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Thermal Transport and Challenges on Nanofluids Performance

José Jaime Taha-Tijerina

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Abstract

Progress in technology and industrial developments demands the efficient and successful energy utilization and its management in a greater extent. Conventional heat-transfer fluids (HTFs) such as water, ethylene glycol, oils and other fluids are typically low-efficiency heat dissipation fluids. Thermal management is a key factor in diverse applications where these fluids can be used, such as in automotive, microelectronics, energy storage, medical, and nuclear cooling among others. Furthermore, the miniaturization and high efficiency of devices in these fields demand successful heat management and energy-efficient materials. The advent of nanofluids could successfully address the low thermal efficiency of HTFs since nanofluids have shown many interesting properties, and the distinctive features offering extraordinary potential for many applications. Nanofluids are engineered by homogeneously suspending nanostructures with average sizes below 100 nm within conventional fluids. This chapter aims to focus on a detail description of the thermal transport behavior, challenges and implications that involve the development and use of HTFs under the influence of atomistic-scale structures and industrial applications. Multifunctional characteristics of these nanofluids, nanostructures variables and features are discussed in this chapter; the mechanisms that promote these effects on the improvement of nanofluids thermal transport performance and the broad range of current and future applications will be included.

Keywords: nanofluids, thermal conductivity, nanoparticles, challenges, thermal transport

1. General overview

With global population rapid growth and industrialization surge, resources have reached unprecedented levels. Energy has been pointed out as the most important issue facing Humanity in the next years [1]. Energy management becomes crucial for meeting the rising

needs of mankind [2]. Nowadays, with increasing pressure of globalized markets and companies' profit race, a dramatic search to obtain proper materials performance, optimizing components and devices designs, improving efficiencies, reducing tools wear, materials consumption and pollution, and obtaining the most possible revenue. In addition to issues regarding materials scrap, maintenance and components wear among others, a hot topic in industry is the heat dissipation. Among diverse forms of energy used, over 70% is produced in or through the form of heat [2]. Heat transfer is a crucial area of research and study in thermal engineering. Heat is transferred either to input energy into a system or to remove the energy produced in a system. Hence, reducing energy loss and intensifying heat transfer processes are becoming paramount tasks to be addressed. Therefore, thermal management plays a vital factor concerning devices, machinery or apparatuses performance; thermal transport role has been subjected to countless investigations and is under the scope of the operational useful life of these components and devices. Being this an opportunity area for successful heat management and energy efficient fluid-based heat transfer systems, with aid of reinforced materials.

Nanotechnology is a science that deals with diverse characteristics and properties of materials at a nanometric level (1 nm = 10^{-9} m). Recently, diverse techniques, equipment, and instrumentations have been devised, as well as various relevant and interesting characteristics and properties of these materials were sorted out. Hence, with aid of nanotechnology, with novel developments linking electronic, optical, mechanical, and magnetic properties, industrial devices have emerged, and this trend is certainly continuing in this century. Cooling of electric, electronic and mechanical devices has been a hot topic in today's fast-growing technologies. The heat required to be dissipated from systems is continually increasing due to industrial and economic trends to miniaturize designs, make better use of resources, obtain more power output, develop and use more environmentally friendly materials, and obtain more profits.

2. Introduction to nanofluids

Nanofluids are a new generation of HTFs with anomalous behavior, engineered by homogeneously suspending nanometer-sized materials or structures within conventional fluids. In other words, nanofluids are nanoscale colloidal suspensions containing condensed nanomaterials. Nanofluids have been found to possess enhanced thermo-physical properties such as thermal conductivity, thermal diffusivity, viscosity, and convective heat transfer coefficients compared to those of base fluids such as water (DiW), ethylene glycol (EG) or oils. They have demonstrated great potential applications in many fields such as microelectronics, transportation, industrial cooling, magnetic sealing, reducing pollution, space and defense, energy storage, air conditioning, power transmission systems, medical therapy and diagnosis, antibacterial activity nanodrug delivery, fuel cells, components and tools wear, friction reduction and nuclear systems cooling, etc. [3–8]. Among diverse techniques to cool down or maintain certain temperature in these systems, the use of fins, vanes or radiators as well as forced air/fluids through cooling channels are being used, even though these are costly. Diverse machinery and devices use inexpensive conventional HTFs to intensify heat dissipation. However, the inherent limitation of these fluids is the relatively low thermal conductivity; water for instance, is roughly three orders of magnitude less conductive than copper or aluminum (**Table 1**). What these conventional fluids lack in thermal conductivity however, is compensated by their ability to flow.

Material		Thermal conductivity (W/m K)	Reference
Conventional fluids	Water (DiW)	~0.598–0.609	[9–11]
	Ethylene glycol (EG)	~0.251	[12–14]
	Engine oil	~0.145	[12, 14]
	Mineral oil	~0.115	[3, 15]
	Kerosene	~0.139	[16]
	R141b refrigerant	~0.089	[17]
Carbon structures	Single wall nanotubes (SWCNTs)	3000–6000	[18–21]
	Multi wall nanotubes (MWCNTs)	~3000	[22, 23]
	carbon (diamond)	900–2320	[24, 25]
	Carbon (graphite)	119–165	[24]
	Graphene	~3000	[4]
	Graphite	130–2000	[26]
Metallic solids	Aluminum	237	[27]
	Copper	398	[27]
	Gold	315	[27]
	Silver	424	[27]
Nonmetallic solids	Alumina (Al_2O_3)	31–41	[26, 28]
	Aluminum nitride (AlN)	319–550	[29]
	Boron nitride (h-BN)	~300	[30, 31]
	Boron nitride nanotubes (BNNTs)	~600–960	[32–34]
	Cobalt oxide (Co_3O_4)	12.8	[35]
	Copper oxide (CuO)	76.5	[36]
	Molybdenum disulfide (MoS_2)	34.5 ± 4	[37]
	Silicon carbide (SiC)	148–270	[27, 38]
	Silicon oxide (SiO_2)	1.4–12	[39–42]
	Titania (TiO_2)	8.4–11.2	[13, 39, 42]
	Tungsten disulfide (WS_2)	32–124	[43, 44]
	Zinc oxide (ZnO)	13–29	[13, 39]
	Zirconia (ZrO_2)	2.2	[45]

Table 1. Typical thermal conductivities for diverse conventional fluids and solid materials.

The main mechanism for heat transfer in fluids is convection; its efficacy mostly depends on the thermo-physical properties of the conventional fluids. Furthermore, if the thermal conductivity of conventional fluids were enhanced, it would be much more effective. Hence, since the solid materials possess several orders of higher thermal conductivities, compared

with that of conventional fluids, an idea to introduce conducting particles to fluids was considered. Among diverse particles geometry, different particle shapes occur naturally or are engineered for specific applications, as shown in **Figure 1**.

Heat transfer using fluids is a very complicated phenomenon, and various factors such as fluid stability, composition, viscosity, surface charge, interface, and morphology of the dispersed nanostructures influence the observed results [3, 6, 46–59]. Optimization and high efficiency of components and devices have gained great importance since these factors play a crucial role in diverse fields. Solid materials such as metals, CNTs, oxide/nitride/carbide ceramics, semiconductors, and composite materials having higher thermal conductivity can be homogeneously suspended and stabilized within conventional fluids, resulting in better thermal transport performance composite fluids. Nevertheless, improvement in thermal conductivity cannot be achieved by just increasing the solid filler concentration because each system presents a threshold, in which beyond a certain limit, increasing the filler fraction will also increase the viscosity, which will adversely affect the fluid properties and performance.

Most early studies used suspensions of millimeter or micrometer-sized particles, which led to countless problems, such as a tendency to rapidly sediment, unless flow rate is increased; not only losing the improvements in thermal conductivity, but also forming sludge sediments, increasing the thermal resistance and impairing the heat transfer capacity of the conventional fluids. Furthermore, fluids of this scale size could have considerably larger pressure drops [60–64], thus making flow through small channels much more difficult since diverse parameters are critical for device performance, such as morphology and stability of nanostructures, fluids composition, viscosity, fast sedimentation, channels clogging, erosion or wear, among others, which are often very serious for systems consisting of small channels [3, 65–69].

