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Review Article

Critical Review on Nanofluids: Preparation, Characterization, and Applications

Mohamoud Jama,[1] Tejvir Singh,[1] Seifelislam Mahmoud Gamaleldin,[1] Muammer Koc,[1] Ayman Samara,[2] Rima J. Isaifan,[2] and Muataz A. Atieh[2]

[1] *College of Science and Engineering, Hamad Bin Khalifa University (HBKU), Qatar Foundation, P.O. Box 5825, Doha, Qatar*
[2] *Qatar Environment and Energy Research Institute (QEERI), Hamad Bin Khalifa University (HBKU), Qatar Foundation, P.O. Box 5825, Doha, Qatar*

Correspondence should be addressed to Muataz A. Atieh; mhussien@qf.org.qa

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Heat transfer fluids are a crucial parameter that affects the size and costs of heat exchangers. However, the available coolants like water and oils have low thermal conductivities, which put many limitations to the development of heat transfer to achieve high performance cooling. The need for development of new classes of fluids which enhance the heat transfer capabilities attracted the attention of many researchers. In the last few decades, modern nanotechnology developed nanoparticles, which have unique thermal and electrical properties that could help improve heat transfer using nanofluids. A "nanofluid" is a fluid with suspended fine nanoparticles which increases the heat transfer properties compared with the original fluid. Nanofluids are considered a new generation of heat transfer fluids and are considered two-phase fluids of liquid solid mixtures. The efficiency of the fluid could be improved by enhancing its thermal properties, especially the thermal conductivity, and it is expected that the nanofluids will have a greater thermal conductivity than the base fluids. This paper reviews the preparation of metallic and nonmetallic nanofluids along with the stability of the produced nanofluids. Physical and thermal properties as well as a range of applications are also discussed in detail.

1. Introduction

Heat transfer is vital area of research and study in thermal engineering. Selection of an appropriate heat transfer fluid for heat dissipation is crucial consideration in designing heat exchangers. Heat transfer fluid (HTF) is one of the critical parameters as it affects the size and cost of heat exchanger systems. Conventional HTFs like water and oils have limited heat transfer potentialities. There is urgency to develop new group of HTFs so as to reduce cost and meet the burgeoning demand of industry and commerce. Fortunately, the advances in nanotechnology have made it possible to achieve higher efficiency and cost saving in heat transfer processes. Nanoparticles are considered to be new generation materials having potential applications in the heat transfer area.

Any host liquid, either organic or inorganic, which contains nanoparticles in a suspended state, is known as nanofluid. Nanofluids are two-phase fluids of solid-liquid mixtures and are considered to be new-generation HTFs. Recently, in near past, nanofluids have developed as promising thermal fluids for heat transfer applications. Also, the thermal conductivity of nanofluids is expected to be greater than that of the base liquids [1].

When two-phase suspensions of microparticles were tested, it was reported that they produce sedimentation and obstructions to smooth fluid flow because of channel clogging and also erosion of tube materials was noticed. However, nanofluids offer many merits over single-phase pure fluids and suspensions with microparticles. The issues of particle sedimentation, clogging of microchannel passages, and erosion of tube material are mitigated largely with nanofluids. Besides, nanofluids form stable suspensions with uniform dispersion of nanoparticles in the host fluid.

Thermophysical properties of traditional heat transfer fluids such as oils, glycols, and water are well established and are available in literature and handbooks. However, similar properties of two-phase nanofluids have not been explored extensively yet. An accurate and precise measurement of properties is essential for determination of heat transfer coefficients of nanofluids. The aptness of a particular nanofluid in a heat transfer application is then analyzed on the basis of its heat transfer performance and requirement of application. Nanofluids are considered as novel alternative, new-generation liquids, for heat energy transport and can be employed as HTFs in heat exchangers, thereby replacing pure traditional fluids. The applications of nanofluids for heat transfer include radiators in automobiles, components in chemical engineering and process industries, solar water heaters, refrigeration units, and the cooling of electronics devices. The main objective of obtaining heat transfer enhancement using nanofluids is to accommodate high heat fluxes and, hence, to reduce the cost and size of heat exchangers which, in turn, results in the conservation of energy and material.

Over the last several years, substantial research has been carried out for development of heat transfer enhancement methods. Generally, many additives have been used to ameliorate the heat transfer features of base fluids. Therefore, nanofluids may be perfectly suited in actual applications as their use may have little increases in pressure drop and may positively change the heat transfer characteristics and transport properties of the fluid. Due to the fine nature of these nanoparticles, nanofluids act as a single-phase fluid instead of dual-phase mixture.

2. Preparation of Nanofluids

Preparation of nanofluids is the first key step to synthesize fluids with improved thermal conductivity. These nanofluids are obtained by suspending nanoparticles in the range of 1–100 nm in conventional regular fluids in suitable volume fractions. Theoretically, when solid particles with high thermal conductivity are added to fluids, the overall thermal conductivity is improved due to the change in flow, heat, transport, and heat transfer features of the liquid [1]. Some of the vital requirements that nanofluid must fulfill are adequate durability, even and stable suspension of particles, no chemical change of particles or fluid, and negligible agglomeration of particles. Several types of particles have been reported in literature to prepare nanofluids, which include (1) nonmetallic particles (SiO_2 [2], SiC [84], TiO_2 [68], Al_2O_3 [85], ZnO [28], CuO [86], Fe_3O_4 [14], and AlN [45]), (2) metallic particles (Cu [87], Ag [88], and Au [88]), and (3) different particle shapes such as carbon nanotubes [89], nanodroplets [90], nanofibers [67], and nanorods [91]. The base fluids commonly used are water, oil, acetone, decene, ethylene glycol, and mineral oil. Two methods have been employed in producing nanofluids which can be classified as single-step and two-step methods [1].

The single-step method involves the preparation of nanoparticles and dispersion of them in the host or base fluid simultaneously. The nanoparticles can be directly prepared via physical vapor deposition technique or liquid chemical method. Therefore, the process of drying, storage, dispersion, and transportation is avoided, so that agglomeration is minimized and, hence, nanoparticle dispersion in the host fluid is improved [15]. The main demerit of this process is that the residue *s* of reactants is left behind in the nanofluid due to incomplete reaction or stabilization which diminishes the purity of the nanofluid [92]. Another shortage in this process is that only low vapor pressure fluids can be used, which limits the application of the method.

In the two-step method, which is the most widely used method for preparing nanofluids, the nanoparticles, nanotubes, nanofibers, or nanorods are first produced by chemical vapor deposition, inert gas condensation, or any other technique as a dry powder. The second step involves dispersing this nanopowder into the base fluid with the help of intensive magnetic force agitation, ultrasonic agitation, high shear mixing, homogenizing, and ball milling. The two-step method is more economical than the one-step method to produce nanofluids commercially. The main disadvantage of this method is that, due to the high surface area and surface attractively, the nanoparticles tend to agglomerate. The agglomeration of nanoparticles in the fluid results in decreasing the thermal conductivity and increasing the settlement and clogging of microchannels. Therefore, surfactants are widely used to stabilize nanoparticles in the fluids. Nevertheless, this method is suitable for wide range of particles such as oxide particles and carbon nanotubes and it is attractive to industry because it is simple for nanofluid preparation [93].

