35%, the density difference has been found to be relatively smaller than 35% PG and water. The maximum density increase rate was found 16.71% for EG–water nanofluid.

Electrical conductivity

Nanomaterials have high electrical conductivity. Therefore, dispersion of nanomaterials in base fluids enhances electrical conductivity significantly as compared to base fluid. Various parameters affect the electrical conductivity of nanofluids such as size and shape of nanomaterials, temperature, preparation methods, instruments, surfactant and volume concentration [160]. Ramalingam et al. [161] observed that the electrical conductivity of Cu–S nanofluid increased linearly with temperature. Therefore, the improvement electrical conductivity of nanofluids decreased from 2847 to 1925% with the variation of 30 ºC–55 ºC in temperature, respectively. Giwa et al. [162] investigated electrical conductivity of deionized water-based γ-Al_2O_3–MWCNT hybrid nanofluids. They obtained maximum enhancements of 442.9 and 26.3% at 55 °C for the electrical conductivity of nanofluids at particle mass ratios of 90:10 and 20:80, respectively, according to base fluid. Giwa et al. [163] also investigated electrical conductivity of (MWCNT)-Fe_2O_3/deionized water nanofluid at temperatures and volume concentrations ranging from 15 to 55 °C and 0.1–1.5%, respectively. Their results showed that electrical conductivity of the hybrid nanofluids increases with respect to increasing volume concentration and temperature.

Thermo-hydraulic performance of nanofluids in thermal systems

The importance of thermo-hydraulic performance of a system is increasing. Therefore, alternative methods for improving thermo-hydraulic performance in such flows are being searched. These methods include applications related to the geometric arrangements of pipes, which are mostly known as passive heat transfer improvement methods, as well as the improvement of fluid-related properties. The flowing through pipe bundles is quite often used in applications such as heating and cooling in industry. The use of nanofluid is also increasing day by day to improve the heat transfer in thermal systems. The use of nanofluids instead of conventional working fluids is an effective way to increase the thermo-hydraulic performance of these systems at different types of heat exchangers. It is also significant to increase the heat transfer performance of different types of solar collectors and it is aimed at increasing the thermal efficiency of these systems. For this, different types of nanofluids are used to improve thermo-hydraulic performance in solar power technologies. The improvement in heat transfer and enhancement in friction should be considered together. Thermo-hydraulic performance (THP) has been defined as the ratio of the improvement rate expressing the increase in heat transfer to the friction factor. The main criterion in the evaluation of thermo-hydraulic performance of the thermal system is given in Eqs. 2 and 3 [164]. Models with a THP coefficient above 1 are considered advantageous, while models below this value are considered unfavorable models.

$$\eta = \frac{\left(Nu_{\mathrm{m}}/Nu_{\mathrm{f}}\right)}{\left(f_{\mathrm{m}}/f_{\mathrm{f}}\right)^{1/3}} \tag{2}$$

$$\eta = \frac{\left(Nu_{\mathrm{m}}/Nu_{\mathrm{f}}\right)}{\left(f_{\mathrm{m}}/f_{\mathrm{f}}\right)^{1/3}} = \frac{h_{\mathrm{m}}/h_{\mathrm{f}}}{\left(\Delta P_{\mathrm{m}}/\Delta P_{\mathrm{f}}\right)^{1/3}} \times \frac{\lambda_{\mathrm{f}}}{\lambda_{\mathrm{m}}} \times \left(\frac{\rho_{\mathrm{f}}}{\rho_{\mathrm{m}}}\right)^{1/3} \times \left(\frac{\mu_{\mathrm{m}}}{\mu_{\mathrm{f}}}\right)^{2/3} \tag{3}$$

The thermal and hydraulic properties of nanofluids are key to evaluating and improving their performance. Thermal properties such as thermal conductivity, viscosity and density are affected by many parameters such as friction factor, Re number and pump efficiency [165]. The factors affecting thermo-hydraulic performance are given in Fig. 8.

There are many works about effects of solid particle concentration, Reynolds number, pressure drop, flow rate and regime of nanofluids on thermo-hydraulic performance. Particle concentration is one of the parameters affecting the convective heat transfer on nanofluids. The fluid properties change greatly as the concentration increases. Particularly, the viscosity of a nanofluid is typically significantly larger than that of the base fluids, meaning that velocity and pumping power are also larger if Reynolds numbers are set equal. In order to obtain a proper comparison concerning the practical efficiency of the fluids, pumping powers must also be considered. This is a reasonable result, since the practical efficiency must naturally eventually worsen with increasing fraction of solid material. Asirvatham et al. [166] investigated the convective heat transfer of nanofluids

