

An Extensive Review on Nanofluids - Based on Available Experimental Studies

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Presentation/Paper Type: Oral / Full Paper

Abstract – In recent years, nanofluids, the dispersion of nanoparticles with sizes less than 100 nm in base fluids, have been attracted the interest of many researchers due to their capability of enhancing thermophysical properties. In this review paper, experimental studies on nanofluids have been analysed collectively for the period from 1993 to 2018. Preparation techniques and thermophysical properties of nanofluids were given in tabular form. Despite the fact that there are a lot of review studies, the aim of this work is to give all of the studies about nanofluids on a common objective basis to facilitate future research in this area.

Keywords – Nanofluids, preparation, characterization, stability, thermophysical properties

I. INTRODUCTION

Nanofluid is a fluid produced by dispersing nanometer-sized materials (nanoparticles, nanofibers, nanotubes, nanowires, nanorods and nanosheets, generally less than 100 nm) in base fluids such as water, ethylene glycol, propylene glycol, oil and refrigerants with or without surfactants. This term was first used by Choi who developed a new class of heat transfer fluids at Argonne National Laboratory in U.S.A [1]. Researchers used different types of nanoparticles including single elements (e.g., Al, Cu), oxides (e.g., Al₂O₃, CuZnFe₄O₄), carbides (e.g., SiC, B₄C), metal nitrides (e.g., SiN, TiN), carbon materials (e.g., graphite, carbon nanotubes, diamond) and hybrid nanoparticles.

Two primary methods are used to prepare nanofluids: the one-step method and the two-step method. In the one-step method, the agglomeration of nanoparticles is minimized and dispersion of nanoparticles is avoided. In the two-step method, nanomaterials are first produced as dry powders by chemical or physical techniques and later the nanosized nanosized powder is dispersed into a base fluid. Two-step method can be preferred for synthesizing nanofluids in large scale. However, a homogeneous mixture in the two-step method is still a problem. In order to overcome the stability problem in nanofluids, different methods are available (ultrasonic treatments, stirring, adding surfactants and adjusting pH value). The stability of nanoparticle in the base fluid and the shape, size and structure of nanoparticles are evaluated by different characterization techniques (transmission electron microscopy (TEM), scanning electron microscope (SEM), dynamic light scattering (DLS), x-ray diffraction (XRD), fourier transform infrared (FT-IR) spectroscopy, energy dispersive spectroscopy (EDS), ultra violet-visible (UV-Vis) spectrophotometer, centrifugation,

sediment photograph capturing, sedimentation balance and zeta potential analysis).

Recent experimental investigations have indicated that nanofluids have different thermophysical properties compared to those of base fluid. Most of them have focused on thermal conductivity because of adding small amount of nanoparticles leading to a significant increase in thermal conductivity of base fluids. However, other thermophysical properties such as viscosity, density and specific heat of nanofluids are also different from those of basefluid.

In this work, experimental studies related to enhancement of thermophysical properties (thermal conductivity, dynamic viscosity, density and specific heat) of nanofluids and different preparation techniques in their synthesis are reviewed and presented in tabular forms for the convenience of the audience.

II. PREPARATION, STABILITY AND CHARACTERIZATION OF NANOFLUIDS

Preparation process is the first significant step in experimental studies because of its remarkable effect on stability and thermophysical properties of nanofluids. The available experimental studies on the preparation, stability and characterization of nanofluids are summarized according to different base fluids of water, ethylene glycol, ethylene glycol-water and some other in Table 1.

Two-step method [2]-[22], [24]-[71] has been more commonly used method comparing to one-step method [23]. However, in two-step method, the agglomeration and sedimentation of nanoparticles are big challenges for a homogeneous suspension.