2.1. Stability of Nanofluids. Agglomeration of nanoparticles has severe ramifications ranging from clogging of microchannels to reduction in thermal conductivity of nanofluids. Sundry of methods have been developed to assess the stability of nanofluids and the simplest of all is sedimentation method. The nanofluids are said to be stable when their concentration remains constant. Physical inspection by naked eyes is also usually considered one of the methods for observing stability of nanofluids. Below, some methods are described for analyzing stability of nanofluids.

2.1.1. Zeta Potential Analysis. The electric potential difference between the dispersion medium and the stationary layer of fluid is termed as zeta potential. This potential is crucial for depicting the stability of colloidal suspensions. The higher zeta potential is, the more stable colloidal suspension will be and vice versa.

2.1.2. Spectral Absorbency Analysis. Spectral absorbency analysis (SAA) is another efficient way in addition to zeta potential analysis in order to assess the steadiness of nanofluids. Generally, there exists a linear relationship between concentration of nanoparticles in fluid and the absorbency intensity. If nanomaterials, which are dispersed in base fluids, possess characteristic absorption bands in the wavelength range of 190–1100 nm, then stability of nanofluids can be evaluated by using UV-vis spectroscopy reliably.

2.2. The Ways to Enhance the Stability of Nanofluids

2.2.1. Surfactants Used in Nanofluids. Surfactants or dispersants are used for increasing the stability of the nanofluids. Normally, surfactants are required in order to stabilize the nanofluid suspensions produced from two-phase method. Surfactants stabilize nanofluids by reducing the surface tension of fluids and hence are essential for increasing the stability or preventing agglomeration of nanoparticles in base fluids. Two-phase method is normally used commercially, since it is an easy and economically viable method for nanofluid production at large scale. Surfactants are composed of hydrophobic tail portion (long-chain hydrocarbon) and a hydrophilic polar head group. Surfactants help in achieving higher wettability, that is, increased contact between two materials. Water-soluble surfactants are selected when base fluid is polar solvent; otherwise, oil-soluble solvents are chosen. On the other hand, there are several issues associated with surfactants such as the fact that dispersants may contaminate the heat transfer media by producing foams while heating. Further, addition of surfactants may lead to enlargement of nanoparticles, which in turn mitigates the effective thermal conductivity of the nanofluid. Hence, the system (surfactant addition to nanofluid) needs to be optimized.

2.2.2. Surface Modification Techniques: Surfactant-Free Method. The other method which is utilization of functionalized nanoparticles is a capable way to deal with accomplishing long haul strength of nanofluid. It characterizes the surfactant-free technique. Some researchers experimented on the combination of functionalized silica (SiO_2) nanoparticles by joining silanes specifically to the surface of silica nanoparticles in unique nanoparticle solutions which resulted in peculiar qualities of nanofluids in which no deposition layer formation on warmed surface after a pool bubbling procedure was observed. Some other researchers introduced hydrophilic functional groups on the surface of the nanoparticles by mechanic-chemical reaction and thus produced nanofluids, which possess qualities such as no contamination, great smoothness, low viscosity, high thermal conductivity, and high stability. These nanofluids may find applications as coolants in advanced thermal systems.

2.2.3. Stability Mechanisms of Nanofluids. Particles while in dispersion medium may pile together and agglomerate giving inflated size of particles, which may find their fate by settling down in the solution due to gravity. Steadiness of nanofluids signifies that particles do not aggregate and settle down at a noteworthy rate. The rate of aggregation is defined by the recurrence of impacts and the likelihood of union during collision. Derjaguin and his research groups' hypothesis proposes that the stability of a particle in solution is dictated by the resultant of van der Waals attractive and electrical double layer repulsive forces that exist amongst particles as they approach each other due to the Brownian motion they are undergoing. If the attraction force is higher than the repulsion force, then the particles will collide, and the suspension will not be stable, while if the other way around was the case, then the colloidal suspensions will stay stable. Table 1 summarizes the effects of different nanoparticles types, size of nanoparticles, loading of nanoparticles, synthesis process, and dispersion method on the stability of different types of nanofluids.

3. Characterization of Nanofluids

Over the past decade, researchers have tried to improve the heat transfer properties of the nanofluids by optimizing the physical and thermal properties of the nanofluid. Experimental studies involved a wide range of nanoparticles and some correlations were established. However, they have come up with diverse results, thus making those correlations inconsistent and sometimes contradictory. In this section, the physical and thermal properties of nanofluids and their varying effect on heat transfer behavior are studied through reviewing several researches in the literature [74, 91, 94–106].

3.1. Physical Properties

3.1.1. Density (ρ). The density is a factor that affects the heat transfer properties. However, reports on the effect of density are found to be scarce. Since the nanoparticle's density is higher than liquids', it led to believing that an increase in the volume concentration of the nanoparticles would lead to increased density values of the nanofluid. Most researchers obtain the theoretical density values from the mixing equation introduced by Pak and Cho [74].

$$\rho_{nf} = \phi \rho s + (1 - \phi) \rho_f, \quad (1)$$

where ρ is the density, ϕ is the volume concentration, and "nf" and "f" subscripts are the nanofluid and base fluid, respectively. Table 2 shows the experimental results reported by Saeedinia et al. [107], which seem to be in agreement with Pak and Cho's correlation.

As it is evident from the table, the above equation holds for various weight fractions with negligible differences. However, it should be noted that the difference slightly increases for 2% weight fraction, which means it could further increase at higher concentrations. Some investigations report on the effect of volume concentration and temperature on the density in water based Al_2O_3 nanoparticles and came up with a model that is a function of both [108].

$$\rho_{\text{eff}} = 1001.064\ 2738.6191\phi_p - 0.2095T; \quad \text{for } 0 \le \phi_p \le 0.4,\ 5 \le T\,(^\circ\text{C}) \le 40, \quad (2)$$

where ρ_{eff} represents the effective density of the nanofluid, ϕ_p is the volume concentration, and T is the temperature. The correlation shows that the density of the nanofluid is linear with volume concentration and inversely linear with increasing temperature.

Nanoparticle Concentration Effect on Density. It has been reported that increasing the volume concentration of metal oxides such as Al_2O_3, Sb_2O_5, SnO_2, and ZnO with both ethylene glycol and water as base fluids leads to the increase of

Table 1: Summary of the effects of different nanoparticles types, size of nanoparticles, loading of nanoparticles, synthesis process, and dispersion method on the stability of different types of nanofluids.