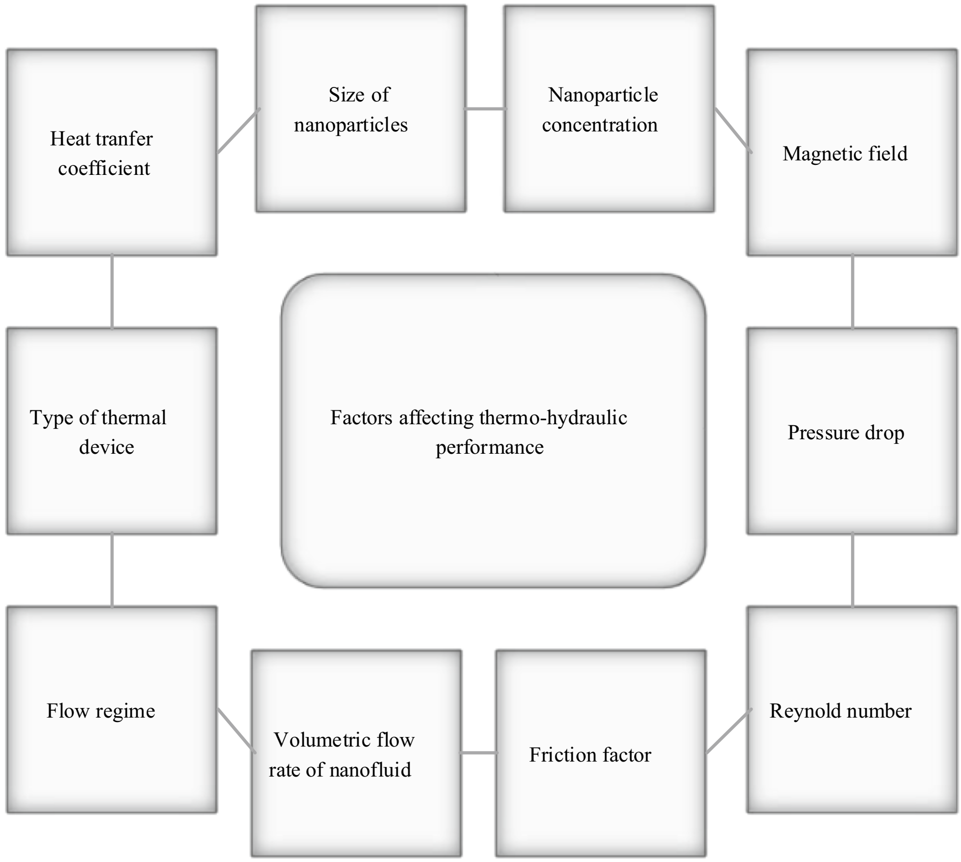

Fig. 8 Factors affecting the thermo-hydraulic performance of nanofluids

in a countercurrent heat transfer test section under laminar, transition and turbulent flow regimes. Experiments showed that convective heat transfer coefficient improved with the suspended nanoparticles by as much as 28.7 and 69.3% for 0.3 and 0.9% of silver content, respectively. However, some studies have also reported that addition of nanoparticles deteriorate the heat transfer efficiency of fluids in all cases, regardless of the concentration. Mikkola et al. [167] investigated effect of particle properties on the convective heat transfer of nanofluids. They used polystyrene, SiO_2, Al_2O_3–water nanofluids with concentrations of varying the range of 0.1–1.8 vol%. Convective heat transfer experiments were carried out using an annular tube heat exchanger with the Reynolds numbers varying in the range of 1000–11,000. They observed increasing the nanoparticle concentration decreased the convective heat transfer efficiency in all cases.

Khoshvaght-Aliabadi et al. [168] prepared Cu–water nanofluid with different nanoparticles mass fractions (0.1, 0.2, 0.3 and 0.4%). They used plate-fin heat exchangers. They found that the nanofluid with the minimum nanoparticles concentration exhibited the highest thermo-hydraulic performance. The maximum enhancement in thermo-hydraulic performance of 0.1% nanofluid was 23.1%. They showed that the using nanofluids with the lower mass fractions performed better.

Khoshvaght-Aliabadi et al. [169] investigated heat transfer performance of two types of fin, plate and plate-pin, in water-cooled corrugated miniature heat sinks (MHSs) using Al_2O_3–water nanofluid with different concentrations (0.1 and 0.3 mass. %) and different Re number (100–900). They performed for triangular, trapezoidal and sinusoidal configurations. They observed that the use of nanofluid improves the overall hydrothermal performance of miniature heat sinks. They determined a maximum hydrothermal performance factor of 1.84 for 0.3% nanofluid flow in sinusoidal plate-pin finned slotted miniature heat sinks.

Sarafraz et al. [170] studied on the thermal–hydraulic performance of Ga–CuO nanofluid in a rectangular microchannel. They evaluated the effects of nanoparticle concentration and flow rate of nanofluid on the heat transfer coefficient, pressure drop and thermo-hydraulic performance of the system. They revealed that the thermo-hydraulic performance was significantly dependent on Reynolds and the nanofluid concentration. In addition, they achieved the highest thermo-hydraulic performance in laminar regime due to small pressure drop.

Akçay et al. [171] determined that although there is no increase in thermo-hydraulic performance at low frequency and amplitude, there is a frequency value at which the thermo-hydraulic performance is maximum. Achieving the best thermo-hydraulic performance at high amplitude and a certain frequency (Wo = 10) has shown that pulsative flow significantly increases heat transfer, although it causes some increase in friction. They have observed that as the frequency increases above the critical value (Wo = 15), the improvement in thermo-hydraulic performance reduces due to the decrease in heat transfer performance and more friction losses.

Sarafraz et al. [172] also investigated the thermo-hydraulic performance of Ga–Al_2O_3 nanofluid in a copper made rectangular microchannel solar thermal receiver. They prepared the gallium nanofluids at mass fractions of 5%, 10% and 15% of aluminum oxide in gallium. They noted that although the Reynolds number was small, less energy, friction loss and pumping power are needed to overcome the pressure drop due to the relatively low pressure drop subject to the system. Thus, they have achieved higher hydraulic performance in the laminar area. They observed that increasing the Al_2O_3 concentration increased the heat transfer coefficient and pressure drop of pure Ga. They also observed that the thermo-hydraulic performance decreased when 15% of Al_2O_3 by mass was used due to the increase in viscosity and agglomeration of Al_2O_3 nanoparticles in Ga.

Type of thermal device is also an important parameter that affects the thermo-hydraulic performance of systems using nanofluids. Bahiraei et al. [173] examined the thermo-hydraulic performance of the green graphene nanoplatelet nanofluid through the tube equipped with the rotating twisted tape. The variable parameters consist of rotational speed, twisted ratio and nanoparticle mass fraction, which their influences were evaluated. They revealed that adding the nanoplatelets has a smaller effect on the convective heat transfer coefficient at higher rotational speeds. They also presented that the convective heat transfer coefficient and pumping power enhanced by increasing the rotational speed and mass fraction and decreased by increasing the twisted ratio.

Ajeel et al. [174] investigated of thermal–hydraulic performance of silica nanofluid in corrugated channels namely semicircle-corrugated channel and the new form of a trapezoidal-corrugated channel in addition to the straight channel. Their experimental results indicated that the nanofluid showed better performances in comparison with the base fluid where heat transfer and pressure drop were increased with increasing volume fractions of SiO_2. They is also found that the use of corrugated channel (TCC) enhanced heat transfer rates up to 63.59%, pressure drop by 1.37 times and thermal performance up to 2.22 times as compared to those of straight channel.

