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A review on preparation, characterization, properties and applications of nanofluids

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ABSTRACT

Selection of suitable heat transfer fluid for heat dissipation is an important consideration in the design of heat exchanging systems. Nanofluid, a colloidal mixture made of a base fluid and a nanoparticle, is a new generation of heat transfer fluids becoming a high potential fluid in heat transfer applications due to enhanced thermal conductivity. Research studies about nanofluids are on the rise owing to the mounting interest and demand for nanofluids as heat transfer fluids in a wide variety of applications. Recently, nanofluid technology has a new dimension of impregnating two or more nanoparticles in base fluids, namely hybrid or composite nanofluids. This paper reviews the preparation of metal and metal oxides nanofluids and hybrid nanofluids and the various techniques used to study the physical and chemical characteristics of nanofluids. Thermo-physical and heat transfer properties of nanofluids including the improved thermal conductivity, viscosity and specific heat models for nanofluids are presented. Finally, various application areas of nanofluids, such as transportation, electronic cooling, energy storage, mechanical applications etc. are discussed.

Contents

Abbreviations: CNT, carbonnanotube; CTAB, centrimoniumbromide; HTC, heattransfercoefficient; PVP, polyvinylpyrrolidone; SDBS, sodiumdodecylbenzenesulfonate; SEM, scanningelectronmicroscope; TEM, transmissionelectronmicroscope; XRD, X-raydiffraction; FT-IR, fouriertransforminfraredspectroscope; DLS, dynamiclight scattering; TGA, thermogravimetricanalysis; ATF, aviationturbinefuel; HRTEM, highresolutiontransmissionelectronmicroscope; PU, polyurethane; AFM, atomicforce microscopy; VSM, vibratingsamplemagnetometer

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1. Introduction

Heat exchangers are widely used in many engineering applications, such as chemical industry, power production, food industry, environment engineering, waste heat recovery, air conditioning, automobile radiators and refrigeration. Efforts have been made to enhance heat transfer rate in heat exchangers to reduce the heat transfer time and improve energy efficiency. Although various techniques have been applied to enhance heat transfer, their performances are often limited by the low thermal conductivities of the heat transfer fluids, which limit the performance enhancement and compactness of heat exchangers. With the growing demands of modern technology for miniaturization of devices, there is a need to develop new types of heat transfer fluids that are more effective in terms of heat transfer performance. It has been proved that the dispersion of small amounts of nano-sized (<100 nm) solid nanoparticles in base fluids, commonly known as nanofluids, enhance thermal conductivity and improve the thermal performance of heat transfer systems. The concept of nanofluids was coined by Stephen U.S. Choi in the year 1995 at Argonne National Laboratory in U.S.A. [1]. Nanofluid is a colloidal mixture in which the properties of both the nanoparticles and the base fluid contribute to the change in the transport and thermal properties of the basefluid [2]. Nanofluids are fundamentally characterized by the fact that Brownian agitation overcomes any settling motion due to gravity. Thus, a stable nanofluid is theoretically possible as long as particles stay small enough (usually 100 nm) [3]. Keblinski et al. [4] have reviewed literatures about the properties of nanofluids and future challenges and reported that the development of nanofluids is still hindered by several factors such as the lack of good theoretical property models, agreement between theoretical and experimental results, poor characterization of suspensions, and the lack of theoretical understanding of mechanism.

Nanocomposites, i.e., composites containing two different dispersed particles in the nanometer range, are significant part of nanotechnology and one of the fastest growing areas in materials science and engineering [5,6]. The hybrid nanofluids are new kind of nanofluids, which can be prepared by suspending two or more nanoparticles in the base fluid, in other words hybrid (composite) nanoparticles in base fluid. A hybrid nanoparticle is a substance which combines physical and chemical properties of the constituent materials simultaneously and provides these properties in a homogeneous phase. Furthermore, the hybrid nanofluid is expected to yield better thermal conductivity compared to individual nanofluids due to synergistic effect [7]. A significant amount of research has been done regarding the properties of these composites [8] and hybrid materials consisting of carbon nanotubes (CNTs) which have been used in electrochemical-sensors, bio- sensors, nanocatalysts, etc. [7] but the use of these hybrid nanomaterials in base fluids has not developed as such. Reported research work on hybrid nanofluids is very limited and a lot of experimental studies are still to be done.

In this context, a detailed review of nanofluid research works assumes a great significance as it would facilitate the researchers to update the recent developments and realize the potential research gap in the field of nanofluid. This paper focuses on the existing knowledge and research gap in all fields of nanofluids from synthesis of metallic and nonmetallic nanofluids and hybrid nanofluids to the application of nanofluid. An exclusive review section on characterization techniques, improved and recent theoretical models for thermal conductivity, viscosity and specific heat developed by different researchers are presented and major applications areas of nanofluids are discussed in this review paper. Nanofluid is found to be a potential candidate for many applications. However, there are still many challenges that need to be overcome. These challenges include the long term stability of nanoparticle dispersions, increased pressure drop, pumping power requirements, nanofluid thermal performance in turbulent flow and in fully developed flow regions, higher viscosity, lower specific heat, thermal conductivity, high production cost, and difficulties in production processes. Especially, nanofluid stability and production costs are obstacles for the commercialization of nanofluids. A discussion on challenges of nanofluids is included in this review paper.

2. Preparation of nanofluids

Preparation of nanofluids is the first key step in experimental studies with nanofluids. Nanofluids are produced by dispersing nanometer-scale solid particles into base liquids such as water, ethylene glycol (EG), oils, etc. In synthesis of nanofluids, agglomeration is a major problem [9]. The delicate preparation of a nanofluid is important because nanofluids need special requirements such as an even suspension, stable suspension, low agglomeration of particles, and no chemical change of the fluid [10]. Xuan and Li [11] suggested methods used for stabilizing the suspensions: (i) changing the pH value of suspension, (ii) using surface activators and/or dispersants, (iii) using ultrasonic vibration. These methods can change the surface properties of the suspended particles and can be used to suppress the formation of particle clusters in order to obtain stable suspensions. The use of these techniques depends on the required application of the nanofluid. Selection of suitable activators and dispersants depends

Nomenclature

d	*particle diameter*
h	*heat transfer co-efficient*
Nu	*Nusselt number*
Pe	*Peclet number*
Pr	*Prandtl number*
Re	*Reynold's number*
k	*thermal conductivity*
D	*tube diameter*
Cp	*specific heat*

Greek symbol

ø	*dimensional nano particle volumetric fraction*
ρ	*density*
μ	*dynamic viscosity*
Ψ	*inclination angle*
η	*ratio of the nanolayer thickness to the original particle radius*

Subscripts

f	base fluid
nf	nanofluid
p	particle

Acronyms

CNT	carbon nanotube
CTAB	centrimoHTCnium bromide
HTC	heat transfer coefficient
PVP	polyvinylpyrrolidone
SDBS	sodium dodecylbenzene sulfonate
SEM	scanning electron microscope
TEM	transmission electron microscope
XRD	X-ray diffraction
FT-IR	Fourier transform infrared spectroscope
DLS	dynamic light scattering
TGA	thermogravimetric analysis
ATF	aviation turbine fuel
HRTEM	high resolution transmission electron microscope
PU	polyurethane
AFM	atomic force microscopy
VSM	vibrating sample magnetometer

mainly upon the properties of the solutions and particles. It should be mentioned that the addition of dispersant/surfactant which affect the thermophysical properties of nanofluids. Stability of nanoparticle dispersion in base fluid is indicated by zeta potential value, high zeta potential value ($\pm$) indicates good stability. For the preparation of hybrid nanofluid most researchers adopted two step method.

There are mainly two techniques used to produce nanofluids: the one-step and the two-step method. One-step technique combines the production of nanoparticles and dispersion of nanoparticles in the base fluid into a single step. There are some variations of this technique. In one of the common methods, named direct evaporation one-step method, the nanofluid is produced by the solidification of the nanoparticles, which are initially in gaseous phase, inside the base fluid. The single-step direct evaporation approach was developed by Akoh et al. [12] and is called the Vacuum Evaporation onto a Running Oil Substrate (VEROS) technique. The original idea of this method was to produce nanoparticles, but it is difficult to subsequently separate the particles from the fluids to produce dry nanoparticles. Another one step is laser ablation method, which has been used to produce alumina nanofluids [13]. Zhu et al. [14] also used a one-step pure chemical synthesis method to prepare nanofluids of copper nanoparticles dispersed in ethylene glycol.

The two-step method is extensively used in the synthesis of nanofluids considering the available commercial nano powders supplied by several companies. In this method, nanoparticles are first produced and then dispersed in the base fluids. Jeena et al. [15] prepared nanocomposites from chemically prepared reactant mixtures using hydrogen reduction technique and dispersed it in base fluid (distilled water) using two step method. Nanofluid was prepared by dispersing a specified amount of nanoparticles in deionized water with sodium lauryl sulfate (SLS) as dispersant by using an ultrasonic vibrator [16]**.** Preparation methods of various nonmetallic and metallic nanofluids and hybrid nanofluids reported in the literature are discussed below.

2.1. Alumina nanofluids

Alumina is the most cost effective and widely used material in the family of engineering ceramics [17]. Beck et al. [18] prepared Al_2O_3/ethylene glycol in ultrasonic mixing for several minutes to obtain uniform dispersion. They reported that the resulting dispersions remained uniform for the duration of the experiments because of the surface charges on the particles. Jung et al. [19] produced two types of water-based alumina nanofluids with/without polyvinyl alcohol (PVA), using a horn-type ultrasonic disrupter for 2 h. The PVA concentration was set to be the same as the nanoparticle concentration. They found that the particles in the prepared nanofluids with/without PVA were below 300 nm, and the aggregated particles were stably suspended for more than 1 month. Hung et al. [20] produced Al_2O_3/water nanofluid using a homogenizer operating at 8000 rpm for 30 min, an electromagnetic agitator running at 600 rpm for 90 min, and an ultrasonic vibrator operating at 400 W for 60 min. The base liquid was prepared by adding 0.2 wt% of water-soluble Chitosan as a cationic dispersant to distilled water. They confirmed that the difference between initial and final concentrations (after 2 weeks) of Al_2O_3/water nanofluid was less than 5% indicating the stability of the prepared nanofluids. Singh et al. [21] dispersed two sizes Al_2O_3 nanoparticles produced by vapor condensation techniques in ethylene glycol and water. The alumina–water nanofluids were stabilized through electro-static method; a few drops of hydrochloric acid were mixed to maintain the pH value and zeta potential. The pH value was fixed at 4 and the zeta potential for these nanofluids was 58.7 mV. They concluded that a pH of 3.5–5.0 was able to keep the nanofluids stable for a long times. For Ethylene Glycol based nanofluids, nothing was added and it was found that only sonication is enough to get a stable suspension. Esmaeilzadeh et al. [22] stabilized alumina water nanofluids through a 4 h process of ultrasonication with 170 W and 50 Hz and electromagnetic stirring. No sedimentation was observed throughout the testing period.

2.2. Aluminum nitride nanofluids

Aluminum nitride (AlN) is a nontoxic newer material in the technical ceramics family. While its discovery occurred over 100 years ago, it has been developed into a commercially viable product with controlled and reproducible properties within the last 20 years. AlN is one of the typical ceramics that have special properties such as high thermal conductivity (8–10 times that of Al_2O_3) low dielectric coefficient (about 8.15), high electrical resistance, corrosion and erosion resistance and low density. Because of these properties it is used in various engineering applications and has attracted the intense interest of researchers. However, till date very few results concerning AlN nanofluids have been reported in the literature [17]. Hu et al. [23] were the first to disperse AlN nanoparticle, produced by plasma arc in the gas phase into ethanol with castor oil as a dispersant to improve suspension stability. The suspension was then stirred with a high speed magnetic stirrer. The resulting suspension was placed in an ultrasonic homogenizer for 10 min. It was observed that the prepared sample can remain stable for more than 2 weeks without settling.