Nanoparticles type	Base fluid	Synthesis process	Particle loading (vol. %)	Particle size (nm)	Dispersion method	Stability	Ref.
SiO_2	Water	Two-step	10	NR	3-Glycid oxyl proyl tri-methy oxy silane (mass ratio of silane to silica = 0.115) + solution kept at 50°C for 12 hours	12 months	[2]
SiO_2	Deionized water	Two-step	NR	NR	Oscillated in an ultrasonic bath for 12 h	Several days	[2]
SiO_2	Deionized water	Two-step	0.45, 1.85, and 4	12	Ultrasonic vibration	NR	[3]
SiO_2	EG, water, EG/water solutions, and TO/water solution	Two-Step	NR	10 nm with 600 $m^2 \cdot g^{-1}$ specific surface area	Ultrasonic disrupter technique	NR	[4]
SiC	Water	Two-step	9	NR	Sonicated for 15 minutes and pH of solution = 9.5	NR (not reported)	[5–7]
TiO_2	EG/water	Two-step	0.5–1.5	50	Ultrasonic bath of 2 hours	NR	[8]
TiO_2	Water	Two-step	1, 1.5, and 2.0	6	Mixture sonicated in magnetic stirrer followed by ultrasonic vibration for 2 hours	NR	[9]
TiO_2 & C-TiO_2	EG	Two-step	0.04 and 0.08	NR	Sonicated at a frequency of 42 kHz	NR	[10]
TiO_2 & C-TiO_2	water	Two-step	0.04 and 0.08	NR	Sonicated at frequency of 42 kHz	NR	[10]
TiO_2	Distilled water	Two-step	NR	NR	Ultrasonic cleaner used for 30 min	NR	[11]
TiO_2	Distilled water	Two-step	0.01	NR	Ultrasonication for 30 min	NR	[12]
TiO_2	Distilled water	Two-step	NR	NR	Ultrasonic vibration (400 W and 24 kHz) for 3–5 hours	Several days	[13]
Al_2O_3	Wide range	NR	NR	28	Mechanical blending, coating particles with polymers, and filtration method	NR	[14]
Al_2O_3	Water	Two-step	NR	60.4	Ultrasonic disrupter + homogenization by magnetic force agitation	NR	[15]
Al_2O_3	Water and EG in polyethylene container	Two-step	NR	38.4	Mixture shaken thoroughly	NR	[16]
Al_2O_3	EG	Two-step	NR	NR	Ultrasonic mixing for several minutes	Duration of experiment	[17]
Al_2O_3	Water	Two-step	Wt.% 1 2 4 6	45 and 150	Ultrasonication + pH kept away from the isoelectric point (IEP) = zero zeta potential pH 6.5 6 5.5 5	Several weeks	[18]

Table 1: Continued.

Nanoparticles type	Base fluid	Synthesis process	Particle loading (vol. %)	Particle size (nm)	Dispersion method	Stability	Ref.
Al_2O_3	Water	Two-step	NR	NR	Ultrasonic pulses of 100 W and 36 ± 3 kHz for 6 h and pH = 4.8	Several weeks	[19, 20]
Al_2O_3	Water	Two-step	20	40.2	Mixture diluted by 1% nitric acid + sonication continuously for 4 h at 60 Hz and 130 W	One week	[21]
Al_2O_3	Water	Two-step	NR	NR	Ultrasonic pulses of 100 W and 36 ± 3 kHz for 6 h. pH = 4.8, and zeta potential = 45 mV.	Several weeks	[22]
Al_2O_3	Water	One-step	0.5, 1, & 3	NR	Homogenizer at 8000 rpm for 30 min + an electromagnetic agitator at 600 rpm	More than 2 weeks	[23]
ZnO	Water	Two-step	NR	150–80	Acetyl acetone + sonication for 10 minutes	Over 9 months to 1 year	[20]
ZnO	EG	Two-step	NR	NR	Continuous stirring & sonicating (40 kHz and 150 W) for 3 hours	NR	[24]
ZnO	Water	Two-step	NR	210	Mixture stirred for 30 min at 25°C + sonication using single piezoactuated bath, a solenoid-actuated bath, and a static bath with an immersed horn	NR	[22]
ZnO	EG/H_2O	Two-step	0.1, 0.5, and 1	NR	Stabilize mixture by 5 wt.% PVP or 1 wt.% PVA + solution stirred by magnetic stirrer before ultrasonication	NR	[25]
ZnO	Water	Two-step	NR	NR	Ultrasonication for 3 h + sodium hexametaphosphate (surfactant: NP ratio = 1 : 5) + high shear homogenization for 20 min at 7000 rpm, followed by ultrasonication for 180 min (750 W and 20 kHz)	NR	[26]
ZnO	PEG	Two-step	NR	NR	Sonication	At least 140 min	[27]
ZnO	EG	Two-step	0.005 and 0.0375	<50	Intense ultrasonication at 200 W up to 100 h + no surfactant	NR	[28]
CuO	Water	One-step	NR	NR	Pulsed laser ablation in liquids using a single-pulsed laser beam for 8 h	Better than two-step	[29]
CuO	Deionized water	Two-step	NR	NR	Continuous sonication for 6 h	NR	[29]
CuO	Water	Two-step	NR	NR	Ultrasonication for 6 h + surfactant Tiron (CuO : Tiron = 2.5 : 1). Zeta potential = 30 mV ensured	NR	[30]

Table 1: Continued.

Nanoparticles type	Base fluid	Synthesis process	Particle loading (vol. %)	Particle size (nm)	Dispersion method	Stability	Ref.
CuO	Distilled water	Two-step	0.05 vol.%	NR	Sodium dodecyl benzene sulphonate (SDBS) of 10 wt.% of nanoparticles (reason: to prevent immediate settlement as CuO NPs have high density (6310 kg·m^{-3}) compared to water (995 kg·m^{-3})) + sonication for 60 min	Best with SDBS	[31]
CuO	Oleic acid	Two-step	1, 1.5, & 2	NR	Ultrasonicated at a frequency of 40 kHz	NR	[32]
CuO	EG + water	Two-step	NR	<40	Polyvinylpyrrolidone (PVP) with weight ratio of 0.25 : 1 (PVP : CuO) + mixture stirred and agitated thoroughly for 30 min	NR	[33]
CuO	Water	Two-step	NR	NR	Ultrasonic bath (100 W) for 4 hours	25 days	[34]
CuO	Distilled water	Two-step	NR	NR	Vibrated for 10 h in an ultrasonic mixer	5 hours	[35]
Fe_3O_4	Water + EG (50% : 50%)	Two-step	NR	NR	Sonicated for two hours with vigorous agitation for 30 minutes	More than 8 hours	[36]
Fe_3O_4	Water	Two-step	NR	NR	Oleic acid	NR	[37]
Fe_3O_4	Kerosene	Two-step	1 vol.%	NR	Oleic acid	NR	[38]
α-Fe_2O_3	Glycerol	Two-step	NR	NR	Ultrasonication at 700 W for 30 min	NR	[39]
Fe_3O_4	Water	Two-step	NR	NR	Sonication for 1 hour	12 hours	[40]
Fe_3O_4	Water	Two-step	NR	NR	Sonication for 2 hours + pH = 3 (use sulfuric acid (H_2SO_4))	NR	[41]
Fe_2O_3	Water	Two-step	0.02 vol.	40	PH = 11.1 + PEG as surfactant + magnetic stirring for 1 hour	7 days	[42]
Fe_2O_3	MAAS (30 mM KOH and 10 mM LiOH in deionized water)	Two-step	NR	40–150	(Ultrasonic bath, 37 kHz) for 4–6 h + agitation for at least 1 hour with sonication	NR	[43]
α-Fe_2O_3	Water	Two-step	0.25, 0.5, 1, 2, 3, & 4	20–40	Sonication + tetramethylammonium hydroxide	NR	[44]
AIN	Polypropylene glycol	Two-step	NR	169	Stirred for 40 min at 3000 rpm	30 hours	[45]
AlN	EG	Two-step	NR	165	Sonication for 3 h	NR	[46]
AlN	Transformer oil (TO)	Two-step	NR	NR	Stirring and ultrasonic vibration without the addition of any surfactant	NR	[47]
AlN	Ethanol	Two-step	NR	20	Castor oil + stirring at high speed + ultrasonic homogenizer for 10 min	More than two weeks	[48]
Cu	Transformer oil	NR	22	NR	Oleic acid + suspension vibrated for 10 h	One week	[49]
Cu	Deionized water	NR	9	NR	Laureate salts + ultrasonic vibration	30 hours	[49]

Table 1: Continued.