Qi et al. [175] also investigated the heat transfer and flow characteristics of nanofluids flowing through a horizontal circular tube and a horizontal elliptical tube. They studied three different mass concentration (0.1 mass%, 0.3 mass% and 0.5 mass%) effect. They found that TiO_2–water nanofluid with 0.5 mass% enhanced the Nusselt number by 9.7–16.1% and 25.8–32.9% at best compared with water in the circular tube and elliptical tube, respectively. Qi et al. [176] studied effects of twisted tape structures on thermo-hydraulic performances of TiO_2–water nanofluids in a triangular tube. They investigated effects of nanoparticle mass fractions, Reynolds numbers and different structure twisted tapes on the Nusselt number and enhancement of resistance coefficient ratios. They found that triangular tube with twisted tape improved the Nusselt number by 52.5% and 34.7% at best in laminar and turbulent flow, respectively, compared with the smooth tube with the same fluid.

Ajeel et al. [179] investigated the effects of volume fractions and geometric parameters he thermal–hydraulic performance of hybrid nanofluid (CuO/MgO–water) through the curved–corrugated channel. They showed that thermal–hydraulic performance (THPF) of binary hybrid nanofluid enhanced with increasing volume fraction and the blockage ratio and decreasing the pitch angle while recording the best improvement at the particular gap ratio. Thermo-hydraulic performance of radiator with hybrid nanofluid were investigated by Sahoo et al. [177]. He investigated effects of spherical, cylindrical and platelet shape-based graphene–CNT–Al_2O_3 hybrid nanofluids as new radiator coolant. They showed that particle shape in ternary hybrid nanofluid has a significant impact on the thermo-hydraulic performance. They also revealed that the performance index of the radiator system gradually decreases with an increment in the coolant flow rate and vol. fraction of ternary hybrid nanofluids.

The influence of various magnetic fields on the thermo-hydraulic performance of magnetic nanofluids has been the focus of recent research. Fan et al. [178] investigated thermo-hydraulic performance of Fe_3O_4–water–arabic gum nanofluids in an improved heat exchange system. A corrugated tube and a perforated turbulator were used in this study. The experimental results reveal that a high nanoparticle mass fraction, high magnetic flux density, bilateral staggered magnetic field and perforated turbulator can provide superior thermo-hydraulic performance.

Mei et al. [180] studied effects of paralleled magnetic field on thermo-hydraulic performances of Fe_3O_4–water nanofluids in a circular tube. Experimental data showed that Nusselt number was proportional to nanoparticle mass fraction but had an opposite relationship with magnetic induction intensity. They also found that resistance coefficient enhanced with the nanoparticle mass fraction and by magnetic field.

Thermodynamic performance of nanofluids in thermal systems

One of the most important parameters to be considered for the design of heat transfer systems is the thermodynamic performance of the system. Therefore, the design parameters of thermal systems vary not only with the increase in the heat transfer but also with the amount of power input to the system. Therefore, determining the optimum consistency between the heat transfer rate and the amount of power input appears as a key element in the design of a thermal system. There is a need to reduce the entropy generated in the system and entropy generation analysis must be performed in order to determine the useful models of thermal systems [177]. It has been stated in the studies that the irreversibility should be reduced in order to maximize the thermodynamic performance. Two types of irreversibility are known to be effective in total entropy calculations. These are the heat transfer irreversibility and fluid friction irreversibility [181]. Therefore, the development, design and method of thermal system performance need to be thoroughly investigated within the scope of second law analysis. Bejan number and experimental results of entropy generation are important parameters for minimum entropy for a thermal system efficiency. The Bejan number reveals the contribution of the irreversibilities in the second law analysis [182, 183]. Bejan gave the equation for the rate of entropy generation per unit length as

$$\dot{S}'_{\mathrm{gen}} = \frac{q''^2 \pi D^2}{kT^2 Nu((\mathrm{Re})_{\mathrm{D}}, \mathrm{Pr})} + \frac{8\dot{m}^3}{\pi^2 \rho^2 T}\frac{f((\mathrm{Re})_{\mathrm{D}})}{D^5} \quad (4)$$

$$\dot{S}'_{\mathrm{gen}} = (\dot{S}'_{\mathrm{gen}})_{\text{heat transfer}} + (\dot{S}'_{\mathrm{gen}})_{\text{fluid friction}} \quad (5)$$

The total entropy generation rate is contributed by two elements, thermal and fluid friction, as shown in Eq. (4). Equation (4) demonstrates the significance of the Nusselt number (Nu) and the friction factor (f), which vary depending on the geometry and flow regime.

Nanofluids are widely used as materials that can adapt to thermal systems. It has been determined by the studies that nanoparticles in nanofluid improve the thermophysical properties of nanofluid for heat transfer. Increasing thermal efficiency means maintaining the system in maximum heat transfer and minimum pumping power, reducing system energy consumption and exergy destruction. Exergy loss is directly related to total entropy production. Minimum entropy analysis has become important in the performance development and design of the thermal system. Minimum entropy generation is an important