2.3. Zinc oxide nanofluids

Raykar and Singh [24] synthesized water soluble ZnO nanoparticles. The solutions were sonicated for 1 h and a proper amount of acetylacetone (acac) was added as a dispersant to the solutions, which were sonicated again for 10 min. They found that the nanofluids were stable over 9 months to 1 year, and the size of ZnO nanoparticles was reduced from 150 nm to 80 nm due to the reaction. Kole and Dey [25] dispersed fairly agglomerated ZnO nanoparticles in ethylene glycol by intense ultrasonication (200 W). The cluster size of ZnO nanoparticles in suspension was plotted against sonication time to ascertain the optimum time of sonication. It was observed that ZnO clusters size rapidly decreases from 459 nm to 91 nm between 4 and 60 h. However, beyond 60 h of sonication, cluster size increased and for 100 h of sonication ZnO clusters increased to 220 nm. Therefore, an optimum duration for sonication was chosen to be 60 h. As a result, the suspension was stable for 30 days without any trace of visible sedimentation.

Suganthi and Rajan [26] synthesized zinc oxide nanoparticles by chemical precipitation method using zinc nitrate hexahydrate as precursor. The ZnO-water nanofluid was prepared with the aid of ultrasonication for 3 h and stabilization using sodium hexametaphosphate (SHMP) as a dispersant. A predetermined quantity of ZnO was added to the surfactant solution under high shear homogenization and homogenized for 20 min at 7000 rpm, followed by ultrasonication for 180 min (750 W and 20 kHz). Surfactant: nanoparticle ratio was fixed at 1:5. The obtained higher values of absolute value of zeta potential ensured higher colloidal stability of dispersions, which was confirmed through visual observation as well. Moattar and Majdan-Cegincara [27] dried ZnO nanoparticles in an electrical oven at about 110 °C for 24 h prior to use for removing adsorbed water moisture on the surface. The nanoparticles were dispersed in poly ethylene glycol and its aqueous solutions using sonication. It was found that the average particle size measured for the nanofluids investigated was much larger than the size of primary particles. It was also found that ZnO–PEG nanofluid was stable at least for 140 min.

2.4. Titanium dioxide nanofluids

Titanium dioxide has three types of crystal habits which are brookite, anatase and rutile. Brookite is one kind of unstable crystal, with no industrial value, while anatase and rutile have stable properties, which are very important white pigment. Compared with other white pigments, it is well accepted for its super whiteness, tinting strength, covering power, durability, heat resistance, chemical stability, and especially without any toxicity [17]. Utomo et al. [28] prepared diluted 30–40 wt% of alumina–distilled water and titania–distilled water nanofluid whilst keeping pH constant, and ultrasonicating the suspension for 3 min to obtain homogenous mixtures. It was reported that according to the manufacturer, the alumina and titania suspensions were stabilized by using octyl silane and ammonium polyacrylate respectively. It was observed that even after sonication, nanoparticles formed relatively large aggregates with the size of the order of 200 nm and 140 nm for alumina and titania, respectively. Longo and Zilio [29] verified the dispersion efficiency of Al_2O_3–water (15 wt %) and TiO_2–water (25 wt%) nanofluids, that were prepared and mixed by the supplier. Each nanofluid was subdivided into two parts: the first was subjected to mechanical stirring, and the second was sonicated at 25 kHz for 48 h. It was concluded that the ultrasound treatment shows better dispersion efficiency than simple mechanical stirring, and that both nanofluids showed stability for more than one month.

2.5. Silicon dioxide nanofluids

Silica is a widely used ceramic material both as a precursor to the fabrication of other ceramic products and as a material on its own. Silica has good abrasion resistance, electrical insulation and high thermal stability [17]. Fazeli et al. [30] dispersed SiO_2 nanoparticles in distilled water, and then the suspension was sonicated by an ultrasonic bath for at least 90 min. They found that silica nanofluids stayed stable for a period of 72 h without any visible settlement. Pang et al. [31] mixed nanoparticles of Al_2O_3–pure methanol and SiO_2–pure methanol by using ultrasonic vibration (750 W, 20 kHz) for 2 h to break down the agglomeration. They studied the effect of nanoparticle concentration on the zeta potential and pH of methanol-based nanofluids. They showed that zeta potential is highly related to the pH of the suspension. The measured zeta potential of Al_2O_3 nanofluids was over 60 mV, and the zeta potential of SiO_2 nanofluids was over 30 mV, which indicates the good stability of both nanofluids. The photos of visualization and Tyndall effect (study of light scattering in nanoparticles) showed that methanol based nanofluids were well dispersed. Bolukbasi and Ciloglu [32] prepared SiO_2 nanofluids by using magnetic stirrer. Then, the suspensions were transferred into an ultrasonic vibrator (600 W and 40 kHz) and sonicated continuously for 2 h. The researchers reported that no sedimentation was observed during the period of experiment. Darzi et al. [33] added distilled water to a specified amount of SiO_2 nanoparticles and mixed together by magnetic stirrer for half an hour. After that, it was dispersed by ultrasonic vibrator for 2 h to get the stable suspension. No surfactant/dispersant additives were added during the synthesis process, which otherwise affected the thermophysical properties of nanofluid.

2.6. Iron oxide nanofluids

Abareshi et al. [34] synthesized magnetic nanoparticles of hematite, α-Fe_2O_3 by solvothermal method using $Fe(NO_3)_3$ as a starting material. The nanoparticles were dispersed in glycerol using an ultrasonic processor at 20 kHz and 700 W for 30 min. Also the measured zeta potential for $\o = 2\%$ vol was -41.7 mV at pH = 12.8 indicating that Fe_3O_4 nanofluids have good dispersion and stability. From the many literatures it can be seen that the nanoparticles synthesized by chemical precipitation method can be well dispersed by using only sonication for 2 h [35].

2.7. Copper nanofluids

Essentially, high resistance to corrosion makes copper as an ideal metal for heat exchangers of all kinds, including solar water heating systems [17]. Kathiravan et al. [36] prepared copper nanoparticles by the sputtering method. Then the nanoparticles were dispersed in water and water with 9.0% of sodium dodecyl sulfate (SDS) anionic surfactant using an ultrasonic bath for about 10 h. It was found that the nanoparticles were dispersed in water evenly even after 10 h of ultrasonic vibration with some agglomerates. The mentioned copper nanofluids cannot be stable for more than one month. Also they reported that the stability is dependent on pH value, sonication time, volume fraction, nanoparticle size and type, base fluids, surfactants and nanofluid production methods.

2.8. Carbon nanotubes and nanofluids

Nanoparticles could be either spherical or cylindrical. Carbon nanoparticles of cylindrical form are called carbon nanotubes (CNT). One type of carbon nanotube is called multiwalled carbon nanotubes (MWCNT) because they have multiple concentric tubes in a single configuration [37]. One of the critical steps in preparing carbon nanofluids is dispersing carbon nanotubes in the base fluid. Due to the high aspect ratio of carbon nanotubes and strong Van der Waal's forces between carbon surfaces, dispersion of CNT in aqueous medium can be challenging. CNTs are hydrophobic in nature and thus cannot be dispersed in water under normal conditions. There are usually two methods to disperse carbon nanotubes in base fluids: mechanical and chemical [38].

Surfactants are used to disperse carbon nanotubes in several cases. Some examples of previously used surfactants are sodium dodecyl sulfate (SDS), sodium dodecyl benzene sulfonate (SDBS), hexadecyltrimethyl ammonium bromide (CTAB) and Nanosperse AQ. Through studies, it was found that SDBS failed at elevated temperatures [39]. Additionally, Gum Arabic (GA) was found to be a better surfactant than sodium dodecyl sulfate (SDS) and cetyltrimethylammoniumchloride (CTAC) for dispersing carbon nanotubes in DI water [40]. CNTs have attracted many researchers due to their higher thermal conductivity and very high aspect ratio. Carbon nanotubes have strength and stiffness properties several thousand times better than that of steel and conductivity better than copper, carbon nanotubes has extraordinary intrinsic electrical, thermal and mechanical properties making them potentially attractive materials for use in different fields [17]. Su et al. [41] modified the surface of CNTs with nitric acid; One gram of CNTs was suspended in 40 ml of concentrated nitric acid and refluxed for an hour at 120 °C. After washing with deionized water until the supernatant attained a pH value is 7, the CNTs were dried at 55 °C. Then, the chemically treated CNTs were added directly into the base fluid. The suspension was agitated for 2 h by ultrasonic applicator, with the frequency of 100 kHz. It was found that almost all of pristine CNTs (PCNTs) with 0.2 wt% deposited, having upper fluid transparent. In sharp contrast to PCNTs, Chemically treated CNTs (TCNTs) were well dispersed in aqueous ammonia. Meibodi et al. [42] synthesized carbon nanotubes by catalytic decomposition of 20% methane in hydrogen over Co–Mo/MgO catalysts at 800–1000 °C. They reported that a typical process to make nanofluid stable for months involves sonicating a functional single walled nanotubes (FSWNTs) sample in ultrasonic bath for over 2 h, or disruptor for 30 min and dispersing the sonicated FSWNTs into a preset amount of distilled water and adjusting the suspension to a preset pH level. Lamas et al. [43] functionalized the MWCNTs produced by the chemical vapor deposition method. The pristine MWCNTs were refluxed at 413 K in nitric and sulfuric acid at 1:3 volume ratio for 30 min, followed by exhausting wash with distilled water (DW) until no signs of acidity and dried in an oven at 373 K, for at least 72 h, to evaporate the humidity. The functionalized MWCNTs were dispersed in 50 ml of base fluid with a magnetic stirrer combined with ultrasonication for 60 min. It was observed that after 24 h, the sedimentation rate was slow and constant.

2.9. Gold and silver nanofluids

Metal nanoparticles such as gold (Au) and silver (Ag) have recognized importance in chemistry, physics, and biology because of their unique optical, electrical, and photo thermal properties. Such nanoparticles have potential applications in analytical chemistry and have been used as probes in mass spectroscopy, as well as in colorimetric detection for proteins and DNA molecules. The ease of synthesizing Au and Ag nanoparticles and their affinity for binding many biological molecules, makes them attractive candidates for study [17]. Parametthanuwat et al. [44] prepared silver nanofluids using an ultrasonic bath at 43 kHz for 3 h. It was found that the stability was up to 48 h. Hajian et al. [45] produced silver in DI-water nanofluid by a chemical method which consists of a reduction of Ag ions. The nanofluids were put in an ultrasonic bath for about 15 min before injection into the heat pipe. Moreover, Ag–deionized water nanofluids prepared using multi-pulse laser ablation in liquid approach was stable for several months without using dispersant [46]. Tamjid and Guenther [47] used a colloid of silver nanoparticles produced by the vacuum evaporation on running liquids (VERL) at volumetric solids concentration of 4.37%. The colloid was stirred and agitated systematically for 5 min by an ultrasonic agitator in continuous mode to ensure uniform dispersion of the nanoparticles in diethylene glycol. Lo et al. [48] prepared silver nanofluid by the submerged arc nanoparticles synthesis system (SANSS). They observed that the nanoparticles were well dispersed in deionized water after using ultrasonic vibration for 15 min. Paul et al. [49,50] synthesized nano-gold and silver dispersed water based nanofluids by wet chemical bottom up approach. It was revealed that uniform distribution, chemical nature (metallic) or purity of the gold nanoparticles and color of the nanofluid remained unchanged without sedimentation or agglomeration even after 48 h. They also noted that gold and silver-citrate or Au-thiolate nanofluids can be kept stable for a period of several months. Some of the details of preparation of nanofluids are summarized on Table 1.