Nanoparticles type	Base fluid	Synthesis process	Particle loading (vol. %)	Particle size (nm)	Dispersion method	Stability	Ref.
Cu	NR	Two-step	NR	NR	Sodium dodecyl sulfate, cetyltrimethylammonium bromide, and sorbitan monooleate	24 hours	[50]
Cu	Water	Two-step	NR	NR	9.0% anionic surfactant in an ultrasonic bath for about 10 hours	NR	[51]
Cu	NR	Two-step	NR	NR	Ultrasonic bath for 1.5 hours	4 hours	[52]
Cu	Distilled water	Two-step	NR	NR	Intense ultrasonication for 10 h at 200 W + magnetic stirrer for another 10 h	15 days	[53]
Cu	Water	One-step	0.1–0.3	30–50	NR	More than 2 weeks (for 0.1%) & 5 days (for 0.3%)	[54]
Ag	Diethylene glycol	Two-step	NR	NR	Continuous stirring & agitation for 5 min by an ultrasonic agitator	NR	[55]
Ag nanorods	NR	Two-step	NR	NR	CTAB surfactant micelles	Maximum one week	[56]
Ag	NR	Two-step	NR	NR	Ultrasonic bath for 3 h	48 hours	[57]
Ag	Deionized water	Two-step	NR	NR	Ultrasonic bath for about 15 min	NR	[58]
Au	Distilled water	Two-step	NR	NR	Solution boiled for 10 min at 80°C	NR	[59]
Au	Water (laser ablation)	One-step	NR	NR	Stirred magnetically	NR	[60]
MWCNT	NR (first treated with hydrophilic functional groups)	Two-step	NR	NR	NR	Several months	[61]
MWCNT	NR (not treated)	Two-step	NR	NR	With or without oleylamine	5 minutes	[61]
CNTs	Gum Arabic + deionized water	Two-step	NR	NR	Ultrasonication + magnetic stirring for 5 minutes	Over 1 month	[62]
CNTs	Water	Two-step	NR	NR	0.2 wt.% chitosan	2 months	[63]
CNTs	Glycol	Two-step	NR	NR	Ultrasonic vibration (Gum Arabic, Tween 80, and CTAB)	More than two months	[64]
CNTs (S-WNTs) (L-SWNTs) (M-SWNTs)	Deionized water	Two-step	NR	NR	Hexadecyl-trimethyl-ammonium bromide (CTAB)	120 minutes	[65]

Table 1: Continued.

Nanoparticles type	Base fluid	Synthesis process	Particle loading (vol. %)	Particle size (nm)	Dispersion method	Stability	Ref.
Alumina CNFs	EG	Two-step	5.5 vol.%	NR	Sonication for 1 hour	NR	[66]
NCFs & sodium dodecyl sulphate	Deionized water	Two-step	NR	NR	Stirring + ultrasonication for 1 hour at 25°C	NR	[67]
TiO_2 nanorods	Deionized water	Two-step	0.05	10 × 40	Ultrasonic Dismembrator for 8–10 hours	NR	[68]
ZnO nanorods	Deionized water	Two-step	0.01–0.1	140	Ammonia citrate at a ZnO/ammonium citrate ratio of 1 : 1 (sonication for about 15 min.)	NR	[69]
CuO nanorods (stearic acid-modified)	Heat transfer oil	Two-step	0.8%	40–60 nm in diameter and 100–120 nm in length	NR	NR	[70]

Table 2: Different volume concentration and the theoretical and experimental densities.

Nanoparticle weight percentage	Base oil	0.2%	0.5%	1%	2%
Theoretical density (kg/m^3)	871.13	872.66	874.97	878.75	886.93
Experimental density (kg/m^3)	871.13	872.21	875.11	880.34	889.07

Table 3: Theoretical models for predicting the viscosity.

Author	Model for μ	Notes
Einstein [71]	$1 + 2.5\phi$	For spherical nanoparticles with low volume concentration
Batchelor [72]	$1 + 2.5\phi + 6.5\phi^2$	A modification of Einstein's equation to account for Brownian motion effect
Brinkman [73]	$\frac{1}{(1-\phi)^{2.5}}$	Used for copper, gold, and carbon nanotubes and graphene nanoparticles dispersed in water
Pak and Cho [74]	$1 + 39.11\phi + 533.9\phi^2$	At room temperature

their densities in all of the mentioned nanofluids [109]. Furthermore, after investigating propanol based Al_2O_3 nanofluids, it has been proven that a linear relationship existed between the density and the volume fraction [110]. This effect is also valid for water based carbon nanotubes nanofluids, where results showed that, with 0.02 and 0.04 weight percentage of carbon nanotubes loading, the density increased by 0.01% to 0.39% [111].

Temperature Effect on Density. Contrary to the volume concentration, temperature has a reverse effect on density. It has been reported that the density of Al_2O_3 nanofluid increases with the increase of volume concentration of nanoparticle but decreases with increasing the temperature [112, 113]. This is also consistent with (2).

3.1.2. Viscosity (μ). Researchers have found viscosity to be a key parameter in determining the convective heat transfer coefficient. However, this property is troublesome due to lack of understanding of viscosity mechanisms and lack of a general mathematical model that predicts the behavior of viscosity in nanofluids.

Several efforts were made to come up with a model that predicts the viscosity in nanofluids. The first model is Einstein's model [71] of effective viscosity for suspended rigid spherical solids in liquids as a function of volume. The model was developed in 1906 and it was derived from linear hydrodynamic equations. Still, Einstein's model could only predict the viscosity behavior for spherical rigid particles and for a low particle concentration of 1.0 volume percentage.

Numerous modifications of Einstein's model were made to further enhance the viscosity correlations. Brinkman [72] developed a model based on Einstein's equation to include higher particle concentrations, while Batchelor [73] added Brownian motion to his model. Nevertheless, experiments have shown discrepant results from the mentioned models. Researches on alumina and titania nanofluids showed higher levels of viscosity when compared with Einstein-Batchelor correlations [114]. Moreover, these models are all function of volume fraction of nanoparticles; however, they do not include the temperature effect. Researchers have continued to work on measuring the viscosity for different nanofluids and came up with their own correlations. These correlations listed in Table 3 are a function of volume fraction only, ϕ.

In the recent years, researches started using instruments called *viscometers* to measure the viscosity of nanofluids.

Nanoparticle Concentration Effect on Viscosity. Several researches have confirmed that nanoparticle volume concentration in nanofluids increases the heat transfer coefficient [115–119] along with increasing the viscosity. It was found that varying the concentration of Al_2O_3 in water with values of 0.3, 0.5, 0.7, 1, and 2% leads to an increase of viscosity, which in turn led to increased friction factor [115]. A similar behavior was observed in both water and ethylene glycol based Al_2O_3 and water based SiC nanofluids [120, 121]. This trend is also true for nonmetallic nanofluids, where several studies on the rheology of carbon nanotubes nanofluids confirmed that increasing the carbon nanotubes loading increases the viscosity of the nanofluid [122–124].

It is important to mention that there are some inconsistencies in the literature regarding viscosity behaviors. Pak and Cho [74] examined water based Al_2O_3 and TiO_2 nanofluids and observed that at a volume concentration of 3% the heat transfer severely reduced and has become lower than the heat transfer of pure water.