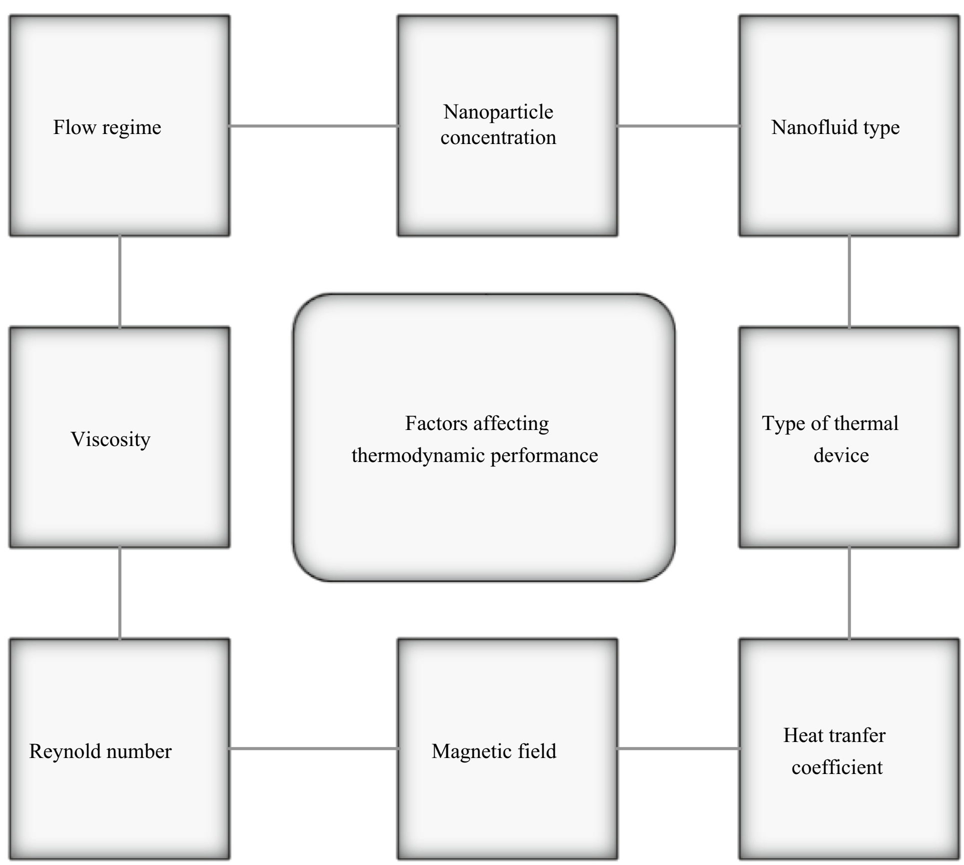

Fig. 9 Factors affecting the thermodynamic performance of nanofluids

parameter to increase the energy efficiency of a system [184] (Fig. 9).

The entropy generation analysis can be divided into two types based on the flow regime: laminar and turbulent flow. Singh et al. [107] proposed two equations to calculate the ratio of entropy generation due to nanofluid flow to that of the base fluid:

Laminar flow: $Nu = \frac{48}{11}$ and $f = \frac{64}{Re}$ $Re = \frac{4\dot{m}}{\pi \mu D}$

$$\frac{\dot{S}'_{gen,NF}}{\dot{S}'_{gen}} = \frac{k}{k_{NF}} \frac{\rho^2}{\rho^2_{NF}} \frac{T^2}{T^2_{NF}} \left(\frac{C_{1l,NF}\, \rho^2_{NF} + C_{2l,NF}\, \mu_{NF}\, k_{NF}\, T_{NF}}{C_{1l}\, \rho^2 + C_{2l}\, \mu\, k\, T} \right) \tag{6}$$

where the constants C_{1l} and C_{2l} are defined as

$$C_{1l} = \frac{11}{48} q''^2 \pi D^2 \text{ and } C_{2l} = \frac{128\dot{m}^2}{\pi D^4} \tag{7}$$

and q'' is heat flux per unit length (W/m).

Turbulent flow: $Nu = 0.023 Re^{0.8}\, Pr^{0.4}$ *and* $f = 0.361 Re^{-1/4}$

$$\frac{\dot{S}'_{gen,NF}}{\dot{S}'_{gen}} = \frac{k^{0.6}}{k^{0.6}_{NF}} \frac{\rho^2}{\rho^2_{NF}} \frac{T^2}{T^2_{NF}} \frac{\mu^{0.25}_{NF}}{\mu^{0.25}} \frac{c^{0.4}_{p}}{c^{0.4}_{p,NF}} \left(\frac{C_{1t,NF}\, \rho^2_{NF}\, \mu^{0.15}_{NF} + C_{2t,NF}\, k^{0.6}_{NF}\, c^{0.4}_{p}\, T_{NF}}{C_{1t}\, \rho^2\, \mu^{0.15} + C_{2t}\, k^{0.6}\, c^{0.4}_{p} T} \right) \tag{8}$$

where

$$C_{1t} = \frac{43.478\, q''^2\, \pi\, D^2}{\left(\frac{4\dot{m}}{\pi D}\right)^{0.8}} \text{ and } C_{2t} = \frac{10.112\, \dot{m}^3}{\pi^2\, D^5} \left(\frac{4\dot{m}}{\pi D}\right)^{-1/4} \tag{9}$$

The entropy generation ratio should be less than unity for nanofluids to be more efficient than base fluid.

There are some studies in the literature on the entropy generation of nanofluid in different thermal systems [185, 186, 187]. Peng et al. [164] calculated the augmentation entropy generation number by using Eq. (10) to assess the thermodynamic performance of liquid metal-based nanofluids. They prepared Ga–Cu and Ga–CNT nanofluids with nanopowder concentrations of 2, 5, 8 and 10 vol%. They revealed that total entropy generation reduced and exergetic productivity enhanced as nanopowder concentration increased. Their results showed that nanopowders provided decreasing of irreversibility and increased the thermodynamic performance of liquid metal, Ga–CNT nanofluids had better thermodynamic performance than Ga–Cu nanofluids under the same conditions.

$$N = \frac{S_{g,nf}}{S_{g,bf}} \tag{10}$$

where $S_{g,\,nf}$ and $S_{g,\,bf}$ are the total entropy generation rates for nanofluid and base fluid, respectively.

Kolsi et al. [188] investigated the generation of three-dimensional entropy due to natural convection in a cavity in which the diamond-shaped body is placed in the middle of the cavity. Al_2O_3–water nanofluid was used in the study as the working fluid. They observed that total entropy generation enhances when the volume fraction of nanoparticles increases.

Ebrahimi et al. [189] experimentally and numerically investigated heat transfer and entropy generation using both nanofluid and vortex generating geometry in a microchannel. In the study, they used CuO and Al_2O_3 nanofluid and calculated entropy production values by the heat transfer and friction irreversibilities. In addition, in the entropy analysis of the thermal systems, the number of Bejan, which was developed to determine whether the system is a thermally useful system or not, was also evaluated. According to the results of this study, the using nanofluids caused a reduction in entropy generation in microchannels compared to pure water. They also found that the number of dimensionless entropy production was higher in using Al_2O_3 nanofluid compared to that CuO nanofluid.