Table 1. An outline of previous studies on nanofluids

Researcher	Base fluid	Nanoparticle	Particle shape - size	Particle concentration (vol.% / wt.%)	Preparation method	Stability enhancement technique	Characterization technique	Reference
Masuda et al. (1993)	Water	Al ₂ O ₃ ; SiO ₂ ; TiO ₂	Spherical 13 nm; 12 nm; 27 nm	5,10,15 wt.% 2.5, 5 wt.% 4, 8, 12, 16 wt.%	Two-step	pH control	TEM	2
Wang et al. (1999)	Water, ethylene glycol, vacuum pump fluid, engine oil	Al ₂ O ₃ ; CuO	Spherical 28 nm; 23 nm	0-15 vol.%	Two-step	Ultrasonication	TEM	3
Putra et al. (2003)	Water	Al ₂ O ₃ ; CuO	Spherical 131.2 nm; 87.3 nm	1-4 vol.%	Two-step	Ultrasonication	TEM	4
Wen et al. (2004)	Water	Al ₂ O ₃	Spherical 27–56 nm	0-1.6 vol.%	Two-step	Ultrasonic bath, adding SDBS surfactant	SEM	5
Murshed et al. (2005)	Water	TiO ₂	Spherical 15 nm; Rod-shapes diameter: 10 nm, length: 40 nm	0.5-5 vol.%	Two-step	Ultrasonication, adding oleic acid and CTAB surfactants	TEM	6
Ding et al. (2006)	Water	MWCNT (Multi-walled carbon nanotubes)	-	0-1 wt.%	Two-step	Ultrasonication, adding GA surfactant, pH control, high shear homogeniser	TEM, SEM	7
Hwang et al. (2006)	Water	MWCNT; CuO; SiO ₂	Cylindrical diameter: 10-30 nm, length: 10-50µm; Spherical 33 nm; 12 nm	0- 1 vol.%	Two-step	Ultrasonication, adding SDS surfactant	Microscopic technique	8
He et al. (2007)	Water	TiO ₂	Spherical 95 nm	0-2.5 vol.%	Two-step	Ultrasonication	SEM	9
Hwang et al. (2007)	Water	MWCNT	Cylindrical diameter: 10-30 nm, length:10-50 µm	0- 1 vol.%	Two-step	Ultrasonication, adding SDS surfactant,	-	10
Zhang et al. (2007)	Water	CNT	Cylindrical diameter: 150 nm length:10µm	0-1 vol.%	Two-step	Ultrasonication, adding SDS surfactant	TEM	11
Li et al. (2008)	Water	Cu	Spherical 25 nm	0.1-0.8 wt.%	Two-step	Ultrasonication, adding SDBS surfactant, changing pH control	TEM, zeta potential	12
Murshed et al. (2008)	Water	Al ₂ O ₃ ; TiO ₂	Spherical 80, 150 nm; 15 nm	0-5 vol.%	Two-step	Ultrasonication, adding CTAB surfactant,	-	13
Nguyen et al. (2008)	Water	Al ₂ O ₃	Spherical 36, 47 nm	1–9.4 vol.%	Two-step	-	-	14
Duangthongsuk and Wongwises (2009)	Water	TiO ₂	Spherical 21 nm	0.2– 2 vol.%	Two-step	Stirring, ultrasonic vibrator, pH control	TEM	15
Mintsa et al. (2009)	Water	Al ₂ O ₃ ; CuO	Spherical 36, 47 nm; 29 nm	0-18 vol.%	Two-step	Stirring	-	16
Zhu et al. (2009)	Water	Al ₂ O ₃	Spherical 15–50 nm	0.02–0.15 wt.%	Two-step	Adding SDBS surfactant, pH control, stirring, ultrasonic vibrator	TEM, zeta potential, UV-Vis Spectrophotometer	17

Table 1. An outline of previous studies on nanofluids (continued)