2.10. Preparation of hybrid nanofluids

Hybrid nanomaterials exhibit remarkable physico chemical properties that do not exist in the individual components. A single material does not possess all the favorable characteristics required for a particular purpose; it may either have good thermal properties or rheological properties. But in many practical applications, it is required to trade-off between several properties and that is where the use of hybrid nanofluid comes. In this section the reported methods of preparation of hybrid nanofluids is presented. Shehata et al. [66] used mechanochemical method with two different routes to synthesize the Cu–Al_2O_3 nanocomposite powders. The first route was carried out by addition of Cu to aqueous solution of aluminum nitrate and second route was also carried out by addition of Cu to aqueous solution of aluminum nitrate and ammonium hydroxide. In both routes, the mixtures were heated in air, reduced in hydrogen atmosphere and milled mechanically to get ultra fine powder oxides of CuO and Al_2O_3. Nanocrystalline alumina–copper hybrid (Al_2O_3–Cu) powder was prepared by a thermochemical synthesis method through the following stages: spray-drying, oxidation of precursor powder, reduction in hydrogen atmosphere and homogenization. Soluble nitrates of copper

Table 1
Summary on preparation of nanofluids.

Researchers	Particle material and shape	Base fluid	Parameters	Surfactant/ pH control	Nanofluid stability
Hu et al. [23]	AlN approximately spherical	Ethanol	ø=0.5–4 vol%, D=20 nm	Castor oil	Stable for more than two weeks.
Choi et al. [51]	AlN spherical Al_2O_3, rod-shape spherical.	Transformer oil	ø ≤ 4 vol%, D=20 nm, D=2 nm × 20–200 nm, D=13 nm	Oleic acid	Sedimentation was very clear for non-filtered Al_2O_3 nanofluid after one month.
Moosavi et al. [52]	ZnO approximately spherical	EG	ø ≤ 3 vol %	Ammonium citrate	Stable for several months.
Mo et al.[53]	Rutile TiO_2 (rod-shape), anatase TiO_2 (spherical)	DI-water (deionized water)	ø=0.05, 0.3, 0.7 wt% D=15 nm, D=20 nm × 50 nm	SDS	Nanofluids kept stable for 286 h.
Fedele et al. [54]	TiO_2[a]	Bidistilled water	ø=1%, 10%, 20%, 35 wt%	Acetic acid	Stable suspension for 35 days using sonication.
Rohini Priya et al. [55]	CuO nonspherical	Water	ø=0.016 vol%, length to thickness ratio 10	Tiron	Stability was confirmed through visual observation.
Selvakumar and Suresh [56]	CuO[a]	DI-water	ø=0.1% and 0.2 vol% D= 27–37 nm	Nil	Nanofluids were stable after a week except very little sedimentation.
Suresh et al. [57]	Al_2O_3 nearly spherical	DI-water	ø=0.3,0.4 and 0.5 vol% D=40.3 nm	Nil	The nanofluid was very stable for several weeks without visually observable sedimentation.
Hegde et al. [58]	Al_2O_3 spherical	DI-water	ø=0.1–0.5 g/l, D= 80 nm	Nil	No agglomeration formed two hours after sonication.
Phuoc and Massoudi [59]	Fe_2O_3[a]	DI-water	ø=1–4 vol% D= 20–40 nm	PVP	Nanofluids were stable for about two weeks.
Kathiravan et al. [36]	Cu polycrystalline	DI-water	ø=0.25,0.5 and 1.0 wt% D=10 nm	SDS	Nanoparticles were dispersed in water evenly even after 10 hours.
Byrne et al. [60]	CuO[a]	DI-water	ø=0.005%, 0.01% and 0.1 vol%	CTAB	Suspension was much stable when using surfactant.
Sonawane et al. [61]	Al_2O_3[a]	ATF	ø=0.1– 1 vol%, D= 50 nm	Oleic acid Tween-20 LR	The solution was found to be stable even after 24 h.
Meng et al. [62]	CNTs[a]	Glycol	ø=0.5%–4 wt%	Nil	Nanofluids could remain stable for more than two months without sedimentation.
Kumaresan and Velraj [63]	CNTs[a]	DI-water – EG	ø=0.25–1.0 vol%, D xH= 30–50 nm × 10–20 μm	SDBS	Nanofluid was stable for more than 3 months.
Yu et al. [64]	Fe_3O_4[a]	Kerosene	ø=0–1.0 vol%, D=15 nm	Oleic acid	Nanofluids were stable.
Paul et al. [50]	Au spherical	Water	ø=0.6×10^{-4} to 2.6×10^{-4} vol% D=21 nm	Nil	No sedimentation or agglomeration even after 48 hours.
Robertis et al. [65]	Cu nearly spherical	EG	D=50 nm	PVP	The particles settlement was about 28.5% in 50 days.

[a] Shape not mentioned.

and aluminum, Cu $(NO_3)_2 \cdot 3H_2O$ and Al $(NO_3)_3 \cdot 9H_2O$ were the starting material. The water solution of the above mentioned salts was first prepared. The proportions of the precursor salts were decided so that the relative proportion of alumina and copper oxide in the powder mixture was 90:10. The above solution was spray dried at 180 °C to obtain the precursor powder. The precursor powder was then heated at 900 °C in air atmosphere for 60 min to form a powder mixture of copper oxide and stable Al_2O_3. The alumina–copper oxide powder mixture thus formed was heated at 400 °C for 1 h in hydrogen atmosphere using a tubular furnace. The powder sample was placed in an alumina boat and then kept in a horizontally placed alumina tube of the furnace which was heated by silicon carbide heating elements. The CuO was preferentially reduced in hydrogen to metallic copper whereas Al_2O_3 remains in the unchanged form. The powder mixture was finally ball milled at 400 rpm for 1 h for obtaining a homogeneous Al_2O_3–Cu nanocomposite powder.

Suresh et al [5] prepared Al_2O_3–Cu hybrid particles by hydrogen reduction technique from the powder mixture of Al_2O_3 and CuO in 90:10 weight proportions obtained from a chemical route synthesis. Al_2O_3–Cu/water hybrid nanofluids with volume concentrations from 0.1% to 2% were then prepared by dispersing the synthesized nanocomposites powder in deionised water. The average grain size of the hybrid particles was calculated to be 15 nm using Scherrer formula.

From the present study, it is clear that, though several nanofluid preparation methods for same or different nanoparticles have been followed, producing homogeneous nanofluids with long-term stability and negligible agglomeration without affecting the thermo-physical properties remains a challenge. Sonication time, optimum value of surfactant and pH are the key factors to make a nanofluid homogeneous and long-term stable with negligible agglomeration. Some researchers sonicated the nanofluid just to ensure stability for the duration of the experiment and some researchers prepared the nanofluids without using surfactants or adjusting pH value. The use of surfactants during synthesis of nanofluid is an important technique to enhance nanoparticle stability in base fluids. However, the functionality of surfactants at different temperatures needs to be thoroughly examined. In some research works, the zeta potential, an indicator of nanofluid

Table 2
Characterization techniques.

Researchers	Particles/base fluids	Characterization techniques used	Results
Nader Nikkam et al. [67]	SiC/water, EG	SEM,TEM,XRD, DLS, FT-IR and Zeta potential analysis	A detailed physico-chemical evaluation showed different characteristics of Silicon carbide (SiC) Nanoparticles NPs, including crystal structure, primary/dispersed particle size, surface functionality, surface charge, and purity levels of SiCNPs used for revealing its promising characteristics for heat transfer applications.
Majid Moosavi et al. [52]	ZnO/EG, glycerol	SEM,TEM,XRD	The samples were stable for several months; it is found that no agglomeration and sedimentation of the particles in the samples. The shape of ZnO nanoparticles is approximately spherical.
Vasant SR, Joshi MJ [68]	Calcium pyrophosphate dihydrate (CPPD)	TEM,XRD,TGA, FT-IR, dielectric study	CPPD nanoparticles were synthesized using surfactant mediated approach. The peak broadening in powder-XRD pattern suggested the nanostructured nature with triclinic system and the average particle size was estimated to be 4 nm. From the TEM, it was confirmed that the particle size varied between 13 nm and 20 nm. Heating of t-CPPD nanoparticles at 900 °C and 1250 °C temperatures in a muffle furnace yielded β-CPP and α-CPP phases of CPP, respectively, this was confirmed by Powder XRD. FTIR study confirmed the presence of pyrophosphate bonds, metal–oxygen bonding and O–H bond in the structure.
Liu et al. [69]	CNTs / EG, Engine oil	TEM,SEM,XRD	Randomly oriented fiber-like CNTs are clearly seen from SEM and TEM. An individual CNT is several microns long. Its inner diameters are about 5–10 nm, and outer diameters are about 20 nm to 50 nm. The peak in XRD image indicates the graphitic structure of the CNTs. The CNT dispersed in base fluid can form an extensive three dimensional CNT network that facilitates thermal transport. It is essential for thermal management.
Abareshi et al. [34]	Fe_3O_4/DI-water	XRD, TEM, FT-IR,VSM	The following techniques were used to characterize the structure, size, purity, and magnetic properties of the nanoparticles. The best crystallinity was observed for MN4 sample (pH initial is 1.5 and pH final is 9.5). The results reveal that the saturation magnetization (M_s) value increases with increase in the crystallinity and particle size.
Sharma et al. [70]	Ag/ EG	TEM,EDX,XRD, UV–vis spectroscopy, Zeta potential analyzer	Stability of silver nanofluid is strongly affected by the characteristics of the suspended particle and base fluid such as the particle morphology, the chemical structure of the particles and base fluid. The result of UV–vis spectroscopy reveals that when the PAA-co-AA/$AgNO_3$ ratio increase, the particle size decreases. The particle size distribution shows better dispersion behavior in the suspension with the addition of dispersant from zeta potential analysis.
Gayatri Paul et al. [71]	Al 5 wt% of Zn/EG	TEM,SEM,XRD, EDS	The SEM and TEM studies show that most of the particles are spherical in shape with a narrow size distribution range of 10–30 nm. XRD studies suggest that the mechanical alloying product is a complex compound having an empirical formula of $Al_{0.403}Zn_{0.597}$ with anorthic crystal structure. EDS analysis suggests that the initial elemental composition (Al–5 wt%Zn) is maintained in the mechanical alloyed product. Absence of any other elemental peak in the EDS pattern confirms the purity of the mechanically alloyed compound.
Raghu Gowda et al. [72]	Al_2O_3/DI-water, EG	TEM	In TEM images the alumina and copper oxide nanoparticles were shown that the alumina nanoparticles are roughly spherical in shape but copper oxide nanoparticles show some deviations from spherical shapes. The size of alumina nanoparticles spans a wide range (from a few nm to 55 nm) but copper oxide nanoparticles do not have very small size particles.

stability and stability period has not been reported. Thus, advanced techniques, including the one-step method, are to be developed to produce homogeneous and stable nanofluids at low cost.

3. Characterization of nanofluids

In this section, the characterization techniques that are commonly used by researchers to characterize nanofluids are discussed. The nanofluids are characterized by the following techniques: SEM, TEM, XRD, FT-IR, DLS, TGA and zeta potential analysis. SEM analysis is carried to study the microstructure and morphology of nanoparticles or nanostructured materials, TEM is like SEM but much higher resolution than SEM. XRD images are taken to identify and study the crystal structure of nanoparticles. FT-IR spectroscopy is done to study the surface chemistry of solid particles and solid or liquid particles, DLS analysis is performed to estimate the average disperse size of nanoparticles in the base liquid media and TGA is performed to study the influence of heating and melting on the thermal stabilities of nanoparticles. Zeta potential value is related to the stability of nanoparticle dispersion in base fluid. Some of the characterization analyses reported in literatures are listed in Table 2.