A revolution in the field of HTFs arose with the advent of nanofluids (NFs), a term introduced by Prof. Choi's research group in the late 1990s at Argonne National Lab [68]. The first investigations were performed by Masuda et al. [69] for Al_2O_3 nanoparticles within water, and by
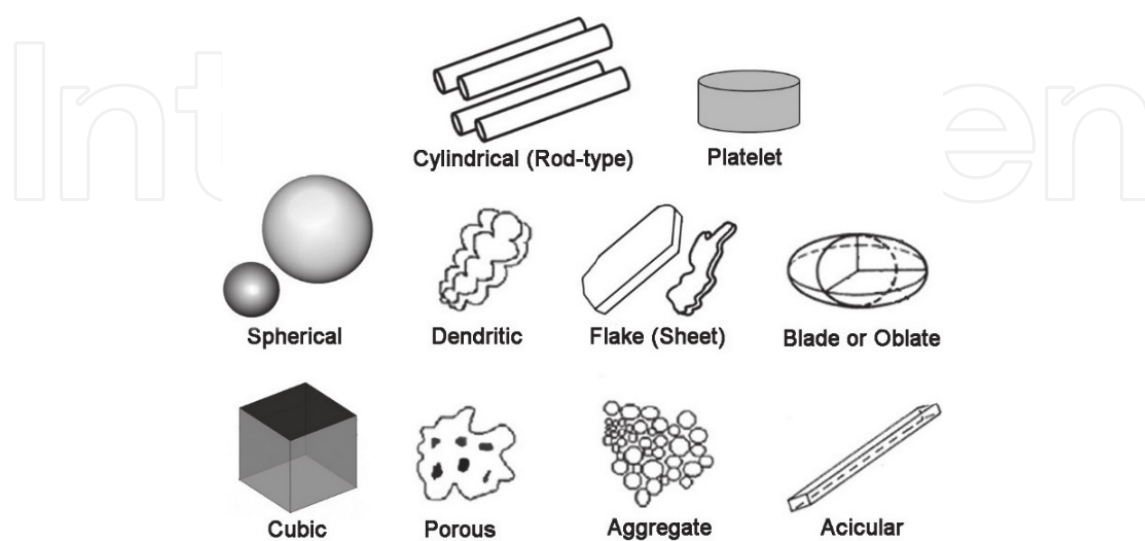
Figure 1. Diverse particle shapes and geometries.

Choi-Eastman group [68] for copper nanostructures dispersed in water as well. Nanofluids research has been exploited and novel developments have been able to fulfill industrial necessities. This research area has been increasing through time, starting at 5 publications in 2003, reaching up to more than 2100 publications by 2017, according to scientific search engine "sciencedirect.com" and keyword Nanofluids. Nanofluids are a novel class of stable heat-transfer suspensions which are engineered containing homogeneously dispersed solid nanofillers. Compared to micro- or millifluids, nanofluids tend to be more stable, since nanofillers possess unique properties, such as large surface area to volume ratio, as well as dimension-dependent physical properties, which make nanostructures better and more stably dispersed in conventional fluids. Nevertheless, some limitations of the effective incorporation of nanostructures within conventional HTFs are dispersion and solubility, because these tend to aggregate and sediment over time. In some cases, additives or surfactants are used to stabilize the nanostructures within the fluids, even though the surfactants could affect and diminish the thermal conductivity of the nanofluids, since surfactants introduce defects at the interfaces [70, 71]. Therefore, one of the main advantages of nanofluids is that they can be specially engineered to optimally fulfill specific objectives, such as enhanced thermal conductivity, a higher thermal energy storage capacity, higher heat transfer coefficients, a better temperature stabilization and less pressure drop, among others. Hence, search for new nanofillers which can get high thermal conductivities at lower filler fractions is important [3, 72].

It has been demonstrated that nanofluids for heat transfer applications have provided better thermal performance than conventional fluids [3, 12, 73, 74]. Hence, the advent of nanofluid-based heat transfer systems can make compact designs with high efficient thermal, physical and electrical performance for instruments and devices. Experiments on convection heat transfer of nanofluids were conducted by several research groups [75–77], showing significant improvements in heat transfer rates of nanofluids. Meanwhile, the thermal conductivity enhancement of nanofluids show a temperature-dependent characteristic and increase of enhancement with rising temperature, which makes the nanofluids more suitable for applications at elevated temperatures [3, 6, 78–81]. Additionally, previous research has shown that nanofluids display better performance in their thermo-physical properties, such as thermal conductivity, thermal diffusivity, viscosity, friction, etc., compared to conventional fluids [3, 4, 82–87]. Hence, nanofluids could be used for aforesaid engineering applications.

3. Synthesis and preparation of nanofluids

The manipulation of matter on the nanometer scale has become a central focus from both fundamental and technological perspectives. Unique, unpredictable, and highly intriguing physical, electrical, mechanical, optical and magnetic phenomena result from the confinement of matter into nanoscale features. Morphology control in nanostructures has become a key issue in the preparation of electronic or mechanical nanodevices and functional materials [88]. A wide variety of combinations of nanostructures and conventional fluids can be used to synthesize and prepare stable nanofluids for diverse applications. Nanofluids could be manufactured by two methods. The first step method is a process in which, simultaneously,

nanostructures are made and dispersed within the base fluid [89–91]. This method avoids diverse processes such as particles drying, storage, handling, and dispersion; so, the agglomeration of nanoparticles is minimized; therefore, stability of nanofluids is improved [89, 90]. In most experimental studies, nanofluids are synthesized in a two-step process [3, 6, 56, 92–96], which is a classic synthesis method of nanofluids. Various nanostructures such as nanofibers, nanotubes, nanosheets, among other nanomaterials used in this technique are initially produced by mechanical comminuting, chemical reaction, inner gas condensation or decomposition of organic complex [97–99] and finally obtained as dry powder. Then, it is followed by the second step in which the as-produced nanostructures are homogeneously dispersed into base conventional fluids through mechanical agitation (stirring) or ultrasonication [6, 97–102]. Furthermore, this process is an economic method to produce nanofluids at large scale, since nanostructures synthesis techniques are readily scaled up to mass production levels. To obtain a good stability and homogeneous dispersion of nanostructures within a fluid, sonication process is used to speed dissolution by breaking intermolecular interactions. The main disadvantage of this method is that due to the high surface area and surface attractively, the nanostructures tend to agglomerate. The nanostructures agglomeration in the fluid results in decreasing the thermal conductivity performance and increasing the settlement and clogging of microchannels. Therefore, to reduce these effects, surfactants or additives are widely used to stabilize nanostructures within the fluids.

3.1. Nanofluids: Variables and features

The concept and strategies of this work have a significant departure from diverse investigations in thermal management applications. Even though there have been several investigations on HTFs with nanoparticles reinforcement, there is still a room for great opportunities to continue developments and understand the implications and effects of this technology. Diverse challenges regarding nanoparticles effect on thermal transport and energetic performance as well as nanofluids industrialization have been studied (**Figure 2**). The heat transfer enhancement in nanofluids has been attributed to many variables, which are presented in the following section.