Bizhaem and Abbasi [190] performed the heat transfer and entropy generation analysis by using Al_2O_3–water nanofluid in a helical pipe in their numerical study. They used five different Reynolds numbers (200–1500) and three different volumetric concentration ratios and stated that the heat transfer-induced entropy generation is mostly concentrated in the pipe inlet. In addition, it is stated that the entropy generation reduces due to the very low temperature difference between the fluid average temperature and the wall.

Huminic and Huminic [191] investigated degree of thermodynamic irreversibility of two types of hybrid nanofluids, namely MWCNT + Fe_3O_4/water and nanodiamond + Fe_3O_4/water used in a flattened tube. They revealed that the increase in volume concentration of hybrid nanoparticles leads to the decrease in the total entropy generation of MWCNT + Fe_3O_4/water and ND + Fe_3O_4/water hybrid nanofluids compared to base fluid in the flattened tube. They observed that maximum reduction of entropy generation for 0.3 vol% MWCNT + Fe_3O_4 hybrid nanoparticles was 1.265 at Re = 2000 and the temperature of 333 K which corresponds to reduction of 26.483% compared to the base fluid.

Bahiraei et al. [192] investigated the entropy generation using graphene–silver nanofluid in a microheat exchanger. According to the results, entropy generation was more intense with the increase in the Reynolds number and the reason for this was the increase in the velocity gradient due to the increasing Reynolds number. Parallel to this, it is stated that the thermal boundary layer becomes thinner with the increase in the Reynolds number and the temperature change is sudden in a region due to this thinning that develops in the pipe wall. Therefore, the thermal entropy production is concentrated in the pipe wall. It was determined that the increase in thermal conductivity coefficient with the use of nanoparticles breaks the thermal gradient in this region and consequently decreases the entropy generation. In the analysis made by the researchers, it has been revealed that the use of nanofluids as fluid minimizes the entropy production in the minichannels and microchannels.

Fan et al. [178] evaluated exergy efficiency performance of Fe_2O_3–water nanofluid in the triangle tubes with different types of twisted tape. They obtained better exergy efficiency performance when Reynolds number was greater than 5000. For isosceles right triangle tube with twisted tape, the largest exergy efficiency was obtained when Reynolds number was 9000, but for isosceles 45° triangle tube, the largest exergy efficiency was obtained when Reynolds number was 8000.

Manay et al. [193] investigated the effects of the volume concentration of TiO_2 nanoparticles (0.25, 0.5, 1.0, 1.5 and 2.0%) and different microchannel height (200 mm, 300 mm, 400 mm and 500 mm) entropy generation of TiO_2–water nanofluid flow. They noted that the presence of TiO_2 nanoparticles in the base liquid reduced the thermal entropy generation. It was stated that the thermal entropy generation rate decreased and the frictional and total entropy generation increased with increasing the Reynolds number and decreasing the height of the microchannel. Thermal irreversibilities are reduced by increasing the volume concentration of nanoparticles.

Thermo-economics of nanofluids in thermal systems

Nanofluids are more effective than base fluids in heat transfer applications, but their high cost sometimes limits their use. The economic performance of nanofluids consists of the production cost of nanoparticles, the preparation cost of nanofluids, the operating cost of the instrument with nanofluids, etc. [194]. In particular, the high price of nanoparticles increases the cost of nanofluid. The cost of different nanoparticles (from Sigma Aldrich, USA.) are given in Table 7. It is also important that nanofluids increase the efficiency of thermal systems such as heat exchangers. The improved heat transfer directly affects the heat transfer area of the heat exchanger, which makes it smaller and lighter. Therefore, nanofluids have the potential to make a significant contribution to the reduction of heat exchanger equipment cost.

The lower cost of a nanofluid with effective thermo-physical properties makes the operating cost of thermal systems more economical. Therefore, along with the thermo-physical properties of nanofluids, economic analysis of system performance is also important. However, there are a few studies in the literature on the economic analysis of nanofluids. The optimization of nanoparticle concentration and temperature is necessary to obtain the best economic value.

Table 7 Prices of most used nanoparticles in studies

Nanoparticles	Purity (%)	Size (nm)	Quantity (g)	Cost (EUR)
Silver	99.5	< 100	5	70.80
Copper	99	25	5	70.20
Gold	99.9	< 100	1	497
Zinc	> 99	< 60	5	69
Iron	99.5	25	5	92.20
Alumina	99.8	13	100	187
Copper oxide	99	< 50	5	28.70
Silica	99.5	< 20	50	139
Titanium dioxide	99.7	< 25	50	188
Zinc oxide	99	< 100	50	97.70
Carbon nanotubes (multi-walled)	> 95	90	25	307
Diamond	> 97	< 10	5	513

Kianifar et al. [195] analyzed the thermo-economic performance of Al_2O_3–EG nanofluid in an isothermal vertical annulus. They measured viscosity and thermal conductivity of nanofluid. They studied the effect of using nanofluids in the annulus on the operational cost due to entropy generation. They showed that using nanofluids is not cost-effective in short periods (i.e., 5–6 months) from the point of view of the second law of thermodynamics.

Alashka and Gadalla [196] performed a thermo-economic analysis using nanofluids as heating fluids in an ISRRC, which consists of a nanofluid-based parabolic trough solar collector (PTSC) and a thermal energy storage system (TES). They investigated the effect of dispersing Al_2O_3, Cu and SWCNT nanoparticles into Syltherm and Therminol on the output performance and cost of the ISRRC. The study results showed that using of nanofluids enhanced the total energy generated by ISRRC and net savings of ISRR. It also caused the reduction in the leveled cost of electricity (LEC). When they used 3% Cu/Therminol nanofluid, annual energy output increased from 166 to 168 GW and the net savings increased from \$ 4.67 million to \$ 4.71 million, while the LEC decreased from 2.95 c/kWh to 2.92 c/kWh.

Prajapati and Patel [197] carried out the thermo-economical optimization of the nanofluid-based organic Rankine cycle system, which recovered waste heat energy by maximizing the first law efficiency and minimizing the leveled energy cost. They used CuO–water nanofluid in the evaporator and condenser. They showed 3.47% decrease in levelized energy cost when using nanofluid compared to conventional organic Rankine cycle with higher thermal efficiency. They also obtained that nanofluid enhances the thermodynamic performance of the system.