There are factors other than volume concentration which affect the nanofluid's viscosity such as the nanoparticle's shape, size, and surface chemistry [114]. Similarly, a study on water based Al_2O_3 and TiO_2 showed that the nanoparticle's size and shape as well as the volume fraction and temperature all were important parameters for determining the viscosity. However, the mentioned factors are poorly studied in the literature and further investigations are required.

Temperature Effect on Viscosity. As mentioned before, the theoretical models for viscosity do not consider temperature. Thus, the previous models can only be true for low concentrations and at room temperature conditions, but they are not true for higher temperatures [125]. Many researches reached a consensus that viscosity decreases with increasing temperatures [120, 121, 123, 126–128]. Previous studies involved CuO, Al_2O_3, SiC, and CNT nanofluids with the focus being on Al_2O_3 nanofluids. Furthermore, it has been found that viscosity decreases exponentially with temperature rise in

CuO, Al_2O_3, and SiO_2 dispersed in both water and ethylene glycol [129]. A research also concluded that if the increase in viscosity is more than the thermal conductivity of nanofluids by four times, then it is rendered useless due to the increase of friction factor [130, 131].

3.2. Thermal Properties

3.2.1. Specific Heat Capacity (C_p). Specific heat capacity measures the ability of a material to store energy in the form of heat and exchange it if a temperature difference exists [111, 112]. It is important to acquire accurate values of the specific heat as specific heat is used to calculate important properties, which include thermal conductivity, thermal diffusivity, and flow's spatial temperature. Researchers mostly use deferential scanning calorimeter (DSC) and double hot wire to measure C_p of nanofluids.

Several models predict the specific heat values of nanofluids at different conditions. One model was based on mixture of liquid and particle and was introduced by Pak and Cho [74]:

$$C_{nf} = (1 - \varphi_v) C_{bf} + \varphi_v C_p, \tag{3}$$

where "C" is for the specific heat, "nf" is the nanofluid, φ_v is the volume fraction of the nanoparticle, and "bf" and "p" represent the base fluid and nanoparticle, respectively. Some researchers proposed a correlation that was a modification of the previous model and was based on thermal equilibrium of the nanoparticles and the base fluid [132]:

$$\begin{gathered}(\rho C)_{nf} = (1 - \varphi_v)(\rho C)_f + \varphi_v (\rho C)_p, \\ \rho_{nf} = (1 - \varphi_v)\rho_f + \varphi_v (\rho_p),\end{gathered} \tag{4}$$

where "C," "ρ," and "φ_v" represent the specific heat, density, and nanoparticle's volume fraction from the nanofluid, respectively, and "nf," "f," and "p" represent the nanofluid, base fluid, and nanoparticle, respectively. A recent study compared the results of heat capacities of water and EG based Al, Cu, and Si nanofluids acquired from DSC with the above models, and it found that there is a significant deviation from (3) but there was an agreement with (4) [133]. This was the same case with Al_2O_3-water, TiO_2-EG nanofluids, and ZnO with ethylene glycol and water nanofluids [134, 135].

Zhou et al. [136] further modified equation one and proposed a correlation for higher volume concentration of nanoparticles

$$C_{nf} = \frac{[(1 - \varphi_v)\rho_f C_f + \varphi_v \rho_{np} C_{np}]}{[\rho_f + (1 - \varphi_v)\rho_{np}]}, \tag{5}$$

where "C" represents the specific heat, ρ is the density, φ_v is the nanoparticle volume fraction from the nanofluid, and "nf," "f," and "p" represent the nanofluid, base fluid, and nanoparticle, respectively.

A comparison study between (3) and (5) found that the latter is more suitable to use at nanofluids with higher volume concentration [137]. Many parameters affect the specific heat of nanofluids; however, nanoparticle volume concentration, type of nanoparticle, and base fluid all have higher influence than the shape, size, or the electrostatic behavior of the nanoparticles [138].

Effect of Nanoparticle's Size and Concentration on C_p of Nanofluids. It has been observed by many researchers that in nanofluids when the volume fraction of the nanoparticle increases the specific heat decreases due to the nanoparticles having lower heat capacities compared to their base fluid. A recent paper investigated the specific heat of five different nanofluids, which are Al_2O_3, ZnO, TiO_2, CuO, and SiO_2, with 60 : 40 ratios of propylene glycol and water, respectively. After varying the volume concentrations of the nanoparticles from 0.5% to 6% and the particle sizes from 15 nm to 76 nm, the paper reported that the size of the particle had no significant impact on the specific heat. On the other hand, the volume concentration played a big part in altering the behavior of the heat capacity. At low concentration, the reduction in specific heat was tolerable mostly because it led to increasing the thermal conductivity, which enhanced the heat transfer efficiency. However, as the volume fraction of the nanoparticle increases, the heat capacity further decreases [139]. Similarly, the specific heat of water and ethylene glycol mixture based MgO, ZnO, and ZrO_2 nanofluids were investigated, and it was observed that although the nanofluids showed a 30% increase in specific heat compared to their base fluids, it still decreases with increasing nanoparticles' volume fraction [140]. Several researchers conducted similar studies and all of them reported the same behavior across a variety of nanofluids [141–144].

For carbon nanotubes nanofluids, it is reported that as the multiwalled CNT concentration in 30 : 70 EG-water increased, the specific heat decreases [145, 146]. However, in contrast, an increase in specific heat with increasing single-walled CNT concentration in water was reported [147]. It is known that carbon nanotubes (CNTs) have high specific heat capacity. It is due to this reason that increased loading leads to the increase in the specific heat, but this has not been agreed upon yet.

Temperature Effect on C_p. Most papers in the literature have reported that the specific heat increased with increased temperature. Experiments with several nanofluids have confirmed that increasing the temperatures will lead to increased specific heat capacities [112, 139, 148]. However, a few papers have found the contrary effect and reported that specific heat capacity decreases with increased temperatures [149–151]. Similar to volume concentration, when the temperature is varied, the previous behavior of specific heat does not hold for all CNT nanofluids. It was observed that specific heat of multiwalled CNT increased with increasing temperatures [146, 152], while it was the opposite in single-walled CNT nanofluid [147].

3.2.2. Thermal Conductivity (k). Thermal conductivity "k" is the rate at which a material passes heat. It is a major factor in increasing nanofluid efficiency in heat transfer and researchers have extensively studied it. The rate of heat

Table 4: Theoretical models for predicting the thermal conductivity.

Author	Formula to get "k" of the nanofluid	Comments
Maxwell [75]	$\frac{k_{\text{eff}}}{kf} = \frac{[ks + 2kf] + [2\varphi s(ke - kf)]}{[ks + 2kf] - [\varphi s(ks - kf)]}$	Spherical particles
Bruggeman [76]	$\frac{1}{4}\left[(3\varphi - 1)\frac{ks}{kf} + (2 - 3\varphi) + \frac{1}{4\sqrt{\Delta}}\right]$	High volume concentration of spherical particle
Hamilton and Crosser [77]	$\frac{k_{\text{eff}}}{kf} = \frac{[ks + (n-1)kf + (n-1)\varphi(ks - kf)]}{[ks + (n-1)kf] - [\varphi(ks - kf)]}$	Spherical and nonspherical particles

transfer through solids is much higher than that through liquids and gases; it is for this reason that nanofluids have higher "k" values compared to their base fluids. There are several methods to measure the thermal conductivity of a material, but the most common method is transient hot wire method.