3.1.1. Brownian motion

Researchers have found that Brownian motion, which is the random movement of particles (**Figure 3**), is a key mechanism for the anomalous increase in the heat transport of nanofluids [55, 78, 103–108]. Brownian motion tends to move the particles from higher concentration areas to the lower concentration areas. Research on fillers motion caused by temperature gradient was studied by Koo and Kleinstreuer [103]; it was shown that the Brownian motion has more impact on the thermal properties of nanofluids than to the effects of a temperature gradient. Aminfar and Motallebzadeh [108] investigated the concentration distribution and velocity field of nanoparticles on water/Al_2O_3 nanofluid in a pipe. It was observed that the Brownian forces have most impact on the nanoparticles filler fraction distribution and the velocity field when compared to other forces such as thermophoretic and gravitational forces. Brownian motion only exists when the particles within the fluid are extremely small and, as the size of the particles gets larger, Brownian motion effects are reduced.
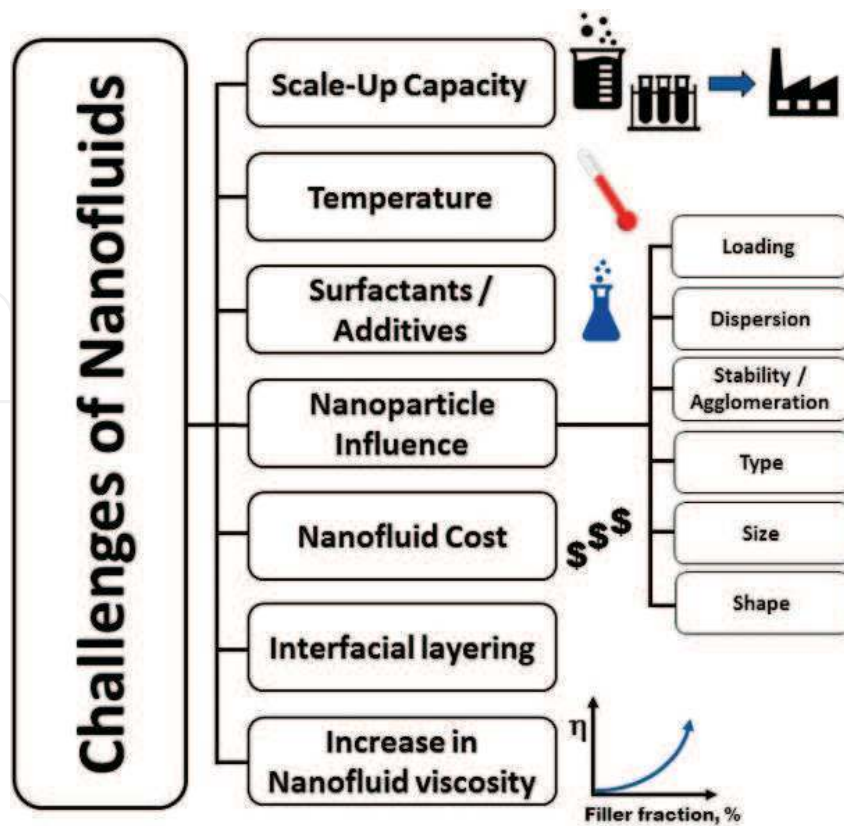
Figure 2. Common challenges of nanofluid developments.

3.1.2. Nanofiller size

Diverse studies have found that as nanostructures are reduced in size, the effective thermal conductivity of the nanofluid increases [13, 109–114]. As the nanoparticle size is reduced, Brownian motion is induced. Also, lighter and smaller nanoparticles are better at resisting sedimentation, one of the biggest technical challenges in experimenting with nanofluids [77]. Li and Peterson [109] investigated the thermal properties of Al_2O_3/DiW nanofluids with particle sizes of 36 and 47 nm at various filler fractions. The nanofluid with 36 nm particles improved the effective thermal conductivity enhancement at ~35°C, as varying the filler fraction from 0.5 vol.% up to 6.0 vol.% (~7% to ~28%, respectively). Agarwal et al. [115] presented the impact of Al_2O_3 size of nanoparticles on thermal conductivity and the dynamic viscosity of kerosene-based nanofluid. Thermal conductivity increases from 1.3% to 9.3% over a particle filler fraction of 0.01 vol.% to 0.10 vol.%. Thermal conductivity performance and viscosity
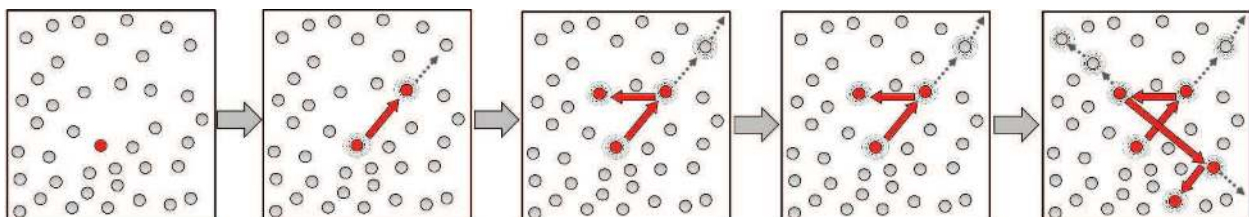

Figure 3. Schematic of Brownian motion of nanoparticles.

were found to be higher for smaller size nanoparticles compared to larger size. At 0.50 vol.%, nanofluid with 13 nm particle size displays 22% improvement in the effective thermal conductivity, compared to only 17% for 50 nm. Beck et al. [116] investigated Al_2O_3/water nanofluids with diverse particle sizes ranging from 8 nm to ~300 nm in diameter; the thermal conductivity enhancement decreases as the particle size decreases below ~50 nm. This behavior was attributed to nanoparticles thermal conductivity, as the particle size becomes small enough to be affected by increased phonon scattering [116]. Teng et al. [112] studied on the effect of particle size, temperature, and weight fraction on the thermal conductivity ratio of Al_2O_3/water nanofluid with filler fraction up to 2.0 wt.% and different Al_2O_3 particle nominal diameters. The results showed a dependence relationship between high thermal conductivity ratios and enhanced sensitivity, and small nanoparticle size and higher temperature. Nguyen et al. [117] studied the heat transfer enhancement and behavior of Al_2O_3/water nanofluid for microprocessors/electronic purposes. It is found that with smaller nanoparticles (36 nm in diameter), nanofluids showed higher convective heat transfer coefficients than with larger ones (47 nm in diameter). From Nguyen's research, thermal transport increased 40% at 6.8 vol.% filler fraction, as compared to water. He et al. [118] studied the heat transfer behavior of TiO_2 water nanofluids with diameters of 95 nm, 145 nm and 210 nm at various filler fractions. For the 95 nm particle size nanofluid, the thermal conductivity showed an increase from 1% to ~5% at 1.0 wt.% and 4.9 wt.%, respectively, compared to water; as filler fraction increased, the thermal conductivity increased as well. It was shown that the effective thermal conductivity decreases as particle size increases. On the other research, Żyła et al. [119] studied the effects of TiN nanoparticles within EG at two different particles size, 20 and 50 nm. It was concluded that the increase in nanoparticle filler fraction led to similar trends for nanofluids properties. At same content, thermal conductivity and surface tension of nanofluids are higher with smaller nanoparticles. Esfahani et al. [120] observed that thermal conductivity of graphene oxide (GO) NFs depends on both particle-size distribution of GO and viscosity of GO NFs. In their work, GO NFs showed enhanced thermal conductivity performance as compared to base water.

There have been a few reports on SiC, CeO_2, and SiO_2 nanoparticles reinforcing conventional fluids that stated a decrease of the effective thermal conductivity with increase in particle size [47, 121–132]. Beck et al. performed studies on water-based ceria (CeO_2) nanofluids [123], which showed an increase in the effective thermal conductivity with an increase of nanoparticle size, although only two particle sizes were studied (12 nm and 74 nm). Silica-ethanol nanofluid was investigated by Hossein Karimi Darvanjooghi and Nasr Esfahany [132] over various particle sizes, temperatures and filler fractions. It was observed that with the increase in particle size and temperature, the thermal conductivity performance of silica–ethanol nanofluid increases for all the investigated filler fractions. 2D nanostructures have also been recently studied; Taha-Tijerina et al. developed a novel nanofluid by adding only 0.10 wt.% of exfoliated hexagonal boron nitride (h-BN) 2D-nanosheets within mineral oil (MO) [30]. Enhancement in thermal conductivity for 0.10 wt.% h-BN/MO nanofluid was more than 75% in comparison with MO. Similarly, Mehrali et al. [133] investigated the effects on thermal transport of graphene-based nanofluids. It was found that at 4.0 vol.%, a significant thermal conductivity enhancement of ~45% was obtained.

The nanostructure size effect is apparently due to interlaying mechanism, van der Waals forces and the micromotions of nanoparticles are stronger when containing lower-sized nanostructures; and the interactions between nanoparticles and fluids are more severe, which results in a stronger energy transmission and a higher thermal transport process in nanofluids. The smaller the particle size, the higher will be the improvement due to the high surface area observed. This trend is observed by most researchers and is supported by two mechanisms: Brownian motion and liquid layering around nanostructures. Hence, nanofillers size is a determinant variable for heat transfer nanofluids, since, as previously stated, its smaller size reduces or avoids critical issues of larger fillers.