Review of characterization studies reveals that the important information like nanoparticle size, shape, chemical bonds, distribution and stability are found from characterization techniques. But, different researchers used different set of techniques and there are no recommended standard tests which would confirm the homogenous and stable nanofluid. There should be standard accelerated tests to confirm the long term stability of dispersed nanoparticles in base fluid.

4. Properties of nanofluids

The properties of nanofluids mainly based on five parameters: thermo fluids, heat transfer, particles, colloid and lubrication. Thermo fluid property includes temperature, viscosity, density, specific heat and enthalpy. Based on the heat transfer are thermal conductivity, heat capacity, Prandtl number and pressure drop. The parameters based on particles are size, shape, BET (Surface area analysis) and crystalline phase. Based on the colloidal properties are suspension stability, Zeta potential and pH. The final properties based on lubrication were viscosity, viscosity index, friction co-efficient, wear rate and extreme pressure. The main properties of nanofluids are discussed in detail. The physical properties of nanofluids are quite different from the base fluid. Density, specific heat and viscosity are also changed which enhance the heat transfer coefficient exceeding the thermal conductivity enhancement results as reported in some experimental studies.

4.1. Thermal conductivity

Since thermal conductivity is the most important properties responsible for enhanced heat transfer and many experimental works have been reported on this aspect. The experimental results have pointed out the improvement of thermal conductivity with the addition of nanoparticle [73]. The Maxwell model was the first model to determine the thermal conductivity of liquid–solid suspensions. The model is applicable for statistically homogeneous and low volume fraction liquid–solid suspensions with random dispersed, uniformly sized, and non interacting spherical particles. The effective thermal conductivity is [73],

$$k_{eff} = \frac{k_p + 2k_f + 2(k_p - k_f)\varnothing}{k_p + 2k_f - (k_p - k_f)\varnothing} k_f \tag{1}$$

The transient hot wire method is extensively used to measure thermal conductivity of nanofluids because the nanofluids are generally electrically conductive and it is difficult to apply in the transient wire method. A modified hot-wire cell and electrical system was proposed by Nagasaka and Nagashima in 1981 by coating the hot wire with an epoxy adhesive which has excellent electrical insulation and heat conduction [74]. Liu et al. [69] measured the thermal conductivity of nanofluids containing CNTs dispersed in ethylene glycol and synthetic engine oil. The increase of thermal conductivity is up to 12.4% for CNT–ethylene glycol suspensions at 1.0 vol% and 30% for CNT-synthetic engine oil suspensions at 2 vol%. The higher thermal conductivities and the larger specific surface area of CNT have big impacts on thermal conductivity. The CNT dispersed in base fluid can form an extensive three dimensional CNT network that facilitates thermal transport. The highest thermal conductivity enhancement is seen in CNT nanofluids.

Eastman et al. [75] reported an experimental study on the thermal conductivity of ethylene glycol-based nanofluids containing copper nanoparticles. The nanofluid exhibited an anomalously increased effective thermal conductivity. The thermal conductivity increased up to 40% for nanofluids consisting of 0.3% (by volume) of Cu nanoparticles of a mean diameter less than 10 nm dispersed in ethylene glycol. Garg et al. [76] measured the thermal conductivity of Cu nanoparticles in ethylene glycol and also found an anomalous increase, i.e., the measured increase in conductivity was twice the predicted value by the Maxwell–Garnett (MG theory) [77]. Chopkar et al. [78] were the first to show experimentally that the effective thermal conductivity of $Al_{70}Cu_{30}$ nanofluids strongly depends on the nanoparticle size. This is a significant feature of nanofluids. In addition, their study shows a nonlinear relationship between the effective thermal conductivity and the particle size in the particle diameter range of 10–80 nm. Their data clearly show steeper size dependence in the small particle size range.

Vladkov and Barrat [79] simulated the thermal properties of nanofluids by using the molecular dynamics (MD) simulations. Based on their simulation results, they conclude that the Brownian motion of the particle does not affect the cooling process and that the Maxwell–Garnett model can predict the effective thermal conductivity of nanofluids. They also concluded that the essential parameter that influences the effective thermal conductivity is the ratio of the Kapitza length to the particle radius and that the large heat transfer enhancements observed in nanofluids comes from aggregation effects, such as particle clustering and percolation or cooperative heat transfer modes.

The platinum hot wire, for instance, is both expensive and brittle. Thus, it is extremely difficult to measure the thermal conductivity of adhesives, fluids with large Prandtl numbers, fluids in extreme temperature environments and nanofluids without risk of damage to the sensor during sample handling and testing. In order to measure the thermal conductivity of these types of materials without risk of damage to the equipment, research groups have increasingly turned to the transient hot disk system. In addition to being a robust and rapid thermal characterization method, the transient hot disk apparatus is able to determine both the thermal diffusivity and thermal conductivity of fluids and solids, which are important to characterize for materials used in transient applications, such as thermal energy storage materials [80–82]. The transient hot disk technique, like the transient hot-wire technique, utilizes a volume element (sensor) that serves as both a heat source and a temperature sensor. The sensor must be fully immersed in a fluid or sandwiched between two solid samples in order to measure thermal conductivity. In principle, when the sensor is powered, its temperature will increase rapidly when immersed or sandwiched between insulating materials and increase slowly for thermally conductive materials [83].

A very recent study carried out by Yu et al [84] in nanofluids containing graphene oxide nanosheets (GON) shows significantly higher thermal conductivities than the base fluids. The thermal conductivity (k) enhancement at a particle loading of 5.0 vol% was 30.2%, 62.3% and 76.8%, for the base fluids of distilled water, propyl glycol and liquid paraffin respectively. The same group has reported $\frac{k}{k_f}$ beyond effective medium theory (EMT) predictions in EG based GON nanofluids, where a maximum thermal conductivity (k) enhancement of 61% was observed at a particle loading of 5.0 vol% [85]. Another very recent study carried out by Yu et al [86] shows a significant thermal conductivity (k) enhancement in nanofluids containing grapheme nanosheets in EG i.e. 86% increase in k for 5.0 vol% of grapheme nanosheets. Jang et al. [87] proposed a theoretical model that involves the following four modes contributing to energy transfer for enhancing the thermal conductivity of nanofluids: (i) collision between the base fluid molecules, (ii) thermal diffusion in nanoparticles, (iii) collision of nanoparticles with each other due to the Brownian motion, and (iv) collision between the base fluid molecules and nanoparticles by thermal induced fluctuations. It still needs further research to develop a sophisticated theory to predict thermal conductivity of nanofluids [88].

Suresh et al. [89] reported that the thermal conductivity of Al_2O_3–Cu/water hybrid nanofluids significantly increases almost linearly with increasing particle volume concentration. This linear relationship between the measured thermal conductivity ratio and volume concentration was because of the formation of larger particle-free regions in the liquid that offer greater thermal resistances by the agglomerated particles. The thermal conductivity enhancements of Al_2O_3–Cu/water hybrid nanofluid are 1.47%, 3.27%, 6.22%, 7.53%, and 12.11%, corresponding to volume concentrations of 0.1%, 0.33%, 0.75%, 1% and, 2% respectively compared with deionised water. Thermal conductivity enhancements of the hybrid nanofluids are greater than that of alumina/water nanofluids, for the corresponding volume concentrations 0.5%, 1.31%, 3.27%, 5.36% and 7.56%. Researchers have developed different thermal conductivity models for nanofluids and are listed in Table 3.

In literatures, there are many models for thermal conductivity of same or different nanofluids which indicates that thermal conductivity depends on many factors such as particle size, shape, distribution, the levels of agglomeration/clustering, surface properties and dynamics of nanoparticles such as particle motion, surfactants, and interactions with base fluids. The proposed mechanisms of the thermal conductivity of nanofluids lack a complete understanding of the scientific basis for these mechanisms. More experiments with well-dispersed, well-characterized nanofluids and a better understanding of the physics of fluid flow and heat transfer at the nanoscale level are needed to establish the underlying mechanisms of heat transfer in nanofluids. Comprehensive science-based models including the particle material, size, shape and temperature that are capable of accurately predicting the thermal conductivity of nanofluids.

4.2. Viscosity

Viscosity is a measure of the tendency of a liquid to resist flow. It is the ratio of the shear stress to shear rate. When the viscosity is constant at different values of shear rate, the liquid is known as Newtonian while that varies as a function of shear rate then the liquid is known as non-Newtonian [89]. Einstein [99] was the first to calculate the effective viscosity of a suspension of spherical solids using the phenomenological hydrodynamic equations. Garg, Poudel, Chiesa et al. [76] conducted an experiment to test the viscosity of copper nanoparticles in ethylene glycol and found that the increase in viscosity was about four times of that predicted by

Table 3
Various thermal conductivity models.