Researcher	Base fluid	Nanoparticle	Particle shape - size	Particle concentration (vol.% / wt.%)	Preparation method	Stability enhancement technique	Characterization technique	Reference
Beck et al. (2010)	Water, ethylene glycol, and ethylene glycol- water (50:50 wt.%)	Al ₂ O ₃	Spherical 10-50 nm	1, 3, 4 vol.%	Two-step	Ultrasonic agitation	-	18
Chandrasekar et al. (2010)	Water	Al ₂ O ₃	Spherical 43 nm	0.33–3 vol.%	Two-step	Ultrasonic vibration	SEM	19
Godson et al. (2010)	Water	Silver	Spherical 60 nm	0.3, 0.6, 0.9 vol.%	Two-step	Ultrasonic vibration, stirring	The powder x-ray diffraction (PXRD)	20
Teng et al. (2010)	Water	Al ₂ O ₃	Spherical 20, 50, 100 nm	0.5–2 wt.%	Two-step	Ultrasonic vibration	TEM	21
Yeganeh et al. (2010)	Water	Nanodiamond (ND)	Spherical 4 nm (average)	0.8-3 vol.%	Two-step	Ultrasonic waves	XRD, TEM	22
Gandhi et al. (2011)	Water	graphene	Graphene sheet length: 5–1500 nm	0.01–0.2 vol.%	One-step	-	TEM, UV–Vis spectrophotometer	23
Suresh et al. (2011)	Water	Al ₂ O ₃ -Cu hybrid particles	Spherical 17 nm	0.1–2 vol.%	Two-step	Adding SLS surfactant, ultrasonic vibrator	SEM, XRD	24
Aladag et al. (2012)	Water	Al ₂ O ₃ ; CNT	Spherical 30 nm; Cylindrical 200 µm × Ø9 µm	1 wt.%	Two-step	Adding surfactant	DLS	25
Hung and Chou (2012)	Water	MWCNT	Cylindrical outer diameter: 20–30 nm	0.25–1.5 wt.%	Two-step	Adding chitosan surfactant used, ultrasonic vibrator	TEM, DLS, UV–Vis spectrophotometer	26
Suganthi and Rajan (2012)	Water	ZnO	Spherical 35–40 nm	0.25–2 vol.%	Two-step	Adding SHMP surfactant, ultrasonication	SEM, zeta potential	27
Yiamsawasd et al. (2012)	Water	TiO ₂ , Al ₂ O ₃	Spherical 21, 120 nm	0–8 vol.%	Two-step	Ultrasonic vibrator	TEM	28
Halefadi et al. (2013)	Water	CNT	Cylindrical diameter: 9.2 nm length: 1.5 µm	0.0055–0.55 vol.%	Two-step	Ultrasonication, adding SDBS surfactant, stirring	SEM	29
Mena et al. (2013)	Water	Al ₂ O ₃	Spherical 13–131 nm	0–1%	Two-step	pH control	-	30
Reddy and Rao (2013)	Water, ethylene glycol-water (40:60, 50:50 wt.%)	TiO ₂	Spherical 21 nm	0.2-1 vol.%	Two-step	Adding oleic acid and CTAB surfactants, ultrasonic bath	-	31
Sundar et al. (2013)	Water	Fe ₃ O ₄	Spherical 40 nm	0–2 vol%	Two-step	Adding CTAB surfactant, ultrasonic bath	Zeta potential	32
Esfe et al. (2014)	Water	MgO	Spherical 40 nm	0.0625, 0.125, 0.25, 0.5, 1, 1.13 vol.%.	Two-step	Ultrasonic vibrator, adding CTAB surfactant	TEM	33
Ghanbarpour et al (2014)	Water	Al ₂ O ₃	Spherical 75 nm	3-50 wt.%	Two-step	Ultrasonic bath	TEM, DLS	34
Hajjar et al. (2014)	Water	graphene oxide (GO)	Nanosheet	0.05, 0.1, 0.15, 0.2 & 0.25 wt.%	Two-step	Stirring, ultrasonication	SEM, XRD, UV–Vis spectrophotometer	35
Said et al. (2014)	Water	Al ₂ O ₃ ; TiO ₂	Spherical 109.4 nm; 126.9 nm	0.05–0.3 vol.%	Two-step	Ultrasonication, high pressure homogenizer, pH control	TEM, FESEM, DLS, zeta potential	36

Table 1. An outline of previous studies on nanofluids (*continued*)