3.1.3. Particle shape/surface area

Particle geometry is an important parameter to be considered since it has critical effects on nanofluids performance. There have been several efforts to understand the effects of nanoparticles shape regarding the thermal transport phenomena. It has been observed by several studies that rod-shaped nanoparticles, such as CNTs, remove more heat than spherical nanoparticles [134–139]; this is most probably due to rod-shaped particles' larger aspect ratio (ratio between a particle's surface area to volume) than spherical nanoparticles. For instance, Elias et al. [134] studied various boehmite alumina (γ-AlOOH) nanoparticle shapes (spherical, cylindrical, blades, bricks and platelets) dispersed within EG/water mixtures. The best performance was achieved by the cylindrical-shaped nanoreinforced fluid, followed by bricks, blades, platelets and spherical-shaped nanoparticles, respectively. Thermal conductivity enhancement of cylindrical shape nanoparticles is observed to be ~3% higher than the spherical shape at 1.0 vol.% concentration. On similar study, Kim et al. [140] investigated the effects of particle shape on suspension stability and thermal transport performance of water-based boehmite alumina nanofluids. The thermal conductivities of nanofluids with blade, brick and platelet shaped particles are maximally enhanced up to 16, 28, and 23% at 7.0 vol.%, respectively.

From various studies, it can be concluded that the rod-shaped nanostructures possess higher thermal conductivity performance compared to spherical shape nanoparticles due to larger surface area and rapid heat transport along relatively long distances due to the greater length, usually of the order of micrometers. However, there is some contradiction observed based on studies performed by Xie et al. [141], where thermal conductivity enhancement using spherical (26 nm average) and cylindrical (600 nm average)-shaped SiC nanoparticles suspended within water were evaluated. An enhancement of ~23% at 4.0 vol.% for cylindrical particles was observed, but only 16% increase at 4.2 vol.% for spherical particles was reported. Results showed higher enhancement at larger particle size. These contradictions with other literature could be explained by the severe clustering of nanoparticles having smaller particle size. Although at a certain level clustering may enhance the thermal conductivity, excessive clustering may create an opposite effect, resulting in the sedimentation of nanoparticles [142]. Sudarsana Reddy and Chamkha[139] studied the effects of shape on nanoparticles on natural convection magnetohydrodynamic (MHD) fluids. Results reveal that significant heat transfer enhancement is noticed as the size of nanoparticles decreases. Moreover, the type of the nanoparticles and the type of the base fluid (water/kerosene) also influenced the natural

convection heat transfer. In another study, Aaiza et al. [143] investigated energy transport in MHD nanofluids with different nanoparticles shapes such as cylinders, platelets, blades, and bricks. It was observed that elongated structures such as cylinders and platelets result in higher viscosity at the same filler fraction due to structural limitation of rotational and transitional Brownian motion, which resulted in effects on thermal conductivity.

3.1.4. Filler fraction

One of the most extensively considered factor on thermal transport performance, the key variable for nanofluids' improvement, is the nanostructures concentration dispersed within conventional fluids. Filler concentration has been stated by weight and volume percentages in research, reports, papers and patents. Effective thermal conductivity (k_{eff}) among other properties of nanofluids improve with increasing nanoparticles filler fraction [144, 145]. Nevertheless, as the nanoparticle concentration increases, it may no longer be valid to assume well-suspended nanostructures, due to particles agglomeration, sedimentation, stability and increase in viscosity, which could cause other problems such as possible abrasion and clogging of microchannels. It has also been observed that pressure drop increases in diverse conventional fluids as filler concentration is increased [10]. This is why it is more effective to use a very small filler fraction in nanofluids [3, 146–151]. At low filler fractions, nanostructures have more intense Brownian motion at higher temperatures, which can significantly enhance the effective thermal conductivity. But at high volume fractions, nanoparticles have high potential to be agglomerated at high temperatures. Higher concentration of particle shows less stability which leads to the agglomeration process due to increase in number of molecules within the fluid. This causes an increase in weight which cannot be maintained in the suspension by Brownian agitation, and settle out of the suspension [152].

Pang et al. [153] studied the effect of Al_2O_3 and SiO_2 nanoparticles dispersed in methanol at various concentrations, such as 0.01, 0.10 and 0.50 vol.%. Effective thermal conductivity increases with an increase of the nanoparticles volume fraction; for Al_2O_3, the increments were 1, 5 and 11%, respectively, compared to pure fluid and, for SiO_2, the increments were 6, 11 and 16%, respectively, as compared to pure fluid, as well. Arulprakasajothi et al. [151] investigated TiO_2 concentrations of 0.1, 0.25, 0.5 and 0.75% using two step method. It was observed that as concentration increases, the surface area of particle also increases and exchange more heat. The effective thermal conductivity for nanofluid concentrations was increased from 1 to 6%, respectively. On research conducted by Wang et al. [147], 2D-graphene structures with average particle size were 0.5–2.0 μm and thickness of 0.8–1.2 nm. Graphene was dispersed uniformly into base oil without any surfactant by ultrasonic oscillation. Graphene/oil nanofluids' concentration was 0.02, 0.05, 0.1, and 0.2 mg/ml. Thermal conductivity for all concentrations was raised 4, 8, 17 and 25%, as compared to pure oil, respectively. On this same path, according to Taha-Tijerina et al., the superb thermal transport performance of 2D-based nanofluid was observed, in which nanosheets of h-BN within MO showed improvements of ~10% and ~80% at 0.01 wt.% and 0.1 wt.%, respectively, without significant increase of kinematic viscosity [3, 145, 154]. Tiwari et al. [47] investigated CeO_2/water nanofluids and its effects of filler fraction, ranging from 0.5 to 3.0 vol.%, and temperature. The experimental results indicate that the convective heat transfer coefficient increases with increase in nanoparticle

filler fraction (up to a threshold-optimum value). It was observed that the increase in particle concentration also increases the fluid viscosity, which should result in an increase in the boundary layer thickness, which overcomes the convective heat transfer coefficient as well. However, significant improvements in thermal conductivity are shown. For instance, at 40°C, the thermal conductivity improvements were significant: 7, 11, 13, 16 and 21% at 0.5, 1.0, 1.5, 2.0 and 3.0 vol.%, respectively. Research by Paul et al. [155] demonstrated that the thermal conductivity of water-based SiC nanofluids could be improved by 12% at only 0.1 vol.%. Studies on mixtures of water and EG-based SiC nanofluids were performed by Timofeeva et al. [121, 156], where nanofluids displayed 1.5–20% thermal conductivity enhancement at different filler fraction and nanoparticle sizes. Ferrouillat et al. [157] estimated that heat transfer of SiO_2/water nanofluid in the particle ranges from 5 wt.% to 34 wt.%, and found an improvement of 10–60% compared to pure water. Lee et al. [158] investigated the thermal conductivity of DI-water-based SiC nanofluids; a ~7% improvement was observed, compared to pure DI-water. Li and Zou [159] prepared homogeneous and stable nanofluids by dispersing SiC nanoparticles within mixtures of ethylene glycol and water. It was observed that thermal conductivity of water/EG-based SiC nanofluids increased with SiC concentrations. Improvements of ~34% at 1.0 vol.% of SiC were achieved. Pang et al. [153] studied the effect of SiO_2 nanoparticles within methanol at various concentrations (0.01, 0.10 and 0.50 vol.%). Thermal conductivity enhancements were 6, 11 and ~16%, respectively, as compared to pure fluid.

3.1.5. Stability/particles agglomeration

A key challenge with nanofluids is that nanoparticles tend to agglomerate due to molecular interactions, such as van der Waals forces [122, 160]. The agglomeration of nanoparticles results not only in the settlement and clogging of microchannels, but also causes the effective surface area to volume ratio to decrease, which impacts the thermal conductivity performance of nanofluids. Nanoparticles agglomeration increases as filler fraction increases, due to closer particles and higher Van der Waals attraction. Similarly, this issue generates other problems such as viscosity increments (**Figure 4**).
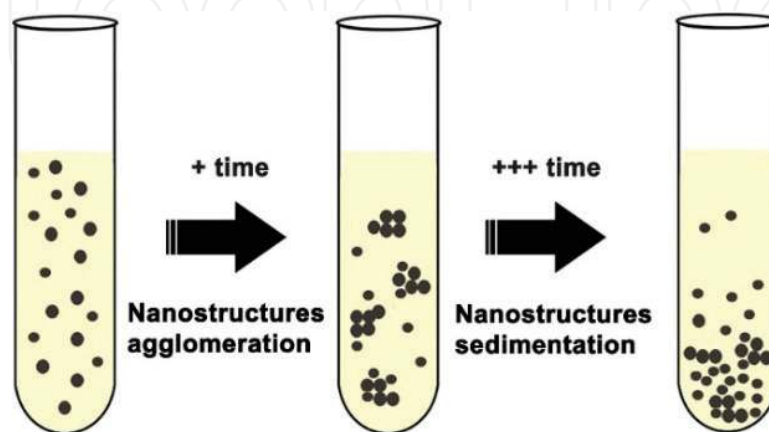
Figure 4. Scheme of nanoparticles sedimentation over time.