Thermal conductivity models	Remarks
Jang and Choi model [90] $\boldsymbol{k_{nf}} = \boldsymbol{k_f}(1-\varnothing)+\boldsymbol{k_p}\varnothing+3\boldsymbol{C}_1\frac{d_f}{d_{nano}}\boldsymbol{k_f}\boldsymbol{Re}^2_{dnano}\boldsymbol{P_r}\varnothing$ where, $\boldsymbol{\beta}=0.01$, $\boldsymbol{C}_1=18\times10^6$ is a proportional constant	The first mode is collision between base fluid molecules, the second mode is the thermal diffusion in nanoparticles and the third mode is neglected because it is much smaller than the other modes in the model, and the fourth mode is collision between base fluid molecules and nanoparticles by thermally induced fluctuations. Reported that model could be used for nanofluids containing oxide, metallic and carbon nanotubes.
Chon et al. [91] $\frac{\boldsymbol{k_{nf}}}{\boldsymbol{k_f}} = 1+64.7\varnothing^{0.746}\left(\frac{d_f}{d_p}\right)^{0.369}\left(\frac{k_p}{k_f}\right)^{0.7476}\boldsymbol{P_r}^{0.9955}\boldsymbol{R_e}^{1.2321}$	Model for temperature and particle size effects based on measurements of Al_2O_3/water nanofluids.
Yu and Choi [92] $\frac{\boldsymbol{k_{nf}}}{\boldsymbol{k_f}} = \frac{\boldsymbol{k_{pe}}+2\boldsymbol{k_b}+2(\boldsymbol{k_{pe}}-\boldsymbol{k_b})(1+\beta)^3\varnothing}{\boldsymbol{k_{pe}}+2\boldsymbol{k_b}-(\boldsymbol{k_{pe}}-\boldsymbol{k_b})(1+\beta)^3\varnothing}$	Modified Maxwell model to account for the nanolayer effect. The new model including the nano-layer can predict the presence of very thin nano-layers having a thickness less than 10 nm. Then $\beta = h/r$ is the ratio of the nano-layer thickness to the original particle radius.
Mintsa et al. [93] $\frac{\boldsymbol{k_{nf}}}{\boldsymbol{k_f}} = 1.72\varnothing+1.0$	Particle volume fraction ($\varnothing$) correlation can be found by simple linear regression. It is obtained for water/ Al_2O_3 nanofluids. The relationship has 95% of R^2 value. The model is applicable for 47 nm Al_2O_3 nanofluids.
Yamada and Ota [94] $\boldsymbol{k_{eff}} = \frac{\frac{k_p}{k_b}+\boldsymbol{K}-\boldsymbol{K}\varnothing(1)-\boldsymbol{k_p}/(\boldsymbol{k_b})}{\frac{k_p}{k_b}+\boldsymbol{K}+\varnothing(1)-\boldsymbol{k_p}/(\boldsymbol{k_b})}\boldsymbol{k_b}$	Proposed the unit-cell model for the effective thermal conductivity of mixture for carbon nanofibers. Where, K is the shape factor and $K = 2\,\phi^{0.2}\,(l_p/d_p)$ for the cylindrical particles, and l_p and d_p are the length and diameter of the cylindrical particle.
Nan et al. [95] $\boldsymbol{k_{eff}} = 1+\varnothing\frac{k_p}{3k_b}\boldsymbol{k_b}$	Generalized the Maxwell–Garnett approximation and derived a simple formula to predict the effective thermal conductivity of carbon-nanotube-based composites. The results within Nan's model agree well with the experimental observations.
Kumar et al. [96] $\boldsymbol{k_{eff}} = \boldsymbol{k_b}+c\,\frac{2\boldsymbol{k_B}\,\boldsymbol{T}}{(\pi\nu \boldsymbol{d_p^2})}\,\frac{\varnothing \boldsymbol{r_b}}{\boldsymbol{k}_b\,{}_{(1-\varnothing)}\boldsymbol{r_p}}\boldsymbol{k_b}$	Comprehensive model to account for the large enhancement of thermal conductivity in nanofluids and its strong temperature dependence, which was deduced from the Stoke Einstein formula it may not be suitable for high concentrations of particles where interparticle interactions become important.
Li and Peterson [97] $\frac{(\boldsymbol{k_{eff}}-(\boldsymbol{k_b}))}{\boldsymbol{k_b}} = 0.764\varnothing+0.0187(\boldsymbol{T})-(273.15)-0.462$	Model for water/copper oxide nanofluids which relate nanofluid effective thermal conductivity to temperature and nanoparticle volume fraction. The developed relationships cover a relatively small temperature range from 27 °C to 36 °C for particle volume fractions (2%, 6% and 10%).
Massimo Corcione [98] $\frac{\boldsymbol{k_{eff}}}{\boldsymbol{k_f}} = 1+4.4\boldsymbol{R_e}^{0.4}\boldsymbol{P_r}^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_f}\right)^{0.03}\varnothing^{0.66}$	Model for the ease of application of the equations proposed, and their wide regions of validity (the ranges of the nanoparticle diameter, volume fraction and temperature are 10–150 nm, 0.002–0.09 and 294–324 K) for the thermal conductivity data, make such equations useful from the engineering point of view, for both numerical simulation purposes and thermal design tasks.

the Einstein law of viscosity given by

$$\frac{\mu}{\mu_{bf}} = 1 + 2.5\varphi \quad (2)$$

Where $\mu$the viscosity of the nanofluid, μ_{bf} the viscosity of the base fluid, and φ the nanoparticle volume fraction.

Chen et al. [100] measured the volume fraction and temperature effects on viscosity for multiwalled carbon nanotubes (MWCNT's) with distilled water for a temperature range of 5–65 °C. They reported that viscosity increases accordingly with nanoparticle loadings when the volume fraction is higher than 0.4 vol%. Also, relative viscosity increases significantly with temperature after 55 °C. Li et al. [101] measured the viscosity of water with CuO nanoparticles suspensions using a capillary viscometer. Results showed that the apparent viscosity of nanofluids decreased with increasing temperature. However, as they pointed out, the capillary tube diameter may influence the apparent viscosity for higher nanoparticles mass fractions, especially at lower temperatures. Wang et al. [102] also measured the relative viscosity of Al_2O_3–water and Al_2O_3–ethylene glycol nanofluids. Results showed similar trend of increase of relative viscosity with increased solid volume fraction for the two nanofluids. That means the desirable heat transfer increase may be offset by the undesirable increase in pressure drop.

In the experimental investigation of Suresh et al. [89], the Al_2O_3–Cu/water hybrid nanofluid is prepared by dispersing Al_2O_3–Cu nanoparticles in water. The concentration of particles varied from 0.001 to 0.02. It is well known that water is a Newtonian fluid because it continues to exemplify fluid properties no matter how fast it is stirred or mixed. Since the experimental results with the nanofluids also showed a linear relationship between the applied shear stress and the rate of shear, it is concluded that the addition of nanoparticles to water with volume concentration ranging from 0.001 to 0.02 do not change the Newtonian behavior of water. From the experimental results the viscosity of the hybrid nanofluid increases with volume concentrations. The increase in viscosity of the Al_2O_3–Cu/water hybrid nanofluids for volume concentrations 0.1%, 0.33%, 0.75%, 1%, 2% are 8%, 22%, 54%, 78%, 115% respectively when compared to viscosity of water. It can also be understood that the difference between viscosity of the Al_2O_3–Cu/water hybrid nanofluids and that of Al_2O_3/water nanofluid at lower volume concentrations is very less while this difference is very significant

Table 4
Various viscosity models.

Viscosity models	Remarks
Vand [103] $\mu_{eff} = (1) + 2.5\varnothing_p + 7.349\varnothing_p^2 + \ldots)\mu_b$	Model for spherical nanoparticles.
Brinkman [104] $\mu_{nf} = \mu_f \frac{1}{(1-\varnothing)^{2.5}}$	Model for simple hard sphere systems, the relative viscosity increases with particle volume fraction ($\varnothing$) and it is applicable to moderate particle volume concentration roughly 4%.
Frankel and Acrivos [105] $\mu_{eff} = \frac{9}{8}\frac{(\varnothing_p)/\varnothing_{pmax})^{\frac{1}{3}}}{1-(\varnothing_p)/\varnothing_{pmax})^{\frac{1}{3}}}\mu_b$	Model is valid for spherical nanoparticles and for $0.5236 \le \varphi \le 0.7405$.
Batchelor [106] $\mu_{eff} = (1 + 2.5\varnothing_p + 6.2\varnothing_p^2)\mu_b$	Model includes the effect due to the Brownian motion of particles on the bulk stress of an approximately isotropic suspension of rigid and spherical particles.
Wang et al. [102] $\mu_{nf} = \mu_{bf}(1 + 7.3\varnothing + 123\varnothing^2)$	Model to predict the viscosity for Al_2O_3- water and Al_2O_3- ethylene glycol nanofluids. It showed similar trend of increase of relative viscosity with increased solid volume fraction for the two nanofluids.
Tseng and Lin [107] $\mu_{eff} = (13.47e^{35.98\varnothing_p})\mu_b$	Plotted the relative viscosity against the particle concentration at shear rate $\gamma = 100^{s\text{-}1}$ and found relative viscosity increases with concentration in an exponential form for TiO_2/water nanofluids.
Namburu et al. [108] $Log\,(\mu_s) = Ae^{-BT}$ $A = 1.8375(\varnothing)^2 - 29.642(\varnothing) + 165.56$ with $R^2 = 0.9873$ $B = 4\times10^{-6}(\varnothing)^2 - 0.001(\varnothing) + 0.0186$ with $R^2 = 0.988$	Correlation to measure viscosity for CuO/ethylene glycol and water mixture, the size of the nanoparticle is 29 nm with different volume concentrations (1%, 2%, 3%, 4%, 5% and 6.12%). The temperature ranges from −35 °C to 50 °C. where *A* and *B* are constants.
Masoumi et al. [109] $\mu_{nf} = \mu_{bf} + \frac{\rho P V_B d_p^2}{72C\delta}$	Model for nanofluids viscosity prediction based on Brownian motion. The model could be used to calculate the effective viscosity in terms of temperature, the mean particle diameter, the nanoparticle volume fraction, the nanoparticle density and the base fluid physical properties. The model is applicable for 13 nm and 28 nm Al_2O_3/water nanofluids. Fluid consisting of two different fluids also can be predicted by this model.
Massimo Corcione [98] $\frac{\mu_{eff}}{\mu_f} = \frac{1}{1-34.87\left(\frac{d_p}{d_f}\right)^{-0.3}\varnothing^{1.03}}$	Correlation for predicting the relative viscosity for Al_2O_3/water nanofluids. d_f is the equivalent diameter of a base fluid molecule.
Nguyen et al. [110] ***i***) $\mu_{nf} = \mu_{bf} \times 0.904e^{0.1482\varnothing}$ ***ii***) $\mu_{nf} = \mu_{bf}(1 + 0.025\varnothing + 0.015(\varnothing^2))$ ***iii***) $\mu_{nf} = \mu_{bf}(1.475 - 0.319\varnothing + 0.051\varnothing^2) + 0.009(\varnothing^3)$	i) Correlation for Al_2O_3/water nanoparticles and size of the particle is 47 nm. ii) Correlation for Al_2O_3/water nanoparticles and size of the particle is 36 nm. The two models determine the viscosity by only considering the viscosity of the base fluid and the particle volume fraction. iii) Correlation for CuO/water nanoparticles.

at higher volume concentrations. Some of the theortical viscosity models proposed by researchers are presented in Table 4.

This review shows that the viscosity of nanofluid depends on many parameters such as base fluid properties, particle volume fraction, particle size, particle shape, temperature, pH value, surfactants, dispersion techniques, particle size distribution, particle aggregation and temperature. The viscosity models discussed here are generally applied to measure the viscosity of nanofluids. However, the criterion for validating their results with experimental results and limitations still need more attention. Further work is required to determine new models for viscosity of nanofluids with different materials and to understand the effect of viscosity variation on natural convection heat transfer.

4.3. Convective heat transfer

The enhancement of the heat transfer coefficient is a better indicator than the thermal conductivity enhancement for nanofluids used in the design of heat exchanger equipment.

Heris et al. [111] did experiments with Al_2O_3 and CuO nanoparticles in water under laminar flow up to turbulence. He found that more heat transfer enhancement as high as 40% with Al_2O_3 particles while the thermal conductivity enhancement was less than 15%. Putra et al. [112] presented the experimental observations on the natural convection of two oxides (Al_2O_3 and CuO)–water based nanofluids inside a horizontal cylinder heated from one end and cooled from the other. The results of forced convection, they found a systematic and definite deterioration of the natural convective heat transfer, which was dependent on the particle density, concentration, and the aspect ratio of the cylinder. The reason for this effect is unclear. The role of particle-fluid slip and sedimentation seems to be important which requires to be investigated more closely in the future. The deterioration increased with particle concentration and was more significant for CuO nanofluids. Xuan and Li [113] presented an experimental investigation on the convective heat transfer and flow feature of nanofluids. In their experiments, a CuO–water nanofluid was used with the particle concentrations varying between 0.3% and 2% volume fraction and the flows being turbulent. The greater heat transfer enhancement was found to be more than 39% at 2% particle volume fraction. They found that they studied single-phase flow for the turbulent flow and developed the heat transfer correlation from the experimental data. The correlation is

$$N_u = 0.0059\left(1.0 + 7.6286\varnothing_p^{0.6886}\right)\left(Pe_p^{0.001}\right)R_e^{0.9238}P_r^{0.4} \quad (3)$$

The Rayleigh number decreases in the Nusselt number previously presented in the experimental work by Putra et al. [112] founded that different results between numerical and experimental for that clarification in the numerical study presented by Khanafer et al. [114] some important factors were not included. These factors include the particle size, particle shape, and particle distribution, which could significantly influence the flow and heat transfer characteristics of nanofluids. However, these factors have not been investigated properly. Summary of experiments on forced and free convective heat transfer of nanofluids are listed in Tables 5 and 6.