Several efforts have been made in order to come up with a correlation that predicts the values of thermal conductivity of nanofluids at different conditions. Using continuum equations and particle-fluid mixtures, scientists have developed equations and tested them. Some of the derived models are shown in Table 4. One of the early models is Maxwell's [75] to determine the effective thermal conductivity of millimeter to micrometer scale spherical particle-fluid mixture. Maxwell's equation includes the thermal conductivity of the solid particles in base fluid and its volume fraction with respect to the total fluid and it can be applied only for low concentrations of particles. Bruggeman [76] considered the interaction between randomly distributed particles and introduced a model for spherical particles. Hamilton and Crosser [77] came up with a model for any particle shape, where in their equation they included a parameter of "n," which accounts for the shape of the particle (as shown in Table 4). Further modifications were made by other scientists to enhance the prediction of thermal conductivity; however, there are none that can determine the thermal conductivity of nanofluids in high volume concentrations and temperatures.

Volume Fraction Effect. It is reported in the literature that a higher volume fraction of the nanoparticle in the nanofluid will increase the thermal conductivity. An increase in the effective thermal conductivity of 32.4% in Al_2O_3 nanofluid was reported when the volume concentration was increased to 4.3% [153]. A similar behavior was reported in another research, observing a 20% increase in the effective thermal conductivity for the same volume fraction increase [154]. The enhancement is notable when compared to nanofluids' base fluids. Moreover, after investigating Al_2O_3 and CuO nanofluids, their thermal conductivities were enhanced by 2% to 9.4% for a volume concentration of 1.0% and 4%, respectively, showing an increase with increasing volume concentration [80]. The same effect can be seen in single-walled CNT [147].

Particle Size Effect. The size of the nanoparticle affects the thermal conductivity of the nanofluid, where smaller particle size will have a larger surface area relative to its diameter and thus will increase the thermal conductivity. A study confirms this after testing Al_2O_3 and CuO with nanoparticle sizes of 28 nm and 23 nm, respectively; the results showed an improvement in the thermal conductivity for the copper oxide nanofluid because their nanoparticles were smaller compared to Al_2O_3 [120]. However, this effect is inconsistent in other nanofluids such as SiC nanofluid. A paper experimented SiC nanofluids with sizes of 26 nm and 600 nm. The paper reported a thermal conductivity increase of 15.8% and 22.9%, respectively. This may be due to the clustering of the nanoparticles [85].

Temperature Effect. Temperature is also a factor in determining the thermal conductivity of the nanofluid. Several papers show that increasing the temperatures will intensify the thermal conductivity of the nanofluid. This effect holds true for water based Al_2O_3, CuO [155], ethylene glycol based ZnO [156], and CNT nanofluids [157].

3.3. Heat Transfer Characteristics. All the previous properties affect and determine the heat transfer rate of the nanofluid. However, it is important to note that volume concentration and temperature are major factors in all of these properties as well as the heat transfer characteristics.

3.3.1. Heat Transfer Coefficient and Nusselt Number. The main objective of using nanofluids is to increase the heat transfer rate so that it can be applied in heat transfer applications. Studies have demonstrated that adding nanoparticles to base fluids would result in a nanofluid with a higher heat transfer coefficient compared with the base fluid. One study compared water based Al_2O_3 nanofluid with pure water; the heat transfer coefficient and the Nusselt number both increased from 399.15 W/m^2 K and 367.8 to 700 W/m^2 K and 587, respectively [115]. Oil based CuO also showed a 12.7% increase in the heat transfer coefficient over oil at a 0.2% volume concentration when operated in a plate heat exchanger [107]. Similarly, another study in a plate heat exchanger reported enhancements of 42% and 50% in heat transfer coefficients for aluminum oxide and carbon nanotubes nanofluids, respectively [158]. Several correlations were made in order to calculate the Nusselt number and the heat transfer coefficient, which are described in Table 5.

Effect of Volume Fraction. Several studies have shown that the volume concentration increases the heat transfer coefficient in the nanofluid. Table 6 lists some of these studies along with remarks made by their authors.

Table 5: Theoretical models for predicting the Nusselt number.

Author (8)	Correlation	Remarks
Pak and Cho [74]	$Nu = 0.021\, Re^{0.8}\, Pr^{0.4}$	For Al_2O_3 and TiO_2
Duangthongsuk and Wongwises [78]	$Nu = 0.074\, Re^{0.707}\, Pr^{0.385} Ø^{0.074}$	For TiO_2
El Bécaye Maïga et al. [79]	$Nu = 0.086\, Re^{0.55}\, Pr^{0.5}$	For Al_2O_3-water, Al_2O_3-EG, and constant heat flux
Das et al. [80]	$Nu = c Re^{m}\, Pr^{0.4}$	c & m depend on the volume fraction

c: complex amplitude ratio.

Table 6: Effect of volume fraction on heat transfer coefficient.

Paper	Heat with volume fraction	Nanofluid	Remarks
Haghshenas Fard et al. [81]	Increase	CuO-water	27% enhancement
Heris et al. [82]	Increase	Al_2O_3-water & CuO-water	Optimum concentration between 2.5% and 3% volume fraction
Corcione [83]	Increase	Al_2O_3-EG & TiO_2-EG	Theoretical study

Some studies are inconsistent and showed different behaviors. One study confirmed an increase in the Nusselt number of SiO_2 and water nanofluid as the volume concentration increased [159]. Another study also confirmed this for both water based $Al_2O_3$and TiO_2; however, it made the observation that the heat transfer coefficient decreases to less than the base fluid at a constant temperature [74]. In another paper, researchers found that although the Nusselt number increased, it only increased for volume concentrations values between 0.2 and 2% and no change was reported for values larger than what is mentioned [160].

4. Applications of Nanofluids

In the previous sections, characteristics, preparation, and properties of nanofluids have been discussed. In this section, the focus will be on application of nanofluids. Nanofluids are used in several industries such as the automobile sector and the energy industry. Specific applications include cooling in electrical, electronic, and mechanical machines or devices, efficient heat transfer in energy generation and process industries, energy recovery from flue gases, cooling and heating of buildings, thermal storage, solar energy systems, desalination, refrigeration, space and defense, and lubrication in moving parts of machines and biomedical equipment. In the following sections, the role of nanofluids in these applications is discussed in detail.

4.1. Nanofluids in Cooling Applications. The use of water as a cooling medium has many limitations; thus there is a need for fluids with higher heat transfer efficiencies [161]. It is known that solids have higher thermal conductivities than fluids; this suggests that they provide improved thermal properties [162–164]. Since fluids are required to substitute water and coolants, nanofluids are the best candidates because they provide the necessary properties for better heat transfer properties. Nanoparticle concentration has a direct effect on nanofluid's thermal conductivity, heat transfer, and viscosity [165, 166]. Therefore, the effects must be considered before utilizing nanofluids in any applications. There are various cooling applications of nanofluids, which are described below.