The stability of nanofluids is considered one of the critical issues, which should be addressed before any application [48, 145]. Synthesis of nanoparticles and preparation methods of nanofluids play an important role on stability, which effects are observed on nanofluids' thermal transport characteristics. In addition to filler fraction and working temperature, pH has an important role in stability of nanofluids. For instance, Nikkhah et al. observed that by controlling the pH value, the stability of CuO/water nanofluids (50 nm in diameter) can be increased and thus the thermal conductivity performance [161]. Due to nanostructures interlayer adhesion forces, nanoparticles become agglomerated and their settlement can be observed due to gravity forces. Nanostructures sedimentation overcomes one of the major drawbacks of suspensions; nanoparticle aggregates promote settling of particles; hence, the dispersion stability may decay with time. To increase the stability of nanofluids, diverse techniques have been employed, such as extended ultrasonication [162–164]. Ultrasonic vibration is a possible way to break-up cluster formation of nanoparticles and help to scatter the nanostructures within base fluids, so that ultrasonication processes were widely used for nanofluid preparation. Furthermore, to enhance the stability of nanofluids, surfactants or additives are used; nevertheless, these have impacts on thermal characteristics and there could be certain drawbacks by using them.

Timofeeva et al. [122, 165] studied the thermal conductivity and viscosity of Al_2O_3 nanoparticles dispersed in water and EG. It was observed that the main parameters for controlling nanofluids' thermal conductivity enhancement are the geometry, agglomeration state and surface resistance of nanoparticles. Karthikeyan et al. [144] identified that CuO nanoparticles and clusters size have a significant influence on thermal conductivity of water and EG. It was also found that nanoparticles agglomeration is time-dependent; as time elapsed, agglomeration increased, which decreased the thermal conductivity performance. However, some reports show aggregation in water-based Al_2O_3 nanofluids significantly increases the thermal conductivity of the fluid [166], such as research by Shima et al. [167], where an increase in thermal conductivity with particle sizes of average diameters of 2.8–9.5 nm was observed. For 5.5 vol.%, the improvement was 5% and 25%, for 2.8 nm and 9.5 nm, respectively. According to their studies, interfacial resistance, nature, and aspect ratio of agglomerates dictate heat conduction enhancement in nanofluids. Yu et al. observed that stable nanofluids could be able to withstand or maintain no significant variation in thermal conductivity with time. This was observed for EG-based ZnO nanofluids [168] and kerosene-based Fe_3O_4 nanofluids [169].

3.1.6. Surfactants/additives

Surfactants have been widely used to stabilize the nanofillers within conventional fluids, even though these surfactants may affect the nanofluids performance; since surfactants thermal conductivities are generally lower than the base fluids *per se*, the addition ratios of surfactants are generally extremely low to prevent from reducing the thermal conductivity or increasing the viscosity of nanofluids. Surfactants could also introduce defects at the molecular interfaces [170]. The use of surfactants and dispersion agents has shown to be effective providing repulsion between nanoparticles and reducing agglomeration [6, 95, 171]. Additives are also incorporated to materials to enhance their mechanical properties. Nevertheless, the functionality of the surfactants under high temperature is also a big concern, especially for high-temperature applications [39].

Utomo et al. [172] concluded that surfactants in high-loading ratios could reduce the effective thermal conductivity performance of water-based Al_2O_3 and TiO_2 nanofluids. Khairul et al. [173] studied the effects of Al_2O_3 and CuO nanoparticles, as well as sodium dodecyl benzene sulfonate (SDBS) surfactant on viscosity and thermal conductivity of water-based nanofluids. It is observed that increasing the SDBS concentration, thermal conductivity for both systems tend to rapidly decrease, which is attributed to the increased nanostructures aggregation. Murshed et al. [135] observed that low concentration (≤0.02 vol.%) of oleic acid (OA) or a cationic surfactant, cetyl trimethyl ammonium bromide (CTAB), as dispersants could greatly improve the dispersion stability of TiO_2 nanofluids without reducing the thermal conductivity of TiO_2 nanofluids. From other studies, non-ionic surfactants were found to strongly interact with graphite surfaces in case of CNTs stabilization within aqueous suspensions [174]. Quite a few results indicated that surfactants played positive roles in the thermal conductivity. Saleh et al. [175] found that each of the three kinds of surfactants: CTAB, anionic surfactant, sodium dodecyl sulfate (SDS) and nonionic surfactant sorbitan monooleate (Span80) could greatly improve the dispersion behavior and thermal conduction performance of TiO_2 nanofluids. Chen et al. [176] investigated the effects of SiC on saline water, for solar distillation systems. Nanofluids with 0.4 vol.% of SiC were dispersed within saline water, and additionally, polyvinyl pyrrolidone (PVP) dispersant was used (0.02 wt.%) to keep nanoparticles homogeneously dispersed. It was observed that thermal conductivity of seawater/SiC nanofluids improved ~5% compared to pure seawater, which confirms the feasibility of nanofluids application in solar desalination system. Therefore, it can be concluded that the right amount of surfactant can play positive roles in both dispersion and heat conduction performance nanofluids.

3.1.7. Viscosity

Among diverse nanofluid properties, viscosity is a paramount parameter. Viscosity describes a fluid's internal resistance to flow. Many parameters affect the nanofluid's viscosity, including the preparation method, base fluid type, operating temperature, nanostructure size and geometry, filler fraction, acidity (pH value), shear rate, usage of additives or surfactants, and particle aggregation and sedimentation [3, 93, 177–181]. It has been demonstrated that the viscosity of nanofluids increases with the nanoparticle volume fraction. This property is troublesome due to lack of understanding of viscosity mechanisms and lack of general mathematical models to predict the viscosity behavior in nanofluids. Nguyen et al. [177] investigated the nanostructures size effect for Al_2O_3 aqueous-based nanofluids and observed that particle size effects on viscosity are more significant for high filler concentrations. Yiamsawas et al. [178] measured the viscosity of Al_2O_3/water nanofluids at high filler concentrations and high temperatures. The filler fraction ranges varied from 1.0 vol.% to 8.0 vol.%, while the temperature evaluation varied between 15°C and 60°C. It was observed that the viscosity decreases with a temperature increase. Nanofluids prepared in higher viscosity base fluids exhibit more enhancement compared to low viscosity base fluids.

Li et al. [179] investigated EG-based nanofluids containing ZnO nanostructures at different concentrations ranging from 1.75 wt.% and 10.5 wt.%. Results showed that viscosity increases with increasing the concentration of ZnO nanoparticles and decreases with temperature. Attari et al. [180] explored the effects of adding TiO_2, Fe_2O_3 and ZnO nanoparticles to crude

oil at different filler fractions, ranging from 0.5 to 2.0 wt.% at different temperatures. It was observed that with the increase in nanoparticle loading, the relative viscosity of ZnO-crude oil nanofluid increases. At the mass fraction lower than 1.0 wt.%, the relative viscosity of nanofluid decreases slightly with the increase in temperature and the main factor which can influence the relative viscosity is nanoparticle type. On research by Jeong et al. [181], the viscosity behavior of water-based ZnO nanofluids with two nanoparticle shapes and semi-rectangular and spherical at various filler fractions ranging from 0.05 to 5.0 vol.% was investigated. Their results indicated that the viscosity increased from 5.3 to ~70% with increase in the filler concentrations. Moreover, the enhancement of the viscosity of the nearly rectangular shape nanoparticles was found to be more than 7%, rather than the spherical nanoparticles. Williams et al. [182] studied ZrO_2-water nanofluid for 60 nm particle size, at small filler fractions (0.2–0.9 vol.%) and found a 54% increase in viscosity, when compared to pure water.

3.1.8. Temperature dependence

Thermophoresis or thermodiffusion is an interesting consequence of the Brownian motion of the nanostructures. High energy molecules in a warmer region of a liquid migrate in the direction opposite the temperature gradient to cooler regions; small particles tend to disperse faster in hotter regions and slower in colder regions. Thermophoresis and Brownian motion effects are the mass transfer mechanisms which also influence the convective heat transport performance of nanofluids [78–81, 183–189]. As Michaelides [189] explained, interparticle collisions in the colder regions where the nanostructure concentrations are higher, partly hinder this accumulation and a dynamic equilibrium for nanoparticle concentration is established, with lower concentrations in the hotter regions and higher concentrations in the colder regions. **Figure 5** schematically depicts the differential dispersion and the resulting thermophoresis which shows the effects of the magnitude of the molecular collisions on small particles.