Nanofluids are shown to have great potential for heat transfer enhancement and are highly suited for application in different heat exchangers. According to the majority of experimental and theoretical studies, suspensions of nanoparticles significantly enhance heat transfer and the heat transfer coefficient of nanofluids is found to be larger than that of its base fluid both under natural and forced convection heat transfer. The enhanced heat transfer potential of the base liquids will offer an opportunity for engineers to develop highly compact and effective heat transfer equipment for many industrial applications, including transportation, nuclear reactors, electronics cooling, and biomedical. Additionally, increasing the volume fraction of solid nanoparticles increases the heat transfer of nanofluids.

4.4. Density

Density of nanofluid is proportional to the volume ratio of solid (nanoparticles) and liquid (base fluid) in the system. Since the density of solids is higher than that of the liquids, generally the density of nanofluid is found to increase with addition of nanoparticles to the fluid. In the absence of experimental data, the density of the nanofluids has been reported to be consistent with the mixing theory [127] given by

$$\rho_{nf} = (1-\phi)\,\rho_{bf} + \phi\,\rho_s \quad (4)$$

where, ρ_{nf} *is the* density of nanofluid, ρ_{bf} is the density of base fluid, ρ_s is the density of solid particles, ϕ is the volume concentration.

Sommers and Yerkes [128] measured the density of the Al_2O_3/propanol nanofluid at room temperature using two methods and compared them. In the first method, a hydrometer was used to measure the specific gravity of a fluid sample. In the second method, a fluid sample of known volume was taken and then weighed on a high precision balance. Data collected using these two methods were then averaged and a nearly linear relationship between density and particle concentration was observed.

There are a few limited works and hence correlations for density of nanofluids. Further experimental works should be conducted to develop a comprehensive model including the dependence of density on nanoparticle size, shape, temperature and surfactant.

4.5. Specific Heat

Zhou and Ni [129] have presented an experimental investigation of the specific heat of water-based Al_2O_3 nanofluid with a differential scanning calorimeter. Their result indicates that the specific heat of nanofluid decreases gradually as the nanoparticle volume concentration increases. The relationship between them exhibits good agreement with the prediction from the thermal

Table 5
Experimental studies on forced convective heat transfer of nanofluids.

Authors	Dimensions	Nanofluids	Findings
Chien et al. [115]	Disk-shaped heat pipe (D=9mm, H=2mm)	Au/water (17 nm)	Significant reduction of thermal resistance.
Ding et al. [116]	tube (D=4.5, L=970 mm)	CNT/water	Significant enhancement of convective heat transfer, which depends on the flow condition,CNTconcentration and the pH level.
Yang et al. [117]	tube (D=4.57, L=457 mm)	graphite nanofluid	The enhancement of h is lower than the increase of the effective thermal conductivity.
Heris et al. [111]	annular tube ($D_{in=}$1 mm, D_{out}=32 mm, L=1 m)	Al_2O_3 (20 nm), CuO (50–60 nm)/water	Enhancement of h with Ø and Pe. Al_2O_3 showed more enhancement than CuO.

Table 6
Experimental and theortical studies of natural convection of nanofluids.

Authors	Particles/base fluids	Experimental/theortical study	Observations
Jang and Choi [118]	Cu and diamond/water	Theortical	The nanofluids are more stable and have larger heat transfer coefficient compared with a classical fluid.
Kim et al. [119]	Cu and Ag/water	Theortical	Heat transfer coefficient of a nano fluid is enhanced by all parameters with respect to the volume fraction.
Corcione [120]	Cu, $Al_2O_{3,}$ TiO_2/water and EG	Theortical	The heat transfer enhancement increases with increasing the nanoparticle volume fraction up to an optimal particle loading and increases with increasing the aspect ratio at which the amount of heat transferred across the enclosure has a peak.
Jahanshahi et al. [121]	SiO_2/water	Experimental	The mean Nusselt number increases with volume fraction for the whole range of Rayleigh numbers.
Putra et al. [112]	CuO,Al_2O_3/water	Experimental	A systematic degradation of natural convective heat transfer with increasing particle concentration for a given Rayleigh number.
Wen and Ding [122]	TiO_2/water	Experimental	Nanofluids decrease the natural convective heat transfer coefficient, such deterioration increases with nano particle concentrations.
Nnanna [123]	Al_2O_3/water	Experimental	Nusselt increased with small volume fraction $0.2 \le ø \le$ 2% and no significant change in Nusselt number is observed in the range $2\% \le ø \le$ 7.9%.
Li and Peterson [124]	Al_2O_3/water	Experimental	The heat transfer rate was found increasingly deteriorated with the volume fraction of the nanoparticles.
Ho et al. [125]	Al_2O_3/water	Experimental	Systematic heat transfer degradation for the nanofluid containing nanoparticles of $ø \ge 2\%$ over the entire range of Rayleigh number.
Chen et al. [126]	Titanate nanotube/ water	Experimental	Convective heat transfer enhancement was higher than that of thermal conductivity. Particle shape plays a major role.

equilibrium model while the simple mixing model fails to predict the specific heat of nanofluid. Mansour, Galanis, and Nguyen [130] plotted both functions as a ratio to the specific heat of the base fluid with respect to the nanoparticle concentration in the nanofluid. They were not sure which correlation was correct, so they assumed both to be valid, but Zhou and Ni [129] investigated both correlations more closely, and found that it was valid. Their results for alumina nanoparticles in water mimic those of Mansour, Glanis, and Nguyen. In an experimental work the specific heat is calculated as

$$C_{p\ nf} = \frac{\varnothing\, \rho\, (C_p)_p + (1+\varnothing)\rho C_{pf}}{\rho_{nf}} \tag{5}$$

where, $(\rho C_p)_p$ is the density and specific heat of particle, $(\rho C_p)_f$ is the density and specific heat of fluid, $(\rho C_P)_{\ nf}$ is the density and specific heat of nano fluid.

Sekhar and Sharma [131] mentioned that, more studies on temperature-dependent specific heat capacity over a wide range of nanoparticle size and concentration combinations have to be conducted to get the results. Teng and Hung [132] investigated the deviation between the calculated and experimental results of the specific heat and density of Al_2O_3–water nanofluids with 0.5, 1.0 and 1.5 wt% of the nanoparticles and added 0.2 wt% of dispersant (Chitosan) in all mixtures. They found good agreement with calculated and experimental value for 0.5 wt% of Al_2O_3 nanoparticles in water. The deviation of specific heat is in the range of −0.07% to 5.88% and −0.35% to 4.94%, respectively. The calculated results of density and specific heat show a trend of greater deviation as the concentration of nanofluid increases. It may be due to specific surface area, interface layer, grain size, porosity and adsorption. The various specific heat models reported in literatures are given in Table 7.

From this study, it is found that volume fractions, temperature and different types and sizes of nanoparticles and base fluids have significant effects on specific heat of nanofluids. Specific heat of the most of the common nanofluids decreases with the increase of volume fractions while increases with the increase of temperature. Knowledge of the specific heat of the base fluids and nanoparticles is needed to get nanofluid with a desired specific heat capacity.

4.6. Pressure drop

There are only limited theoretical and experimental studies on pressure drop of nanofluid. Further, equations that can model and estimate the pressure drop in nanofluid are to be formulated.

Sajadi and Kazemi [141] were experimentally investigated turbulent heat transfer behavior of TiO_2/water nanofluid in a circular pipe under fully developed turbulent regime for various volumetric concentrations. Their measurements showed that the pressure drop of nanofluid was slightly higher than that of the base fluid and increased with increasing the volume concentration. Peng et al. [142] showed that the frictional pressure drop of refrigerant based nanofluid (R113 refrigerant and CuO nanoparticle) increases with the increase of the mass fraction of nanoparticles, and the maximum enhancement of frictional pressure drop was 20.8% under their experimental conditions. Razi et al. [143] conducted an experimental investigation on the pressure drop and thermal characteristics of CuO-base oil nanofluid under laminar flow in flattened tubes at constant heat flux. For a given flattened tube and at a same flow conditions, there is a noticeable increase in heat transfer coefficient as well as pressure drop of nanofluids compared to that of base liquid. Nanofluids have better heat transfer characteristics when they flow in flattened tubes rather than in the round tube. Compared to pure oil flow, Maximum heat transfer enhancement of 16.8%, 20.5% and 26.4% is obtained for nanofluid flow with 2 wt%. concentration inside the round tube and flattened tubes with internal heights of 8.3 mm and 6.3 mm, respectively.

Tun-Ping Teng et al. [144] carried out an experimental investigation on the pressure drop of TiO_2/water nanofluid in circular pipes. It was reported that the traditional equations for pressure drop failed because of the enhancement and temperature rise. The proportional increase in pressure drop for turbulent flow is lower than that for laminar flow. Recent experimental investigation on viscous pressure loss characteristics of alumina–water and zirconia–water nanofluids in laminar flow regime by Rea et al. [145] also showed that their test results were in good agreement with prediction from conventional correlation for laminar flow. Provided that the loading and temperature-dependent thermophysical properties of the nanofluids are utilized in the evaluation of the dimensionless numbers. In other words, no abnormal heat

Table 7
Specific heat models of nanofluids.