Mukherjee et al. [194] presented the thermal and cost performance of TiO_2–water nanofluids. They took thermal conductivity and viscosity measurements with 0.01–1 mass. % fractions at 25–65 °C. They argued that higher concentrations of nanofluids are unsuitable because of the high cost of nanoparticles and therefore more economical at lower concentrations. The results revealed that the best concentration was 0.01 mass. % the for cost efficiency.

Mukherjee et al. [198] did an economic study on nanofluids about their cooling performance. They prepared Al_2O_3–water nanofluids at 25 °C and 60 °C with different particle concentration of 0.1–1 mass %. They developed a performance index that shows that cost performance related to the concentration of nanofluid and operating temperature. They observed that the index increases with the increasing of concentration at the same temperature. Therefore, they revealed that when nanoparticle concentration increases, the cost of the cooling performance increases. They also observed that the economic performance increased at high temperatures. They suggested that the nanofluid concentration and temperature should be optimized to achieve the best economic value.

Hajabdollahi et al. [199] determined optimum parameters to improve both thermal effectiveness and total annual cost of Boehmite alümina–water nanofluid in multitube heat exchanger. They investigated effect of mass flow rates (0.5, 1, 1.5 and 2 kg/s). They revealed that higher concentrations of nanoparticles increased both initial cost (nanoparticle price) and operational cost (due to increases in the pressure drop) and the total annual cost of the heat exchanger. The greatest effect of the nanofluid on thermo-economic improvement was found as the mass flow rate of 1.5 kg/s. They showed that effectiveness is another parameter affect on thermo-economic performance. The cost reduction in the case of cylindrical shape with the mass flow rate of 1.5 kg/s was found as 14.28% for the fixed value of $\varepsilon = 0.43$, whereas was about 20.99% for the $\varepsilon = 0.54$.

Application of nanofluids

Drug delivery

There has been a gradual increase in interest in the use of nanomaterials in drug delivery systems in recent years in terms of being suitable for delivery to target cells, increasing therapeutic properties and safety, reducing toxicity and providing benefits such as biocompatibility. Regarding the development of a nanofluid formulation for drug delivery, the system must afford drug loading and release characteristics, prolonged shelf life and biocompatibility. Specific nanosized particle can deliver high doses of therapeutic factors into tumor cells without contaminating normal cells. Chahregh and Dinarvand [200] used TiO_2–Ag/blood hybrid nanofluid for application of drug delivery and blood circulation in the respiratory system.

Magnetic nanofluids (MNF) or ferrofluids are obtained by dispersing MNPs such as metallic Fe, metallic Co, Fe_3O_4, Fe_2O_3, $CoFe_2O_4$, etc. in a base fluid. The controllability, small size and surface properties of magnetic nanoparticles allow the carrier to be directed to the desired location via a magnetic field. In magnetic drug delivery, blood acts as the main fluid, while magnetic nanoparticles act as carriers of the drug. The drug-loaded magnetic nanoparticles will be injected near the tumor due to the intense and concentrated magnetic gradient; the tumor can absorb the drug [201]. Magnetic nanofluids could be used as drug delivery vehicles for cancer patients. Compared with other metal-type nanoparticles, magnetic nanoparticles provide distinctive properties for magnetic force treatment of nanofluid. Superparamagnetic nanoparticles also exhibit magnetic properties in the presence of an external magnet, but revert to a non-magnetic state upon removal of the magnetic field. This behavior of superparamagnetic materials is important for the use of drug delivery therapeutics to specific sites [197]. Mannu et al. used PEG-coated $NiFe_2O_4$, $CoFe_2O_4$ and Fe_3O_4 nanoparticles for preparing the magnetic nanofluids. They used the anti-cancer drug, doxorubicin hydrochloride as the model drug for demonstrating the drug loading and release capabilities of the formulated magnetic nanofluids with aqueous phosphate buffer as the base liquid [202].

Gold nanoparticles provide non-toxic carriers for drug and gene delivery applications. With these systems, the gold core adds stability to the assembly, while the monolayer allows for adjustment of surface properties such as charge and hydrophobicity. Another attractive feature of gold nanoparticles is their interaction with thiols, which provides an efficient and selective pathway of controlled intracellular release [203].

Heat exchanger and Heat pipes

Heat pipes are recognized as one of the most efficient passive heat transfer technologies available and they have high thermal conductivity. Generally, heat pipes are devices that can transport large amounts of heat using phase change processes and vapor diffusion.

The difference in wall temperature causes the steam to condense and the latent heat to be released, allowing the fluid to return to the evaporator zone under the influence of gravity (thermosiphons) or a kind of capillary wick structure. There are many parameters that affect performance in heat pipes. One of them is the thermal resistance in the heat pipe. The thermal resistance is the structure of the vapor bubbles at the liquid–solid interface during the phase change in the heat pipe. The large size of the bubble core causes thermal resistance by preventing the heat transfer from the solid surface to the liquid. The nanoparticles in the working fluid act on the vapor bubbles during bubble formation, resulting in much smaller nucleation. This situation facilitates the heat transfer from solid surfaces to the liquid in the heat pipe and causes the thermal resistance of the heat pipes to decrease.

Aydin et al. [13] observed that using bauxite–water nanofluid in the heat pipe reduced the thermal resistance of the system by 24.3% and increased the thermal efficiency by 20.9% under optimum conditions compared to base fluid.

Gürü et al. [8] used a 2% concentration of nanofluid prepared using bentonite, a mineral consisting of many oxides rich in SiO2 and Al_2O_3, as a working fluid in a thermosiphon-type heat pipe. They observed that at 5 g/s cooling water flow rate, the heat pipe thermal resistance decreased by 39% compared to water. They showed that bentonite was more effective in reducing the heat pipe thermal resistance than bauxite.

Heat exchangers are devices used for the transfer of heat between two or more fluids. The use of nanofluids in the different kinds of heat exchangers has been the subject of many studies.