Diverse theoretical and experimental investigations have been developed. For instance, Wang et al. [187] observed the effects of temperature-dependent properties on natural convection
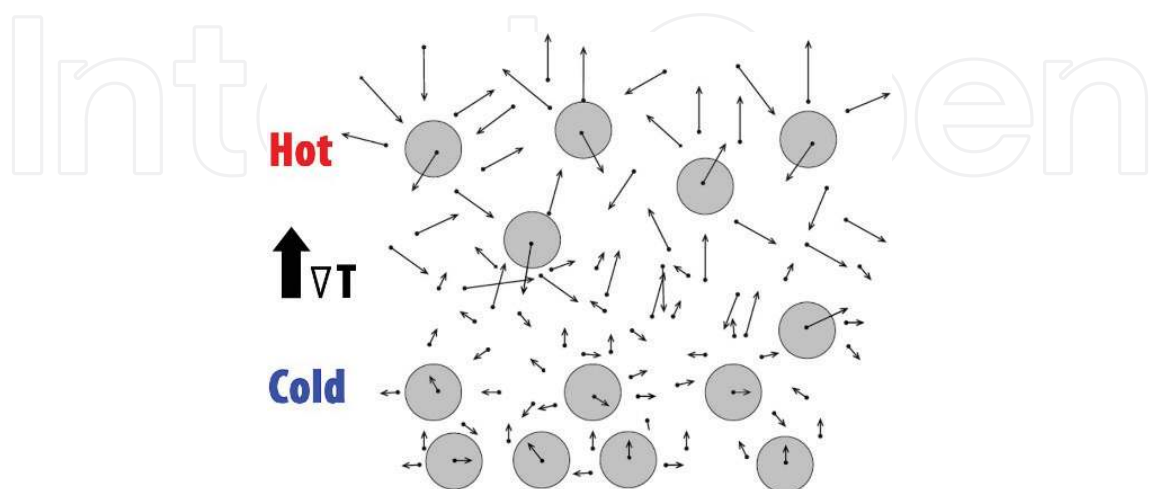
Figure 5. Thermophoretic motion of particles. The Brownian motion brings more particles to the colder region of the system.

of Al_2O_3 nanofluids; lattice Boltzmann (LB) method was considered for their study. It was concluded that for a given nanoparticle filler fraction, the value of the heat transfer enhancement is increased as the temperature increases, and the nanoparticle diameter decreases. On the other hand, Das et al. [78], similarly to Lee et al. [190], observed that thermal conductivity performance of Al_2O_3 and CuO nanofluids has a temperature-dependent influence; they posed motion of reinforced fillers as an important factor for that. Jyothirmayee Aravind and Ramaprabhu [184] observed a temperature dependence on graphene nanosheets reinforcing EG and DiW. It was observed that thermal conductivity performance increases with increasing filler fraction and operating temperature. The thermal conductivity of the base fluids did not show significant improvements as the temperature increases, similar tendency as reported by Jha and Ramaprabhu [191]. An enhancement in thermal conductivity of ~2.4% is observed at 25°C with a very low filler fraction of 0.008 vol.% of the graphene/EG nanofluid; meanwhile, at 50°C, the increment was ~17%. At 0.14 vol.%, the thermal conductivity improvement was 6.5 and 36%, at 25 and 50°C, respectively. On the research conducted by Wen and Ding [192], it was observed that thermal conductivity increases with increasing temperature on the system, showing a nonlinear dependence after temperatures above 30°C.

The influence of temperature on thermal conductivity on 0.5 vol.% and 1.0 vol.% CeO_2—EG nanofluids was studied by Rajan et al. [164]; it was observed that an enhancement in thermal conductivity increases as filler fraction increases. Thermal conductivity enhancements were 5 and 10% for the filler fraction studied. Also, by increasing temperature, the thermal conductivity ratio decreases for both nanofluid concentrations. Li et al. [179] investigated EG-based nanofluids containing ZnO nanoparticles at different filler fractions (1.75–10.5 wt.%. The thermal conductivity increases with increasing the temperature ranging from 15 to 55°C. The thermal conductivity gradually increases with mass fraction and temperature, and it was observed that the growth rate decreases at 15°C in the range of 8.75–10.5 wt.%. It was concluded that thermal conductivity performance depends on filler fraction, and it increases nonlinearly with the mass fraction of nanoparticles. Kandasamy et al. [107] observed that the combined effect of thermophoresis and Brownian motion play a very dominant role on heat transfer in the presence of thermal stratification, mainly due to the nanoparticles geometry and size. Although thermophoresis effect is important in heat transport, there are other characteristics and parameters that may have effects on nanofluids and should be addressed. These effects include the increase in nanofluids viscosity due to the presence of nanoparticles and fluid density variation due to variable volume fraction.

3.1.9. Interfacial layering on the liquid-nanostructure interface

Interfaces are ideal templates for assembling nanoparticles into structures by the nature of the interfaces. Interfacial layering or nanolayer refers to a phenomenon at the liquid-particle interface where liquid molecules are more ordered than those in the conventional fluids; therefore, the interface effect could enhance the thermal conductivity by the layering of the liquid at the solid interface (given that crystalline solids possess much better thermal transport that liquids) [193–195], by which the atomic structure of the liquid layer is significantly more ordered than that of the conventional liquid. At the interfaces, the nanostructures are mobile, and defects could be eliminated [196]. Nanoparticles suspended in base fluids form clusters that

create a low thermal resistance path which can enhance the thermal conductivity, according to Saterlie et al. [197]. The ordered structure could have higher thermal conductivity than that of the conventional, therefore an enhancement of the effective thermal conductivity. Various researchers have suggested that there is liquid layering on the nanoparticles, which helps to enhance the heat transfer properties of nanofluids [197–201]. Yu et al. [200] proved the formation of layers by the liquid molecules close to a solid surface, even though the thickness and thermal conductivity of the nanolayers are not well known yet. According to Elis Josna Mary et al. [164], a temperature-dependent, linear variation in thermal conductivity increase with filler fraction was observed, which could be attributed to liquid layering.

4. Nanofluids application fields

Diverse studies on nanofluids have been carried out by many researchers. This section deals with literature review on nanofluids; nanofluids preparation and characterization, thermophysical properties, as well as nanofluids applications, which lays foundation and basis for further investigations.

4.1. Thermal performance of nanofluids

Heat transfer is classified into various mechanisms, such as thermal conduction, thermal convection and thermal radiation. In diverse fields, thermal transport is a critical parameter to obtain efficient performance of machinery and devices. Heat convection occurs when bulk flow of a fluid (liquid or gas) carries heat along with the flow of matter in the fluid, this process could be "forced," where fluid motion is generated by an external source such as a pump, fan or other mechanical means, or "natural," by density differences in the fluid occurring due to temperature gradients. Radiation heat transfer is the transfer of energy by means of photons in electromagnetic waves in much the same way as electromagnetic light waves transfer light. On the other hand, heat conduction is the direct microscopic exchange of kinetic energy of particles through the boundary between two systems. When an object is at a different temperature from another body or its surroundings, heat flows so that the body and the surroundings reach the same temperature, at which point they are in thermal equilibrium. The thermal conductivity (k) of liquids can be successfully measured if the time taken to measure k is very small so that the convection current does not develop [202].