Specific heat models	Remarks
Pak and Cho [127] $C_{pnf} = \varnothing C_{ps} + (1-\varnothing) C_{pbf}$ *Where* C_{pnf} *– Specific heat of the nanofluid,* C_{ps} *- specific heat of the solid nanoparticle,* $\varnothing$ *the particle volumetric concentration and* C_{pbf} *-specific heat of the base fluid.*	Model for calculating the specific heat capacity of nanofluids which is based on the mixing theory of ideal gas mixtures. The model is based on γ-Al_2O_3 (13 nm) and TiO_2 (27 nm) in water. It is found that specific heat is decreased with the increase of particles volume concentrations.
Ghazvini et al. [133] $C_p = 2.62 - 6\times10^{-3}T + 2\times10^{-5}T^2$	Correlation for the specific heat of nanofluids with 1%weight fraction of Nanodiamond in engine oil as a function of temperature ($278\text{ K} \le T \le 373\text{ K}$) and polynomial goodness of fit $R^2 = 0.994$ (residual degrees of freedom adjusted). Specific heat of all fluids increases with increasing temperature, and it can also be seen that nanofluids with higher weight fractions have higher specific heats. The result shows that the addition of nanodiamond in engine oil the specific heat significantly increases about 20%.
Xuan and Roetzel [134] $C_{pnf} = \frac{\varnothing\rho_s C_{ps} + (1+\varnothing)\rho_{bf} C_{pbf}}{\rho_{nf}}$	Modified correlation by assuming thermal equilibrium between the nanoscale solid particles and the liquid phase by rewriting the above Pak and Cho equation to include the density.
Vajjha and Das [135] $\frac{C_{pnf}}{C_{pbf}} = \frac{\left((A\times T) + B\times\left(\frac{C_{ps}}{C_{pbf}}\right)\right)}{(C+\varnothing)}$ Where, *A,B,C* – Curve fit coefficients Vajjha and Das [136] $\frac{C_{pnf}}{C_{pbf}} = \frac{\left(A\left(\frac{T}{T_o}\right) + B\left(\frac{C_{pp}}{C_{pbf}}\right)\right)}{(C+\varnothing)}$ Where, *A,B,C* – Curve fit coefficients	Correlation for the specific heat as a function of particle volumetric concentration, temperature, and the specific heat for three types of nanoparticles with base fluids. Al_2O_3 (44 nm) and ZnO (77 nm) particles suspended in 60/40% by mass of EG–water mixture, and SiO_2 (20 nm) particles suspended in deionized water. Results showed that the specific heat of all three types of nanofluids decreased when the concentration increased. The specific heat increased when the temperature increased. Modified correlation was developed to measure specific heat of SiO_2, Al_2O_3, CuO nanofluids for 2% volume concentration.
Zhou et al. [137] $C_{pnf} = \frac{(1-\varnothing)\rho_f C_{pf} + \varnothing\rho_{np} C_{pnp}}{\varnothing_f\rho_f + (1-\varnothing)\rho_{np}}$	Correlation to measure the specific heat and volumetric heat capacity of CuO–EG nanofluids at a concentration range of 0.1–0.6 vol%. They concluded that when concentration increased, the specific heat of CuO–EG decreased gradually.
Shin and Banerjee [138] Thermal equilibrium model (also known as the "mixture rule") $C_{p,t} = \frac{\rho_{np}\varnothing_{np} C_{p,np} + \rho_s\varnothing_s C_{p,s}}{\rho_{np}\varnothing_{np} + \rho_s\varnothing_s}$ Shin and Banerjee [139] $C_{p,t} = \frac{\rho_{np}\varnothing_{np} C_{p,np} + \rho_s\varnothing_s C_{p,s} + \rho_{ns}\varnothing_{ns} C_{p,ns}}{\rho_{np}\varnothing_{np} + \rho_s\varnothing_s + \rho_{ns}\varnothing_{ns}}$	Correlation to measure the specific heat of nanofluids which were used in solar thermal energy storage. Silica nanoparticles (1 wt%) suspended in a eutectic of lithium carbonate and potassium carbonate mixture (62/38% by weight). The silica nanoparticles with an average size of 35 nm were tested in a temperature range of 525–555 °C using a differential scanning calorimeter. They found that the specific heat of nanofluids increased by about 19–24% when compared with the base fluid. Temperature had little effect on the change of the specific heat of nanofluids. In comparison with the previous study using silica nanoparticles in the same salt eutectic (Li_2–CO_3–K_2CO_3) almost similar enhancement in specific heat capacity was observed by both the models. First model is a traditional mixture rule model. Second model is a chain like nanostructure formation taken into account for salt-based nanofluids. Quantifying ρ_{ns}, ϕ_{ns}, and C_{pns} needs further investigation since they are not easy to measure using current technology.
Pakdaman et al. [140] $\frac{Cp_{bf} - Cp_{nf}}{Cp_{bf}} = (0.0128\times T + 1.8382)\varnothing^{0.4779}$ *Where* $\varnothing$ *is the weight concentration (0, 0.001, 0.002 or 0.004), and T is the temperature ranging from 313 K to 343 K.*	Correlation based on the least square method to predict the specific heat capacity of the MWCNT/heat transfer oil nanofluid. Dispersing nanoparticles in the base fluid results in a decrease in the specific heat capacity of the fluid. The specific heat capacity of 0.4 wt% nanofluid is almost 42% less than that of the base fluid at 40 °C.

transfer enhancement or pressure loss was observed within measurement errors.

Suresh et al. [5] experimentally measured the pressure drops of the hybrid nanofluid in a tube at different flow rates for laminar flow under isothermal conditions. The pressure drop (Δp) measured across the test section is used to calculate the friction factor. The friction factor variation with Reynolds number in laminar flow for Al_2O_3–Cu/water hybrid nanofluid was studied. The result shows that higher friction factor of hybrid nanofluids when compared to pure water, 0.1% Al_2O_3–Cu/water hybrid nanofluids show slightly higher friction factor when compared to 0.1% Al_2O_3/water nanofluid. It is because of the higher viscosity of the hybrid nanofluid compared to that Al_2O_3/water nanofluid. The average increase in friction factor of 0.1% Al_2O_3–Cu/water hybrid nanofluids is 16.97% when compared to water. For the same volume concentration, Al_2O_3/water nanofluid showed an average of 6% increase in friction factor. This reveals that dilute Al_2O_3–Cu/water hybrid nanofluids will cause extra penalty in pumping power when compared to Al_2O_3/water nanofluid.

More systematic experiments are to be carried out to develop correlations of friction factor and heat transfer for flow of nanofluids through tubes. Furthermore, the effect of the tube geometry (e.g., flat, elliptical or circular) on the hydrodynamics and heat transfer in a tube and heat exchanger need to be understood.

5. Application of nano fluids

Experimentally and theoretically nanofluids have been shown to possess improved heat transport properties and higher energy efficiency in a variety of thermal exchange systems for different industrial applications, such as transportation, electronic cooling, energy storage, mechanical applications etc. Nanofluid plays a vital role in all applications which lead to a major impact in developing next generation of equipment for numerous engineering and medical applications. Some of the applications are discussed below.

5.1. Automobile applications

The addition of nanoparticles and nanotubes to the standard engine coolants (water mixture and ethylene glycol) and lubricants to form nanofluids can increase their thermal conductivity, and give the potential to improve the heat exchange rates and fuel efficiency. The above improvements can be used to reduce the size of the cooling systems or remove the heat from the vehicle engine exhaust in the same cooling system [146]. Tzeng et al. [147] have conducted research to study the effects of nanofluids in the cooling of automatic transmission. They dispersed CuO and Al_2O_3 nanoparticles and antifoam agents in the transmission fluid, and then, the transmission fluid was used in real time four wheel automatic transmissions. The results show that CuO nanofluids have the lowest temperature distribution at both high and low rotating speed and accordingly the best heat transfer effect. A vehicle's kinetic energy is dispersed through the heat produced during the process of braking and this is transmitted throughout the brake fluid in the hydraulic braking system [148] and now there is a higher demand for the properties of brake oils. CuO and aluminum-oxide based brake nanofluids were manufactured using the arc-submerged nanoparticle synthesis system and the plasma charging arc system [149,150]. The two kinds of nanofluids have enhanced properties such as a higher boiling point, higher viscosity, and a higher conductivity than that of traditional brake fluid. By yielding a higher boiling point, conductivity, and viscosity, the nanofluid brake oil will reduce the occurrence of vapor-lock and offer increased safety while driving [151].

5.2. Solar applications

The temporal difference of energy source and energy needs made necessary the development of storage system. The storage of thermal energy as in solar thermal systems in the form of sensible and latent heat has become an important aspect of energy management with the emphasis on efficient use and conservation of the waste heat and solar energy in industry and buildings [152]. The nanofluids PCMs possessed remarkably high thermal conductivities compared to the base material. Liu et al. [153] prepared a new sort of nanofluid phase change materials (PCMs) by suspending small amount of TiO_2 nanoparticles in saturated $BaCl_2$ aqueous solution. The nanofluids PCMs possessed remarkably high thermal conductivities compared to the base material. The cool storage/supply rate and the cool storage/supply capacity all increased greatly than those of $BaCl_2$ aqueous solution without added nanoparticles. The higher thermal performances of nanofluids PCMs indicate that they have a potential for substituting conventional PCMs in cool storage applications. Copper nanoparticles are efficient additives to improve the heating and cooling rates of PCMs. Shin and Banerjee [138] reported the anomalous enhancement of specific heat capacity of high-temperature nanofluids. They found that Alkali metal chloride salt eutectics when doped with silica nanoparticles at 1% mass concentration increases the specific heat capacity of the nanofluid by 14.5%, so that this material can be a suitable one to use in solar thermal-energy storage facilities. One of techniques of storing solar energy is the application of PCMs. Among lots of PCMs available, paraffin is the most suitable due to its desirable characteristics, including large latent heat capacity, negligible super cooling and low cost. However, the inherent low thermal conductivity (0.21–0.24 W/mK) strongly prevents possible applications [154]. Wua et al. [154] numerically investigated the melting processes of Cu/paraffin nanofluids PCMs. Their results revealed that with 1 wt% Cu/paraffin, the melting time can be saved by 13.1%. Therefore, they concluded that adding nanoparticles is an efficient technique to enhance the heat transfer in latent heat thermal energy storage system.

Solar energy plays a vital role in energy application due to shortage of electricity productions. The perceived shortage of fossil fuels as well as environmental considerations will constrain the use of fossil fuels in the future. Therefore, researchers are motivated to find alternative sources of energy. This has become even more popular as the price of fossil fuels continues to rise. In recent years, the use of solar energy has had a remarkable edge. The earth receives in just about 1 h more energy from the sun than that consumed by the entire world for one year [155,156].

Solar collectors are particular kind of heat exchangers that transform solar radiation energy into internal energy of the transport medium. These devices absorb the incoming solar radiation, convert it into heat, and transfer the heat to a fluid (usually air, water, or oil) flowing through the collector. The energy collected is carried from the working fluid, either directly to the hot water or space conditioning equipment or to a thermal energy storage tank, from which it can be drawn for use at night or on cloudy days [157].

Taylor et al. [158] compared a nanofluid-based concentrating solar thermal system with a conventional one. Their results show that the use of a nanofluid in the receiver can improve the efficiency by 10%. They also concluded that for 10–100 MWe power plants, using graphite/therminol VP-1 nanofluid with volume fractions approximately to 0.001% or less could be beneficial. The researchers estimated that combining a nanofluid receiver with a solar thermal power tower with the capacity of 100 MWe operating in a solar resource like Tucson, Arizona, could generate $3.5 million more per year.

In arid remote regions in the world, the provision of fresh water is more critical. In these regions, solar desalination systems can solve part of the problem where solar energy is available. In developing countries, lack of safe and unreliable drinking water constitutes a major problem. Worldwide drought and desertification are expected to increase the drinking water shortage to become one of the biggest problems facing the world [159].

Solar stills can be used to avoid the greenhouse gas emissions from the production of fresh water [160]. Many researchers have carried out research work on solar stills, and different methods are applied to improve their productivity. Gnanadason et al [161] reported that using nanofluids in a solar still can increase its productivity. They investigated the effects of adding carbon nanotubes (CNTs) to the water inside a single basin solar still. Their results revealed that adding nanofluids increases the efficiency by 50%. But, they have not mentioned the amount of nanofluid added to the water inside the solar still. Regarding the addition of nanofluids to the solar still, the economic viability should be considered. In literature, some works reported that adding dyes to solar stills could improve the efficiency. Nijmeh et al. [162] reported that adding violet dye to the water inside the solar still increases the efficiency by 29%, which is considerable. On the other hand, it is evident that nanofluids (especially CNTs) compared to dyes are more expensive, hence this may be a challenge on using nanofluids in solar stills, because in this type of use of nanofluids in solar stills the nanofluids have no flow in a closed loop so that they could be recovered.

5.3. Mechanical applications

5.3.1. Friction reduction

Tribological research greatly emphasizes reducing friction and wear. Advanced lubricants can improve productivity through energy saving and reliability of engineered systems. Nanoparticles have attracted much interest in recent years due to their excellent load carrying capacity, good extreme pressure and friction reducing properties. Zhou et al. [163] evaluated the tribological behavior of Cu nanoparticles in oil on a four-ball machine. The results showed that Cu nanoparticles as an oil additive had better friction-reduction and antiwear properties than zinc dithiophosphate, especially at high applied load. Meanwhile, the nanoparticles could also noticeably improve the load-carrying capacity of the base oil. Dispersion of solid particles was found to play an important role, especially when a slurry layer was formed. Water-based Al_2O_3 and diamond nanofluids were applied in the minimum quantity lubrication (MQL) grinding process of cast iron. During the nanofluid MQL grinding, a dense and hard slurry layer was formed on the wheel surface and could benefit the grinding performance. Nanofluids showed the benefits of reducing grinding forces, improving surface roughness, and preventing workpiece burning. Compared to dry grinding, MQL grinding could significantly reduce the grinding temperature [164].