4.2. Nanofluids in Vapor Compression Cycles. Water based nanofluids can achieve enhanced high heat flux cooling while keeping the benefits of water [99]. Many studies were performed on household fridges utilizing nanorefrigerants. One study utilized R134a as a refrigerant and a blend of mineral POE oil mixed with TiO_2 nanoparticles as a lubricant. It was found that energy consumption decreased by 26% in comparison to R134a and regular POE oil lubricant. Likewise, there was a significant decrease in the power utilization and a large change in freezing capacity. The change in the cycle performance was related to the improvements in the thermophysical characteristics of the lubricant in addition to the presence of nanoparticles with the R134a [167]. In later studies, tests were performed on a household fridge utilizing TiO_2-R600a nanorefrigerant as working liquid. The study demonstrated that utilizing TiO_2 with the R600a refrigerant makes the system perform regularly and productively in the icebox. Furthermore, energy consumption decreased by up to 10% [123, 167–174]. Similarly, a study was conducted to investigate the performance of a residential fridge, which utilized Al_2O_3-R134a nanorefrigerant as the working fluid. It was found that the Al_2O_3-R134a system performance was superior to the system with lubricant and R134a working fluid mentioned before. The system consumed 10.30% less energy with 0.2% volume concentration. Moreover, by utilizing nanosized Al_2O_3, an increase was noticed in the heat transfer coefficient [175].

Another study focused on the performance of a household fridge utilizing TiO_2-R12 nanorefrigerant as the working fluid in a household fridge. The experiment discovered that the freezing capacity enhanced while 3.6% of enhancement was recorded in the heat transfer coefficient by using nanofluids. A decrease of 11% in the pressure work and an increase of 17% in the coefficient of performance by adding nanoparticles to the lubricant were also observed [176].

In another study, TiO_2 nanoparticles were added to R600a and were used as the working fluid; the energy saving and coefficient of performance increase were found to be 11% and 19%, respectively [177]. A CFD study used a working fluid consisting of CuO-R134a as a part of the vapor compression system. The study reported an increase in the evaporator heat transfer coefficient by adding CuO nanoparticles [178]. The conventional refrigerant and lubricant were replaced with a hydrocarbon refrigerant and mineral lubricant that contains Al_2O_3 nanoparticles in order to enhance the grease and heat transfer characteristics. The authors concluded that a volume concentration of 0.1 wt.% Al_2O_3 nanoparticle and a 60% R134a refrigerant were ideal and had decreased energy consumption by around 2.4% while increasing the coefficient of performance by 4.4% [179].

In addition to metal oxide nanofluids, several studies investigated the potential of CNT nanofluids. CNTs were added to the polyester oil by concentrations of 0.01–0.1 wt.% and were experimented with R134a refrigerant as the base fluid. The authors showed that 0.1 wt% was ideal, achieving the higher values of heat transfer improvement as well as increasing the coefficient of performance by 4.2% [180]. CNTs were noticed to have higher thermal conductivity (~3000 W/mK) over other nanoparticles such as CuO, Al_2O_3, SiO_2 diamond, and TiO_2 [181]. In a study, CNT nanofluid with R113a as the base refrigerant was utilized and notable enhancements of the system were observed. This recent study has also found that CNT based nanofluid has higher thermal conductivity when compared with ordinary refrigerants [182].

Nanofluids are expected to contribute largely in decreasing energy consumption as well as emissions in industrial air conditioning applications [183]. It was estimated that savings of 1 trillion Btu can be saved in the energy sector within US by replacing water with nanofluids in cooling and heating applications [184]. Similarly, about 10–30 trillion Btu can be saved annually by utilizing nanofluids in closed loop cooling cycles. Furthermore, this would reduce the related emissions of carbon dioxide, nitrogen oxides, and sulfur dioxide by 5.6 million metric tons, 8,600 metric tons, and 21,000 metric tons, respectively [183].

4.3. Nanofluids in Microchips and Server Cooling. Efficient cooling in electronics is necessary to maintain their performance. Alumina nanofluid was tested in microchannels and has been shown to improve heat transfer. It has been also shown to be effective in microchips cooling applications [185, 186]. A new design for a cooler containing microchannel heat sink was tested using nanofluid and the results showed a decrease in heat resistance as well as temperature gradient between the warmed microchannel walls and the coolant [88].

The heat transfer enhancement of water-Al_2O_3 nanofluid at various concentrations was investigated using a cooler designed with microchannel heat sink [187]. Similarly, a heat sink of silicon microchannels was used to analyze the performance of Cu nanoparticles [188].

4.4. Nanofluids in Automotive Cooling. Nanofluids dispersed in ethylene glycol have pulled in great attention in motor cooling applications [189]. Increment in the conventional coolant working temperature and the heat rejection rate can be done by utilizing nanofluids within the current motor cooling system [190]. A study used a 3.5% volume fraction of aluminum oxide nanoparticles dispersed in a standard motor coolant in a standard car engine and recorded enhanced thermal conductivity of 10.41% at room temperature [191]. A nanofluid composed of CuO and Al_2O_3 nanoparticles was used in the engine transmission oil as a coolant for automatic transmission systems. The outcomes demonstrated that CuO nanofluids lead to a reduced transmission temperature at different turning speeds [192]. The mentioned results show that using nanofluids in transmission systems may have a significant potential.

4.5. Nanofluids in Aerospace and Defense Cooling. Various military equipment needs sufficient amount of cooling in the order of Mw/m^2. Using conventional fluids for cooling in these sectors would require large and heavy operations. An example of military equipment cooling is the cooling requirement in direct energy weapons, high power laser diodes, and submarines. Transformer cooling in order to reduce the size and weight is necessary in naval and energy industries. Retrofitting conventional fluids in transformer may lead to large cost savings. It has been experimentally proven that, with nanofluids, the magnitude of critical flux in pool boiling increases manifold in comparison to the conventional fluids. The high levels of critical flux will help in simplifying cooling requirements in space such as space shuttle or space suits [193].

4.6. Nanofluids in Heat Exchanger Applications. The replacement of conventional heat transfer fluids by nanofluids in heat exchangers is promising [194]. The development of new, highly efficient heat exchanger fluids is an important requirement for heat exchanger design [195]. Nanofluids can improve the heat transfer process more than twice with small volume fraction under 0.3% [196]. One study focused on thoroughly characterizing all the properties of the nanofluid in order to determine its suitability in a particular heat exchanger. The latest experimental work related to the utilization of nanofluids in heat exchangers claimed that the flow type within the heat exchanger is a vital concern in the suitability of a nanofluid [119, 197]. In situations where the heat exchanger works under turbulent conditions, the use of nanofluids is helpful if it is accommodated by a minimum increase fluid viscosity which appears to be extremely hard to accomplish. Yet, improvement in the Nusselt number was achieved by using alumina-water and Titania-water nanofluids in fluids where the flow was described as turbulent [198]. A study showed improvements in the critical convective heat transfer of MWCNTs scattered in water. It was noticed that the improvement relied on the flow conditions and volume concentration [199]. The conductive heat transfer in turbulent flows using copper/water nanofluid was investigated. The study showed an improvement of more than 39% with a volume concentration of 1.5% [200]. Another study found that, by adding 0.2% volume concentration of TiO_2 nanoparticles, an upgrade of 11% in the convective heat transfer coefficient is possible [201]. On the other hand, if a laminar flow exists in the heat exchanger, the utilization of nanofluids appears to be favorable with the main obstacles being the cost and the particles suspension concerns when compared to pure fluids [194]. A study investigated the use of nanofluid under laminar flow and reported a 41% improvement in heat transfer characteristics in the entry region [202]. Similarly, graphite nanofluids were utilized in a horizontal circular tube to study the laminar convective heat transfer performance and were proven to be effective [203].