Diverse techniques have been proposed to measure nanofluids thermal conductivity over the past years. The most common techniques to measure the effective thermal conductivity of nanofluids are the transient hot-wire method [3, 147, 202–207], steady-state method [109, 208–210], cylindrical cell method [211], temperature oscillation method [183, 212, 213], and 3-ω method [40, 214–216] to name some. Eastman et al. reported a 40% enhancement with only 0.40 vol.% of copper oxide (CuO) particles [217], while Choi et al. reported a remarkable 160% increase in thermal conductivity of MWCNTs/engine oil nanofluid at 1.0 vol.% filler fraction of nanotubes [218]. Ilyas et al. [58] study a commercial brand oil (THO) with incorporation of MWCNTs where significant thermal conductivity improvement of ~22 and ~30% was achieved at 35 and 60°C, respectively, at 1.0 wt.%. Hwang et al. [41] investigated the thermal conductivity of

DiW- and EG-based nanofluids reinforced with MWCNTs, CuO and SiO$_2$. It was observed that thermal conductivity was improved almost linearly as filler fraction increased. For DiW-based systems, the addition of SiO$_2$, CuO and MWCNTs at 1.0 vol.% filler fraction showed an increase of 3, 5 and ~12%, respectively. Also, CuO/EG nanofluid at 1.0 vol.% showed an increase of ~9%. Wen and Ding et al. [192] also investigated the effects of MWCNTs within DiW, with addition of 0.25 wt.% gum Arabic (GA) dispersant with respect to DiW. For MWCNTs at 0.50 wt.% and 1.0 wt.%, an increase in thermal conductivity enhancement was achieved up to ~30% and ~38% at 25°C, and ~35% and ~80% at 30°C, respectively. It was found that these improvements were slightly higher than the results reported by Liu et al. [14], Assael et al. [219], Wen et al. [220], and Xie et al. [221], but lower than the results showed by Choi et al. [218]. There are diverse factors that cause these discrepancies among the different groups; as mentioned by Sing [55], these discrepancies should rely on the dependency of thermal conductivity is on diverse important factors such as the structure and properties of the CNTs, their aspect ratio, clustering, addition of dispersants, temperature and the experimental errors involved as well.

Nanodiamonds (NDs) dispersed in EG and mineral oil (with addition of OA) were studied by Branson et al. [222]. It was observed that addition of 0.88 vol.% of NDs enhanced the thermal conductivity by ~12%. In MO, for instance, an enhancement of ~6% and ~11% is achieved at NDs loading of 1.0 vol.% and 1.9 vol.%, respectively. According to Branson et al., the differences on enhancement efficiencies are attributable to divergence in thermal boundary resistance at nanoparticle/surfactant interfaces [222]. Research by Khairul et al. [173] on the effects of Al$_2$O$_3$ and CuO nanoparticles filler fraction and use of SDBS surfactant on viscosity and thermal conductivity of water-based nanofluids was performed. It was observed that thermal conductivity of the nanofluids increased nonlinearly with increasing nanoparticles filler fraction, with a maximum increase of 10 and 14% for Al$_2$O$_3$ and CuO, respectively, at 0.15 wt.%, similar to what Kong et al. found for the maximal enhancement for Al$_2$O$_3$ nanofluids [223]. On the field of oxide nanostructures, Yiamsawasd et al. [224] reported a maximum thermal conductivity enhancement of 20% for TiO$_2$/water nanofluid. Elis Josna Mary et al. [164] investigated CeO$_2$/EG nanofluid and observed a temperature effect on thermal conductivity rise of 17% and ~11% at 10 and 30°C, respectively. Serebryakova et al. [225] investigated the effects of dispersing Al$_2$O$_3$ within EG/water mixtures. It was observed that thermal conductivity performance was improved by 5% at 1.5 vol.%. Mariano et al. [226] estimated thermal conductivity behavior and rheological properties of Co$_3$O$_4$/EG nanofluids and obtained thermal conductivity enhancement of 27% at 5.0 wt.%. Aluminum nitrides (AlN) can also find many applications in the heat exchange process. Thermal conductivity performance of AlN/ethanol nanofluid was investigated by Hu et al. [227]. Results showed a 20% increase in the thermal conductivity of ethanol with 4.0 vol.% at room temperature. Furthermore, a strong temperature dependence of the thermal conductivity was observed in this research. Yu et al. [228] thermal conductivity of AlN dispersed in two different conventional fluids, such as EG and propylene glycol (PG), was investigated. It was found a 39 and 40% thermal conductivity improvement for EG and PG, respectively, having the same particle size and nanoparticles filler fraction.

A great improvement on 2D-nanostructure-based nanofluids was obtained by Taha-Tijerina et al. [3], where exfoliated h-BN and graphene were homogeneously dispersed within mineral oil with superb thermal conductivity increase up to ~80% at very low filler fractions (<0.10 wt.%)

with no significant increase in viscosity. Continuing with 2D structures, several research studies have developed graphene-based nanofluids with high nanoparticle stability and significant enhancements [229–235]. Shaikh et al. studied the effect of exfoliated graphite dispersed within PAO oil at various concentrations, ranging from 0.10 vol.% up to 1.0 vol.%. It was observed that addition of 2D-structures improved the thermal conductivity from 18% up to ~130%, respectively [230]. Hadadian et al. [236] prepared highly stable graphene oxide (GO)-based nanofluid. Thermal transport of EG increased by 30% with 0.07 GO mass fraction. Other EG-based nanofluids synthesized by Yu et al. [237, 238] have shown better enhancements of 61 and 86% with GO [237] and graphene nanosheets [238], respectively, at 5.0 vol.% loading.

Diverse theories explain the mechanisms that could affect the behavior of nanofluids; the most accepted being Brownian motion [40, 104, 239, 240], percolation theory [55, 104, 198, 241, 242], micro convection cell model [104, 198, 239–242], and liquid layering theory [55, 104, 193, 198, 242, 243]. **Table 2** shows the influence of oil-based nanofluids on thermal conductivity.

Filler	Type of oil	Nanoparticles morphology	Filler fraction	TC enhancement	Ref.
Al_2O_3	Engine oil	Spherical ~80 nm diam.	0.5 vol.%	~9%	[194]
			1.0 vol.%	~12%	
Al_2O_3	Engine oil	Spherical ~28 nm diam.	5.0 vol.%	~26%	[209]
			7.5 vol.%	~30%	
Al	Engine oil	Spherical ~80 nm diam.	1.0 vol.%	~20%	[194]
			3.0 vol.%	~37%	
AlN	Mineral oil	Spherical ~50 nm diam.	0.05 vol.%	~8%	[244]
CeO_2	Transformer oil @ 50C	Spherical ~3–7 nm diam.	0.7 vol.%	~15%	[203]
CuO	Mineral oil	Spherical ~100 nm diam.	2.5 vol.%	~12%	[245]
			5.0 vol.%	~23%	
Diamond	Mineral oil	Spherical ~<10 nm diam.	1.0 vol.%	~5%	[222]
			1.9 vol.%	~11%	
Graphene	Mineral oil (50°C)	2D-sheets ~500 by 500 nm ~8–10 atomic layer thick	0.01 wt.%	~10%	[3]
			0.10 wt.%	~80%	
Graphene	Heat-transfer oil	2D sheets ~0.5–2.0 μm ~0.8–1.2 nm thick	0.05 wt.%	8%	[147]
			0.10 wt.%	17%	
			0.20 wt.%	25%	
h-BN	Mineral oil (50°C)	2D sheets ~500 by 500 nm ~5 atomic layers thick	0.01 wt.%	~9%	[3]
			0.05 wt.%	~10%	
			0.10 wt.%	~80%	
h-BN	Synthetic fluid	2D sheets ~500 by 500 nm ~5 atomic layers thick	0.10 wt.%	8%	[6]

Filler	Type of oil	Nanoparticles morphology	Filler fraction	TC enhancement	Ref.
MWCNT	Engine oil (15 W-40)	Rods ~length: 0.3–10 μm Diameter: 10–50 nm	0.25 vol.%	~10%	[18]
			0.5 vol.%	~17%	
			1.0 vol.%	~45%	
MWCNT	Mineral oil	Rods ~length: 10–50 μm Diameter: 10–30 nm	0.5 vol.%	~8.5%	[92]
MWCNT	Synthetic PAO oil	Rods ~length: 50 μm Diameter: 25 nm	1.0 vol.%	160%	[218]
MWCNT	Poly-α-olefin (PAO)	Rods ~length: 1–100 μm Diameter: 20–300 nm	1.0 vol.%	~175%	[19]

Notes: if not specified, measurements were conducted at room temperature.

Table 2. Influence of oil-based nanofluids in thermal management.

Similarly, **Table 3** shows the results from diverse investigations on other water-based nanofluids; and various materials and sizes used as reinforced nanoparticles. **Table 4** shows the influence of various nanofluids in thermal management properties as well.