Researcher	Base fluid	Nanoparticle	Particle shape - size	Particle concentration (vol.% / wt.%)	Preparation method	Stability enhancement technique	Characterization technique	Reference
Esfe et al. (2015)	Water	Fe	Spherical 37, 71, 98 nm	0–1 vol.%	Two-step	Ultrasonic Vibrator	-	37
Afrand et al. (2016)	Water	Fe ₃ O ₄	Spherical 20–30 nm	0–3 vol.%	Two-step	Magnetic stirring, ultrasonic processor	XRD	38
Megatiff et al. (2016)	Water	CNT–TiO ₂ (Hybrid)	–	0.1, 0.15, 0.2 wt.%	Two-step	Ultrasonication, stirring	SEM, XRD	39
Said (2016)	Water	SWCNT	Cylindrical diameter: 1–2 nm, length: 500 nm	0.1, 0.25, 0.5 vol.%	Two-step	Adding SDS surfactant, high-pressure homogenizer, ultrasonication	TEM, zeta potential	40
Sundar et al. (2016)	Water	ND	Spherical 80–100 nm	0.2–1 vol.%	Two-step	Ultrasonic Bath	TEM, XRD, FT-IR, zeta potential	41
Huminić et al. (2017)	Water	SiC	Spherical <25 nm	0.5, 1 wt.%	Two-step	Adding CMCNa surfactant, ultrasonic homogenizer	TEM, XRD	42
Bouguerra et al. (2018)	Water	Al ₂ O ₃	Spherical 50 nm	0.2–2 vol.%	Two-step	pH control, ultrasonication	-	43
Gao et al. (2018)	Water	Graphene nanoplatelet (GNP)	Cylindrical sheet diameter: 20µm, thickness: 6 nm	0–0.15 wt.%	Two-step	Ultrasonication	SEM, UV–Vis absorption spectrum analysis	44
Heyhat and Irannezhad (2018)	Water	Ag; SiC; Graphene oxide (GO)	Spherical 20 nm; 55 nm; Nanosheet	100–1000 ppm; 0.25–1 vol.%; 0.02–0.05 wt.%	Two-step	Adding PVP surfactant for Ag and CTAB for SiC, ultrasonic bath	TEM	45
Liu et al. (2005)	Ethylene glycol, synthetic engine oil	CNT	Cylindrical inner diameter: 5–10 nm, outer diameter: 20–50 nm	0.2–1.0 vol. %, 1.0–2.0 vol.%	Two-step	Magnetic stirring ultrasonic homogenizer, adding NHS surfactant in synthetic engine oil suspensions	SEM, high-resolution transmission electron microscopy (HRTEM), XRD	46
Chopkar et al. (2006)	Ethylene glycol	Al ₇₀ Cu ₃₀	Spherical 20–40 nm	0.2–2.0 vol.%	Two-step	Adding oleic acid surfactant, intensive ultrasonic vibration, magnetic stirring	XRD, TEM	47
Chen et al. (2007)	Ethylene glycol	TiO ₂	Spherical 25 nm	0–8 wt%	Two-step	Ultrasonication	SEM	48
Yu et al. (2009)	Ethylene glycol	ZnO	Spherical 10–20 nm	0–5 vol.%	Two-step	Stirring, ultrasonication	SEM	49
Moosavi et al. (2010)	Ethylene glycol, glycerol	ZnO	Spherical 67.17 nm	0–3 vol.%	Two-step	Adding ammonium citrate surfactant, stirring	TEM, SEM, XRD	50
Paul et al. (2011)	Ethylene glycol	Al ₉₅ Zn ₀₅	Spherical 10–30 nm	0.01–0.10 vol.%	Two-step	Ultrasonic vibration, magnetic stirring	TEM, SEM, XRD, EDS, SAD analysis	51
Yu et al. (2011)	Ethylene glycol	Graphene, graphene oxide (GO)	Nanosheet thickness: 0.7–1.3 nm	1–5 vol. %	Two-step	Ultrasonication, adding SDBS surfactant.	TEM, HRTEM, atomic force microscopy (AFM), FT-IR	52
Yu et al. (2011a)	Ethylene glycol, propylene glycol	Aluminum nitride (AlN)	Spherical 50 nm	1–10 vol.%	Two-step	Stirring, ultrasonication	SEM	53
Gallego et al. (2014)	Ethylene glycol	ZnO	Spherical 40–100 nm	0–6.2 vol.%	Two-step	Ultrasonic homogenizer	SEM, EDS, XRD, TEM	54

Table 1. An outline of previous studies on nanofluids (*continued*)