4.7. Biomedical Applications of Nanofluids. Medical science is also not aloof from technological advancement. The growing field of nanofluids finds many applications in the biomedical industry. One example is the use of nanofluids in order to minimize the side effects of traditional radiation cancer therapy, in which iron based nanoparticles can help in delivering drugs or radiation to the targeted cells (nanofluids can be guided in blood stream with magnets outside) without actually damaging the healthy cells [203]. Moreover, undergoing surgery is an unpleasant experience. However, with help of nanofluids, the effective cooling can be achieved around the surgical area, thus improving the chance of survival for the patient and mitigating the danger of organ damage. On the other hand, nanofluids (heating mode) can also be used for killing tumors or cancerous cells without affecting neighboring healthy cells. Furthermore, researches have confirmed antibacterial properties of nanofluids. ZnO nanofluids are helpful in killing *Escherichia coli* (*E. coli*) bacteria [204]. Increasing nanoparticles volume fraction and decreasing their size were shown to increase the antibacterial activity. In addition, nanofluids also help in nanodrug delivery systems in order to supply controlled dose of drug over desired period of time.

4.8. Application in Mechanical Processes Energy Industry. Heat transfer value may be of a great benefit to the final quality of a product or process in industry. This increase may help in reducing pumping power and in turn may help in saving energy in HVAC systems. In the energy sector, nanofluids can enhance the heat transfer, which in turn will lead to higher temperatures in turbines and more power outputs. In cooling systems such as refrigeration or process of cooling applications, nanofluids are equally trustworthy. Nanofluid coolants can be used in several applications like chemical, food and drinks, and oil and gas industries. In addition, The Massachusetts Institute of Technology (MIT) has a multidiscipline center to research the application of nanofluids in nuclear energy industry. Currently, potential impacts of using nanofluids in nuclear systems on safety, economic performance, and neutronic are under study [203].

4.9. Solar Energy and Desalination Applications. The major problem with solar or other forms of renewable energies is their availability at irregular intervals and the energy cannot be fetched from renewables round the clock. Therefore, storing energy becomes necessary to meet the demand in a more appropriate fashion. With this concept of storage, the technology of solar thermal energy cropped up. However, this technology still faces some serious problems with thermal energy storage for longer durations. The molten salts used for storing energy have certain drawbacks associated with them. The salts have freezing point of about 200°C and, below this temperature, they precipitate down in the system and clog the entire plant within fraction of seconds. Nanofluids prove to be trustworthy for storing energy as nanofluids PCMs (Phase Change Materials) possess extremely high thermal conductivities compared to the base material. Recently, researchers have tested nanofluid based PCMs by suspending nanoparticles from titanium oxide in saturated barium chloride aqueous solution and the result showed that the nanofluid based PCMs possessed considerably high thermal properties.

Solar energy is the major form of renewable energy and has the potential to supply the entire world's demand. Many researchers have proven that installing solar thermal power plants in arid regions of the globe will help in meeting the demands of entire world. The only problem with solar thermal energy is storage for a consistent base load, peak load, and intermediate load power generation. With nanofluids this problem of storage may be sorted out. Recent study from scientists has shown that nanofluid based concentrating solar thermal power plants can improve the efficiency by 10% and installing these nanofluid based plants in solar resource areas of Tucson, Arizona, and Algeria can lead to $3.5 million more earnings per year per 100 MWe.

On the other hand, world is also facing water shortages and in particular the arid regions of globe are water stress zones. Implementing nanofluid based solar thermal power plants along with solar thermal desalination systems will help in solving the problems of water along with electricity or energy. With nanofluids, more heat transfer capacities will be obtained which in turn will give more power output and more potable water. Implementing MED (Multieffect Distillation) systems with solar thermal power plant based on nanofluids energy storage will provide uninterrupted, round the clock water and energy supply [204].

4.10. Optical Application. Optical filters are used to choose various wavelengths of light. A ferrobased nanofluid can help in selecting several bands of the wavelength of the spectrum such as infrared, ultraviolet, or even the visible region. The required wavelengths range in addition to their bandwidths along with reflectivity can be managed by using properly customized ferrofluid emulsions [204].

4.11. Friction Reduction. The major concern of any mechanical industry ranging from manufacturing companies to railways is wear and tear, life, and reliability of moving parts. Nanoparticles have excellent load bearing capabilities and can withstand high pressures, thereby reducing wear and tear in moving parts of machines. Tribology is the science of bearing and it greatly emphasizes the mitigation of friction and wear. Lubrication provided by conventional fluids is not as efficient as lubrication provided by nanofluids. This is shown in the evaluation of tribological behavior of Cu based nanofluids; results have confirmed that the Cu nanofluid showed increased friction reduction as well as antiwear properties even at high loads. In addition, nanofluids proved to be valuable in machining operations such as cutting, grinding, and tapering. Better surface finish was achieved and prevented the burning of the workpiece and the tool [204].

4.12. Magnetic Sealing. In comparison to mechanical sealing, magnetic ones are more cost-effective and provide environment friendly and hazard proof sealing to large number of rotational equipment in the industry. They have low frictional resistance, long life, and high reliability and are capable of withstanding high speeds. Magnetic nanofluids are stable emulsions of magnetic particles like magnetite (Fe_3O_4). The developed seal of magnetic fluid operated for 286 days in constant flow state. Ferrocobalt magnetic fluid can withstand 25 times the pressure when compared with traditional magnetite sealing [204].

4.13. Nanofluid Detergent. In order to discover the method of dispersing dynamics in nanofluids of polystyrene, reflected-light digital video microscopy was used and it was demonstrated that nanofluids can act as a detergent; however, more work is required in this area. Commercial extraction of oil and oil spills removal can also be an application for the same nanofluid type [193].

4.14. Application in Geothermal Energy Extraction. Using zinc oxide nanofluids increases heat transfer ability of geothermal systems. Nanofluids usage increases the efficiency of entire power generation cycle based on geothermal energy. Out of the many renewable energy sources available, geothermal energy is a rarely used source. So far, only 1.5% of the available geothermal energy resource is extractable globally. However, nanofluids can help in extracting more geothermal energy and producing power in a Rankine cycle more efficiently. Moreover, nanofluids can be put in place to cool the pipes, which carry geothermal fluid at high temperatures, that is, in the range between 500°C and 1000°C. Furthermore, nanofluids behave as "fluid superconductors" and hence might be utilized as a working fluid to convert energy into useful form [205].

5. Conclusion

In this paper, the goal was to present an overview of the recent developments in the field of nanofluids. Preparation, characteristics, and applications of nanofluids have been discussed in detail. It is important to mention that thermophysical properties vary with the volume concentration, temperature, and flow rate. However, more research is required to study the effect of nanoparticle's shape, size, and surface chemistry on the properties of nanofluids. In general, the increase of volume fraction of the nanoparticles increases the density, viscosity, and thermal conductivity of the nanofluid. In the case of heat transfer coefficient and Nusselt number, studies showed that there is a limit to enhancement and an optimum volume fraction exists. The application of nanofluids appears promising in a wide range of fields; however, more work is required in some areas such as the stability of these nanofluids in various applications, the use of hybrid nanofluids, and effect of working conditions on the properties of these nanofluids. Furthermore, the experimental and lab scale results must be scaled up to the prototype level in order to evaluate the results and implement them commercially in various fields such as water desalination, power generation, mechanical devices, defense, and space applications. Finally, environmental consequences of nanofluids must be investigated and analyzed using cradle to grave approach or LCA (Life Cycle Assessment) method.

Competing Interests

The authors declare that they have no competing interests.

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