Filler	Nanoparticles morphology	Filler fraction	TC enhancement	Ref.
Al_2O_3	Spherical ~60 nm diam.	5.0 vol.%	~20%	[141]
Al_2O_3	Spherical ~131 nm diam.	1.0 vol.%[1]	~11%	[246]
		4.0 vol.%	~10%	
		4.0 vol.%[1]	~25%	
Al_2O_3	Spherical ~27–56 nm diam.	1.6 vol.%	~10%	[247]
Al_2O_3	Brick ~20 × 40 × 40 nm	7.0 vol.%	16%	[140]
Al_2O_3	Platelet ~15 nm diam., 5 nm thick	7.0 vol.%	28%	[140]
Al_2O_3	Blade ~8 × 15 nm, 5 nm thick	7.0 vol.%	23%	[140]
Au	Spherical ~10–20 nm diam.	0.00026 vol.%	~8%	[11]
Ag	Spherical ~60–80 nm diam.	0.001 vol.%	~5%	[11]
CeO_2	Spherical 74 nm diam.	2.0 vol.%	~9%	[123]
		3.0 vol.%	~14%	
CeO_2	Spherical 30 nm diam.	1.0 vol.%	11%	[47]
		2.0 vol.%	16%	
		3.0 vol.%	21%	
Cu^3	Spherical ~60–100 nm diam.	1.0 vol.%	~48%	[197]
CuO	Spherical ~36 nm diam.	1.0 vol.%	~12%	[12]
		5.0 vol.%	~60%	

Filler	Nanoparticles morphology	Filler fraction	TC enhancement	Ref.
CuO	Spherical ~24 nm diam.	1.0 vol.%	~14%	[78]
		1.0 vol.%[1]	~29%	
		4.0 vol.%	~15%	
		4.0 vol.%[1]	~36%	
CuO	Spherical ~100 nm diam.	2.5 vol.%	~24%	[245]
		5.0 vol.%	~55%	
		7.5 vol.%	~78%	
CuO	Spherical ~25 nm diam.	0.10 vol.%	~7%	[248]
		0.30 vol.%	~12%	
Graphene	Sheets, 1 μm lateral	0.40 vol.%	~9%	[232]
GO	Sheets, range of 200 nm to 1000 nm	0.01 wt.%	~9%	[120]
		0.10 wt.%	~19%	
Graphene + MWCNTs	G sheets, 1 μm lateral; MWCNTs ~19 nm diam.	0.40 vol.%	~11%	[232]
SiC	Spherical ~26 nm	4.2 vol.%	16%	[141]
SiC	Cylindrical ~600 nm	4.0 vol.%	23%	[141]
SiC	Spherical ~37–110 nm diam.	0.1 vol.%	~12%	[155]
SiO$_2$	Spherical ~12 nm diam.	1.0 vol.%	~3%	[92]
TiO$_2$	Spherical ~15 nm diam.	1.0 vol.%	~18%	[135]
		5.0 vol.%	~30%	
TiO$_2$	Spherical ~95 nm diam.	1.0 wt.%	~1%	[118]
		4.9 wt.%	~5%	
CNTs	Rods ~length: 35 μm	0.01 wt.%	~38%	[249]
	Diam.: 20 nm	0.10 wt.%[2]	~126%	
		0.10 wt.%[2]	~288%	
MWCNTs	Rods ~length: 30 μm	1.0 vol.%	~7%	[221]
	Diam.: 15 nm			
ZnO	Semi-rectangular (90–210 nm)	1.0 vol.%	10%	[181]
		3.0 vol.%	21%	
ZnO	Spherical, 20–40 nm diam.	1.0 vol.%	9%	[181]
		3.0 vol.%	18%	

Notes: if not specified, measurements were conducted at room temperature.

[1]At 50°C.

[2]At 60°C.

[3]With addition of CTAB.

Table 3. Influence of water-based nanofluids in thermal management.

Filler	Conventional fluid	Nanoparticles morphology	Filler fraction	TC enhancement	Ref.
Al_2O_3	Ethylene glycol	Spherical ~10 nm diam.	5.0 vol.%	~18%	[217]
AlN	Ethylene glycol	Spherical ~50 nm diam.	5.0 vol.%	~20%	[228]
			10.0 vol.%	~40%	
Au	Toluene	Spherical ~10–20 nm diam.	0.011 vol.%	~9%	[11]
CuO	Ethylene glycol	Spherical ~35 nm diam.	4.0 vol.%	~22%	[190]
CuO	Ethylene glycol	Spherical ~23 nm diam.	~15.0 vol.%	~55%	[209]
Fe_3O_4	Kerosene	Spherical ~15 nm diam.	0.50 vol.%	~15%	[169]
			1.0 vol.%	~34%	
Graphene	Ethylene glycol @ 20°C	2D sheets ~500 × 600 nm	0.14 vol.% 0.14 vol.%	6.5%	[184]
	Ethylene glycol @ 50°C			36%	
h-BN	Stamping lubricant @ 50°C	2D sheets ~500 × 500 nm	0.01 wt.%	~25%	[6]
		~5 atomic layer thick	0.10 wt.%	~30%	
h-BN	Metal cutting fluid @ 50°C	2D sheets ~500 × 500 nm	0.01 wt.%	~14%	[6]
		~5 atomic layer thick	0.10 wt.%	~18%	
MWCNT	Ethylene glycol	Rods length: 30 μm	0.05 vol.%	~7%	[67]
		Diam.: 15 nm	1.0 vol.%	~13%	
MWCNT	Ethylene glycol	Rods length: μm range	0.50 vol.%	~8%	[14]
		Diam.: ~20–30 nm	1.0 vol.%	~13%	
SiO_2	Ethanol	Spherical ~23 nm diam.	1.0 vol.%	~5%	[40]
SiO_2	Ethylene glycol	Spherical ~23 nm diam.	1.0 vol.%	~4%	[40]
TiO_2	Ethylene glycol/water (20/80%)	Spherical ~21 nm diam.	4.0 vol.%	~15%	[224]

Notes: if not specified, measurements were conducted at room temperature.

Table 4. Influence of diverse nanofluids in thermal management.

5. Summary

The heat required to be dissipated from systems is continually increasing due to industrial and economic trends to miniaturize designs, make better use of resources, obtain more power

output, environmentally friendly materials, and obtain more profits. The present work offers a general overview of the recent research and development on preparation and characterization of nanofluids for thermal management applications, with emphasis on experimental data, variables and features. Nowadays, many technologies search for the highest efficiency mainly for energy savings, particularly on cooling or heat dissipation challenges within devices and machinery components. Many interesting properties of nanofluids have been reported in the past decades. Several efforts have been made trying to homogeneously disperse nanostructures within conventional HTFs to improve their properties. Nanofillers size has positive effects on conventional HTFs performance, i.e., compared to larger dispersed solid particles making flow through microchannels much easier, also since diverse parameters are critical for devices performance, such as morphology and stability of dispersed nanostructures, fluids composition, viscosity, fast sedimentation, channels clogging, erosion, wear, among others, which are often very serious for systems consisting of small channels. It is noted that nature of enhancement in thermal transport with nanoparticles concentration and temperature increment differs from fluid to fluid, which is comprehensible due to many factors such as fluids composition, viscosity, nature of fluids (morphology as well as interaction between fluid and nanofillers), etc.

It is found that factors such as temperature and filler fraction are more sensitive in determining the effective thermal conductivity in low viscosity fluids. The lower the filler concentration, the higher the stability (but lower thermal conductivity improvement), which means that a medium must be found between the two to prevent nanoparticles sedimentation/agglomeration, the free phonon/electron movement is affected by these defects, and hence a surfactant-free stable suspension can provide much better thermal conductivity. Nanofluids stability is a key factor to evaluate the quality of the nanofluids, and is considerably valued in the industrial applications. Additives or surfactants could be used to promote nanoparticles stabilization, but with some main drawbacks such as decrease of thermal conductivity, since surfactants could introduce defects at the solution/particle interfaces. Some nanofluids are currently expensive, partly due to the difficulty in manufacturing either the nanostructures to be afterward dispersed within conventional fluids or the nanofluids by themselves. Optimum layer thickness and filler fraction are important parameters in research of thermal transport, electrical and physical behavior and general aspects of both fundamental and applied characteristics. Mass production of nanostructures could further reduce the costs, and also using low filler fractions is another way to make nanofluids more affordable. Although nanofluids have displayed paramount and exciting potential applications, some vital hinders also exist before regular commercialization and industrialization of nanofluids.

Acknowledgements

Author details

José Jaime Taha-Tijerina

Address all correspondence to: jose.taha@udem.edu

Universidad de Monterrey, Engineering Department, San Pedro Garza García, N. L., México

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