5.3.2. Magnetic sealing

Comparing with the mechanical sealing, magnetic sealing offers a cost-effective solution to environmental and hazardous-gas sealing in a wide variety of industrial rotation equipment with high speed capability, low friction power losses and long life and high reliability [165]. Magnetic fluids (Ferromagnetic fluid) are kinds of special nanofluids. They are stable colloidal suspensions of small magnetic particles such as magnetite (Fe_3O_4). The properties of the magnetic nanoparticles, the magnetic component of magnetic nanofluids, may be tailored by varying their size and adapting their surface coating in order to meet the requirements of colloidal stability of magnetic nanofluids with non-polar and polar carrier liquids [166]. Mitamura et al. [167] studied the application of a magnetic fluid seal to rotary blood pumps. The developed magnetic fluid seal worked for over 286 days in a continuous flow condition, for 24 days in a pulsatile flow condition and for 24 h in blood flow. Ferro-cobalt magnetic fluid was used for oil sealing, and the holding pressure is 25 times as high as that of a conventional magnetite sealing [168].

5.4. Other applications

5.4.1. Reactor-heat exchanger

The discovery of high enhancement of heat transfer in nanofluids can be applicable to the area of process intensification of chemical reactors through integration of the functionalities of reaction and heat transfer in compact multifunctional reactors [151]. Fan et al. [169] studied a nanofluid based on benign TiO_2 material dispersed in ethylene glycol in an integrated reactor-heat exchanger. The overall heat transfer coefficient increase was up to 35% in the steady state continuous experiments. This resulted in a closer temperature control in the reaction of selective reduction of an aromatic aldehyde by molecular hydrogen and very rapid change in the temperature of reaction under dynamic reaction control.

5.4.2. Optical application

Optical filters are used to select different wavelengths of light. The ferrofluid based optical filter has tunable properties. The desired central wavelength region can be tuned by an external magnetic field. Philip et al. [170] developed a ferrofluid based emulsion for selecting different bands of wavelengths in the UV, visible and IR regions. The desired range of wavelengths, bandwidth and percentage of reflectivity could be easily controlled by using suitably tailored ferrofluid emulsions. Mishra et al. [171] developed nanofluids with selective visible colors in gold nanoparticles embedded in polymer molecules of polyvinyl pyrrolidone (PVP) in water.

5.4.3. Nanofluid detergent

Wasan and Nikolov [172] were able to use reflected-light digital video microscopy to determine the mechanism of spreading dynamics in liquid containing nanosized polystyrene particles. They were able to demonstrate the two dimensional crystal-like formation of the polystyrene spheres in water and how this enhances the spreading dynamics of a micellar fluid at the three-phase region. The above authors also performed an additional experiment where they introduced an electrolyte into the process in order to decrease the interfacial tension at the interface of the oil and the nanofluid, but found that the drop did not become detached from the surface. They actually observed a diminished disjoining pressure contrary to the logical prediction. Additional work must be done in this area to determine such behavior of the nanofluid. Overall, this phenomenon which involves the increased spreading of the detergent surfactants, which are not only limited to polystyrene nanoparticles, and enhanced oil removal process offers a new way of removing stains and grease from surfaces. This type of nanofluid also has potential in the commercial extraction of oil from the ground as well as the remediation of oil spills [173].

5.4.4. Biomedical applications

For some special kinds of nanoparticles, they have antibacterial activities or drug-delivery properties, so the nanofluids containing these nanoparticles will exhibit some relevant properties [151]. Organic antibacterial materials are often less stable particularly at high temperatures or pressures. As a consequence, inorganic materials such as metal and metal oxides have attracted lots of attention over the past decade due to their ability to withstand harsh process conditions. The antibacterial behavior of ZnO nanofluids shows that the ZnO nanofluids have bacteriostatic activity against *Escherichia coli* (*E. coli*). The antibacterial activity increases with increasing nanoparticle concentration and increases with decreasing particle size. Electrochemical measurements suggest some direct interaction between ZnO nanoparticles and the bacteria membrane at high ZnO concentrations [174]. Jalal et al. [175] prepared ZnO nanoparticles via a green method. The antibacterial activity of suspensions of ZnO nanoparticles against *E. coli* has been evaluated by estimating the reduction ratio of the bacteria treated with ZnO. Survival ratio of bacteria decreases with increasing the concentrations of ZnO nanofluids and time. The antibacterial activity of silver nanoparticles was found to be dependent on the size of silver particles. A very low concentration of silver as low as 1.69 mug/mL Ag gave antibacterial performance [176]. Lyon and Alvarez [177] proposed that C60 suspensions exerted reactive oxygen species ROS-independent oxidative stress in bacteria, with evidence of protein oxidation, changes in cell membrane potential, and interruption of cellular respiration. This mechanism requires direct contact between the nanoparticle and the bacterial cell and differs from previously reported nanomaterial antibacterial mechanisms that involve ROS generation (metal oxides) or leaching of toxic elements (nanosilver).

5.4.5. Electronics cooling

The power dissipation of IC (integrated circuits) and microelectronic components has dramatically increased due to their size reduction. Better thermal management and cooling fluids with improved thermal transport properties are needed for safe operation. Nanofluids have been considered as working fluids in heat pipes for electronic cooling application. Tsai et al. [178] used a water-based nanofluid as the working medium in a circular heat pipe designed as a heat spreader to be used in a CPU in a notebook or a desktop PC. The results showed a significant reduction in thermal resistance of the heat pipe with the nanofluid as compared with deionized water. The measured results also showed that the thermal resistance of a vertical meshed heat pipe varies with the size of nanoparticles. Ma et al. [179] investigated the effect of nanofluids on the heat transport capability of an oscillating heat pipe. Experimental results showed that, at the input power of 80 W, a nanofluid containing 1 vol% nanoparticles reduced the temperature difference between the evaporator and the condenser from 40.9 °C to 24.3 °C. Lin et al. [180] investigated nanofluids in pulsating heat pipes by using silver nanoparticles, and discovered encouraging results. The silver nanofluid improved heat transfer characteristics of the heat pipes. Vafaei et al. [181] discovered that nanofluids are effective in engineering the wettability of the surface and possibly of surface tension. Using a goniometer, it was observed that even the addition of a very low concentration of bismuth telluride nanofluid dramatically changed the wetting characteristics of the surface. Concentrations as low as 3×10^{-6} increased the contact angle to over 40°, distinctly indicating that the nanoparticles change the force balances in the vicinity of the triple line.

Reported theoretical, numerical and experimental works on nanofluid show that there are many potential applications of nanofluids such as cooling in electronics, cameras, micro devices, displays, heat exchangers, spacecraft, military equipments, ships, medicine, nuclear reactors, sensors, and fuel cells. Nanofluid stability is a key challenge amongst the challenges of nanofluid for the commercialization of nanofluids. By solving the challenges, it is expected that there will be considerable developments in many applications. Further research should be done on various applications related to heat and fluids.

6. Challenges of nanofluids

Many are the issues and challenges of nanofluids that need to be addressed and overcome before this field of study can be fully established. The main issues are: (i) the disagreement between most of experimental data, as well as between the experimental findings and the theoretical model predictions (ii) the poor characterization of the nano suspensions, and (iii) the lack of understanding of the complex physical phenomena responsible for the anomalous behavior of nanofluids [182]. Preparation of nanofluids presents several challenges, both technical and financial. The main technical difficulty is in the production of a homogeneous suspension of nanoparticles, mostly because the particles always tend to aggregate due to the strong Van der Waals interactions [182,183].

The stability of nanofluids is very important for practical applications. Stability of nanofluid is strongly affected by the characteristics of the suspended particle and basefluid such as the particle morphology, the chemical structure of the particles and basefluid [184]. Therefore, there are two phenomena that are critical to the stability of nanofluid, aggregation and sedimentation. Kwak et al. [185] in their investigation on CuO–ethylene glycol nanofluid, observed that substantial enhancement in thermal conductivity with respect to particle concentration is attainable only when particle concentration is below the dilute limit, because from the rheological property it has been found that the volume fraction at the dilute limit is 0.002, which is much smaller than the value based on the shape of individual particles due to the aggregation of particles. The aggregation of particles is monitored by measuring the variation of particle size and particle size distribution with time.

The SEM or TEM are good methods to visualize nanoparticles in nanofluids; however, they are not sufficient to obtain statistical results because only from tens to hundreds particles are measured among a large number of particles. Therefore, the particle size was measured using the DLS (Dynamic Light Scattering) method to confirm the particle size over a larger sample size. When the particle size in suspension is under tens of micrometer, the particles undergo random thermal motion by Brownian motion, and the speed of the particle movement varies according to the Stokes–Einstein equation depending on the particle size. The smaller particles move faster, and the larger particles move more slowly [186].

The other main challenges of nanofluids are high production cost, anomalous high thermal conductivity, high viscosity, low specific heat and increased pressure drop as compared to the base fluid. By overcoming these challenges, commercialization of nanofluids will be feasible and successful and there will be considerable developments in many applications.

7. Conclusion

Though there are some reviews on research studies on nanofluids, this paper collectively and comprehensively reviews all aspects of nanofluids such as nanofluids preparation, characterization, properties and its applications. Among the two common methods reported to produce nanofluids, the two-step technique works well for oxide nanoparticles, while it is less successful with metallic particles as compared to the single-step method. An exclusive section on characterization study of nanofluids reviews the commonly used characterization techniques by different researchers. The various characterization tests like SEM, TEM, XRD, FT-IR, DLS, TGA and zeta potential analysis are conducted to identify the crystal structure, particle size, surface functionality and surface charge. There should be well established set of standard characterization techniques to ensure the particle size, distribution, agglomeration and stability and to have a uniformity among characterization studies of nanofluids. The properties of nanofluids mainly based on five parameters: thermo fluids, heat transfer, particles, colloid and lubrication. Thermal conductivity, viscosity and specific heat models of nanofluids are many in literatures, but only the improved nanofluid specific models are discussed here. The requirement to improve the efficiency of thermal systems relies highly on the enhancement of thermal conductivity of base fluid. Thermal conductivity of nanofluids depends on the particle volume fraction, size and shape of nanoparticles, type of base fluid and nanoparticles, pH value of nanofluids and type of particle coating. More systematic experiments with well-dispersed, well-characterized nanofluids and a better understanding of the physics of fluid flow and heat transfer at the nanoscale level are needed to establish the underlying mechanisms of heat conduction in nanofluids. Further At low temperatures, the behavior and properties of nanofluids are to be found out experimentally and it can be a new direction in the field of research work. The experimental work on viscosity, specific heat and pressure drop of nanofluid and their dependence on temperature are limited.

Stability of nanofluids is one of the key challenges hindering the widespread practical application of nanofluids. Studies showed that stability depend on pH, sonication time, different types of shapes and sizes of nanoparticles with different base fluids, nanofluid preparation methods, volume fraction and surfactants. Therefore researchers had concentrated on preparing stable nanofluids by using different surfactants, optimizing pH, temperature for different nanofluids, and by surface modification of the particles. There is no data for optimum size of nanoparticles that can give better stability and less aggregation. Furthermore, the functionality of surfactants under high temperatures is a major concern, especially for high-temperature applications.

Impregnation of single nanoparticle in base heat transfer fluid for heat transfer enhancement is a proven technology, which has led to new research works of suspending two or more metal or metal oxides or combination of both nanoparticles in the same base fluid to enhance the thermal and transport properties further and hence the heat transfer rate. It is understood from the present review that the models for the thermo-physical properties of hybrid nanofluids are yet to be formulated. In the last two decades, a lot of theoretical, numerical and experimental research works have been reported involving nanofluids in a variety of applications. However, only when the challenges associated with the theoretical understanding and models, cost and preparation of nanofluids, agglomeration, dispersion and stability of nanoparticles in base fluids, implementation of nanofluids in real systems could be realized.

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