Ullah et al. [204] investigated effects of using Al_2O_3/water and TiO_2/water nanofluids on heat transfer efficiency of shell and tube heat exchanger. They achieved the maximum heat transfer coefficient enhancement of 41% and 37% using Al_2O_3 ve TiO_2 nanofluid, respectively.

Khanlari [205] studied effect of utilizing Al_2O_3–SiO_2/deionized water in the efficiency of parallel flow tube-type heat exchanger and counterflow tube-type heat exchanger. He demonstrated $Al2_2O_3$–SiO_2/deionized water hybrid nanofluid provide a maximum enhancement of 25%, 60% and 67% of the overall heat transfer coefficient at 0.5%, 1% and 1.5% nanoparticle ratio, respectively.

Variyenli et al. [206] used fly ash nanofluid as working fluid in plate heat exchangers. The maximum enhancement was achieved using nanoparticle mass concentration of 2%. He showed that using the fly ash nanofluid enhanced the overall heat transfer coefficient between 6 and 20%.

Said et al. [207] used CuO/water as heat transfer fluid in shell and tube heat exchanger. Their experimental results demonstrated an increase in the heat transfer coefficient and convective coefficient by 7% and 11.39%, respectively.

Khanlari et al. [208] analyzed the effects of using TiO_2/deionized water and kaolin/deionized water nanofluids as working fluids in the plate heat exchanger. They revealed that a kaolin/deionized water nanofluid had higher thermal performance than TiO_2/deionized water nanofluid. They achieved 12% and 18% maximum increment in the heat transfer rate using TiO_2/deionized water and kaolin/deionized water, respectively.

Automotive applications

Ethylene glycol and water are standard blends used as engine coolants for automotive systems around the world. Ethylene glycol mixed with water increases the freezing temperature of pure water. Engine oil does not perform better and can even be classified as a poor heat transfer medium. However, with the inclusion of nanoparticles in this mixture, a more efficient and compact cooling system can be designed. The use of nanofluids can increase automotive and even industrial engine cooling efficiency. The use of nanofluids increases engine performance and also allows a reduction in radiator size due to better cooling capabilities. Lubricants to improve the convective heat removal efficiency of vehicles lead to fully efficient and low emission vehicles [209].

Kumar and Sahoo [210] investigated energy performance of a wavy fin radiator using Al_2O_3–water nanofluid as a coolant. They resulted that the shape of the nanoparticles used in nanofluid affect the performance of radiator. They observed that the spherical nanofluids provided 21.98% enhancement in heat transfer when compared to the platelet nanofluid.

Kole et al. [211] used Al_2O_3 nanofluid as car engine coolant and investigated the thermal conductivity and viscosity of the coolant. Al_2O_3 nanofluid with 3.5% volume fraction showed a fairly higher thermal conductivity than the base fluid. They observed 10.41% maximum enhancement at room temperature.

Tzeng et al. [212] investigated effect of nanofluids for cooling of automatic transmissions. They used CuO- and Al_2O_3–engine transmission oil nanofluids. They resulted that CuO nanofluid produced the lower transmission temperatures both at high and low rotating speeds. From the thermal performance point of view, the use of nanofluid in conduction has a clear advantage.

Al Rafi et al. [213] investigated potential of Al_2O_3/EG–water and CuO/EG–water nanofluids in a car radiator. They revealed that the addition of EG into the water decreased the overall heat conductance by 20–25%. They also demonstrated that Al_2O_3/EG–water at 0.1 vol% and CuO/EG–water at 0.2 Vol% enhanced the heat transfer of the radiator by 30–35% and 40–45%, respectively.

The increased cooling rate will result in a reduction in the size of the required coolant system. Smaller coolant systems will require smaller and less bulky radiators, resulting in better engine efficiency and lower fuel consumption.

Electronic cooling

Nanofluids have higher heat transfer capabilities than base fluids due to their higher convective heat transfer coefficients. Conventional liquid coolants are being enhanced with nanoparticles to meet the cooling requirements of high-power electronic systems. Thus, nanofluids represent an enhanced dimension to cooling techniques for electronics. Nanofluids increase the heat transfer coefficient of the cooler by increasing the thermal conductivity of the cooler. Nanofluids can be used for liquid cooling of computer processors due to their high thermal conductivity.

Ma et al. [214] used diamond nanoparticles into high-performance liquid chromatography (HPLC) water. The action of the oscillating heat pipe prevents the nanoparticles from collapsing, thereby increasing the efficiency of the cooling device. They observed that at an input power of 80 W, the diamond nanofluid reduced the temperature difference between the evaporator and condenser from 40.9 to 24.3 °C.

Nguyen et al. [215] investigated the heat transfer and behavior of Al_2O_3–water nanofluid for use in a closed cooling system designed for microprocessors or other electronic devices. They found that the nanofluid caused a significant increase in the cooling convective heat transfer coefficient. At a given particle concentration of 6.8%, the heat transfer coefficient increased up to 40% compared to the base fluid of water.

Joy et al. [216] investigated the effect of Cu–water and Al–water nanofluid on increasing the critical heat flux limit in a heat pipe for electronic cooling. They found that nanofluids increased the critical heat flux limit by 140% at a mass concentration of 0.01%.

Vishnuprasad et al. [217] studied the cooling performance of microwave-assisted acid-functionalized graphene in water. They observed that microwave-assisted acid-functionalized graphene nanofluid recorded an increase of 55.38 and 78.5% in thermal conductivity and the convective heat transfer coefficient, respectively. They also revealed that the use of nanofluids under suitable conditions reduced the processor temperature by 15%.

Solar energy

The use of nanofluids in thermal applications of solar energy is one of the methods that emerged as a result of the orientation to alternative energy sources due to the problems experienced due to the use of fossil fuels. Nanofluids are mostly preferred in solar collectors and solar hot water systems in thermal applications of solar energy. Apart from this, several energy storage and solar cell applications are also available in the literature. There are a lot of studies about the solar collector based on nanofluid that demonstrate better result than the base fluid [218–220, 221]. When evaluated from an economic and environmental point of view, it has been seen that this practice helps to reduce CO_2 emissions and increases annual electricity and fuel savings [222].

Dehaj and Mohiabadi [223] investigated performance of magnesium oxide (MgO) and deionized water nanofluids as working fluids with different concentrations. They showed that the performance of the heat pipe solar collector enhanced as the rate of the refrigerant increased and the concentration of the MgO nanoparticle increased.

Dehaj et al. [224] investigated thermal performance of heat pipe solar collector at different high flow rates of water and CuO–water nanofluid with various volume fractions. They obtained that the efficiency of solar collector enhanced with the flow rate and the volume fraction of the nanofluid. They also revealed that the low temperature difference between the ambient and the inlet nanofluid collector improves the efficiency of the collector.

Rangabahsiam et al. [225] studied effect of nanofluid concentration on the efficiency of the heat pipe solar collector. They used Al_2O_3– and MgO–water nanofluids. In this study, results showed that when treated with MgO nanofluids, solar collector exhibited higher efficiency. They also observed that as the concentration of the nanofluid increases, the efficiency of the solar collector enhance regardless of the operating environment and there is an optimized concentration for the existing system.

Environmental impacts of nanofluids

Nanofluids are colloidal dispersions of nanoparticles in the base fluid. Therefore, the environmental impact of nanofluids is a combination of the environmental impact of the base fluid and nanoparticles. Water is the most and widely used base fluid with very important benefits such as being non-toxic, nonflammable, safer and easier to use. The type of nanoparticles, their chemical, physical, toxic and environmental effects are the most important factors that cause the environmental impact of nanofluids. The volumetric ratio of nanoparticles also determines the environmental impact of nanofluids. The reduction and control of the environmental impacts of nanofluids mainly depends on the optimum design of the nanofluid. The use of natural materials such as silica, alumina, iron oxides and others results in much lower environmental impacts as synthetic production of such particles is not required. Using such natural materials helps to reduce production requirements in terms of energy and materials. The use of natural nanoparticles, usually non-toxic types, further reduces the possible toxicity of nanofluids during application and when discharged into the environment. Similarly, using a lower concentration of nanoparticles reduces possible environmental damage [226]. The environmental impact of nanofluids is also due to the preparation method of nanofluids. Barberio et al. [227] investigated the environmental impact of alumina nanofluid depending on the nanofluid preparation method, that is, one-step or two-step approaches. They compared the production of alumina nanofluid using different approaches employing combined life cycle assessment (LCA) and risk assessment (RA). They observed that the one-step approach has environmental impact almost three times that of two-step.

The application of nanofluids to enhance the heat transfer process brings environmental benefits of enhancing the energy efficiency of various processes, which in turn reduces energy consumption, heat losses or heat dissipation. Nanofluids provide environmental and economic savings because they reduce greenhouse gas emissions. The use of nanofluids increases the absorption of CO_2, which reduces the environmental impact of carbon emissions that cause climate change, which reduces air quality. Stalin et al. [228] observed CeO_2/water nanofluid-based solar water heater provided 175 kg less CO_2 emissions in average when compared to a usual solar water heater. Sharafeldin et al. [229] revealed that using copper nanoparticles with a concentration of 0.03% could annually reduce 312.533 kg of CO_2 emission. Sundar et al. [295] found that by using 1.0 vol% of water-based nanodiamond nanofluid in flat-plate solar collector reduce the CO_2 emission by 249.98 kg.

Conclusions and recommendations

This research represents general and recent advances on preparation, stability, thermal properties and performance in thermal systems of nanofluids. Considering the reviewed literature, following major conclusions were drawn regarding the recent developments of nanofluids.

- It has been reported by the researchers that adding nanoparticles to the base fluids improves thermal properties such as heat transfer coefficient, thermal conductivity, viscosity, density and affects many parameters such as friction factor, Reynolds number, Nu number and pump efficiency. Nanofluids find different usage areas according to their properties. There is optimum temperature, concentration and particle size of nanoparticles for enhanced thermal performance. The use of nanofluids with higher heat capacity than the base fluid improves the efficiency of thermal systems. Therefore, in order to enhance heat transfer, nanoparticles that increase the heat capacity as well as increase the thermal conductivity of the base fluid should be used. Stability is very important parameter for nanofluid. The variation of pH in nanofluid is an important parameter for enhancing of stability and thermal conductivity of nanofluids. Higher pumping power is needed to overcome the influence of the size and shape of nanoparticles for pressure drop, stability analysis, rheological properties and thermal improvement.
- The thermo-hydraulic properties of nanofluids are key to evaluating and improving their performance. The improvement of thermo-hydraulic performance is affected by many parameters. They are solid particle concentration, Reynolds number, pressure drop, flow rate, regime, magnetic field, friction factor and type of thermal device.
- In addition, thermodynamic performance is a very important parameter to be considered for the design of heat transfer systems. Thermal entropy generation and exergy efficiency, which are dependent on nanoparticle type, thermal device, flow regime and concentration, are essential to evaluate thermodynamic performance. Increasing thermal efficiency means decreasing pressure and reducing system energy consumption, reducing exergy destruction. Exergy loss is directly related to total entropy production. Minimum entropy generation is an important parameter to increase the energy efficiency of a system. Therefore, there is a need to reduce the entropy generated in the system and entropy generation analysis must be performed in order to determine the useful models of thermal systems.
- The use of nanofluids instead of conventional working fluids provides certain advantages in terms of heat transfer performance. However, the increased pressure drop, pumping power and energy consumption bring some extra costs. There are scarcity studies in the literature on the thermo-economic performance of nanofluids. Therefore, more research should be done to analyze the thermo-economic performance of nanofluids. A cost performance analysis and optimization of nanofluid concentration and temperature should be conducted to get the higher thermo-economic performance of nanofluids for the thermal applications.
- The increase in thermal conductivity and the decrease in viscosity make the nanofluid technology very promising for high-temperature applications. Nanofluids will also provide thermal systems to shrink by expanding the heat transfer area. By using nanofluids with superior thermo-physical properties in automobiles, radiator dimensions and the mass of the car can be reduced and fuel saving can be achieved. It is considered that nanofluids can also find a wide range of uses in the space, aircraft and defense industries.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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