Researcher	Base fluid	Nanoparticle	Particle shape - size	Particle concentration (vol.% / wt.%)	Preparation method	Stability enhancement technique	Characterization technique	Reference
Akilu et al. (2017)	Ethylene glycol	TiO ₂ -CuO/C (hybrid)	Spherical 26, 20 nm	0.5, 1, 1.5, 2 vol. %	Two-step	Wet mixing approach using hexane, ultrasonication	FE-SEM, EDS, XRD	55
Zyla (2017)	Ethylene glycol	MgO	Spherical 20 nm	1.6, 3.4, 5.2, 7.2 vol. %	Two-step	Mechanical stirring, ultrasonication	SEM	56
Zyla and Fal (2017)	Ethylene glycol	SiO ₂	Spherical 7-14 nm	0.5, 1, 1.5, 2, 2.6 vol. %	Two-step	Mechanical stirring, ultrasonication	SEM	57
Ahmadi et al. (2018)	Ethylene glycol	CuO	Spherical 47.6 nm (average)	0-2 vol. %	Two-step	-	-	58
Keyvani et al. (2018)	Ethylene glycol	Cerium oxide	Spherical 10-30 nm	0.25-2.5 vol. %	Two-step	Adding CTAB surfactant, stirring, ultrasonic waves	Zeta potential	59
Namburu et al. (2007)	Ethylene glycol-water (60:40 wt%)	CuO	Spherical 29 nm	0-6.12 vol. %	Two-step	Ultrasonic agitator	-	60
Sahooli and Sabbaghi (2013)	Ethylene glycol-water (65:35 wt%)	CuO	Spherical 30-80	0.01-0.1 wt. %	Two-step	Magnetic stirring, ultrasonication	SEM, Particle Size Analyzer (PSA), zeta potential	61
Elias et al. (2014)	Ethylene glycol-water (50:50 wt. %)	Al ₂ O ₃	Spherical 13 nm	0-1 vol. %	Two-step	Ultrasonic homogenizer	Sediment photograph capturing	62
Sundar et al. (2014)	Ethylene glycol-water (20:80, 40:60, 60:40 wt. %)	Al ₂ O ₃	Spherical 36 nm	0.3-1.5 vol. %	Two-step	Ultrasonic cleaner (bath)	SEM, XRD, zeta potential	63
Kole and Dey (2011)	Gear oil	CuO	Spherical 40 nm	0.5–2.5 vol. %	Two-step	Adding oleic acid surfactant, intensive ultrasonication, magnetic force agitation	FT-IR, DLS	64
Dudda and Shin (2013)	NaNO ₃ -KNO ₃ (60:40 wt. %)	SiO ₂	Spherical 5, 10, 30, 60 nm	1 wt. %	Two-step	Ultrasonication	SEM	65
Lu and Huang (2013)	NaNO ₃ -KNO ₃ (60:40 wt. %)	Al ₂ O ₃	Spherical 13, 90 nm	0.9, 2.7, 4.6 vol. %	Two-step	Ultrasonication	SEM, EDS	66
Moghaddam et al. (2013)	Glycerol	Graphene	Nanosheets size of the few layer graphene: 15–50 nm	0.25–2 mass fractions%	Two-step	Ultrasonication	TEM, SEM, Raman spectroscopy, FT-IR, HRTEM, EDX analysis, XRD, Boehms titration analysis, N ₂ adsorption-desorption technique.	67
Rashin and Hemalatha (2013)	Coconut oil	CuO	Spherical 20 nm	0–2.5 wt. %	Two-step	Ultrasonication	TEM, HRTEM, XRD	68
Tiznobaik and Shin (2013)	Li ₂ CO ₃ -K ₂ CO ₃ (62:38 molar ratio)	SiO ₂	Spherical 5, 10, 30, 60 nm	1 wt. %	Two-step	Ultrasonication	SEM	69
Manikandan et al. (2014)	Propylene glycol	Sand	Spherical 20–25 nm	0 to 2 vol. %	Two-step	Stirring by bead milling, ultrasonication	XRD, zeta potential, FT-IR	70
Sang and Liu (2017)	K ₂ CO ₃ -Li ₂ CO ₃ -Na ₂ CO ₃ (4:4:2 mass ratio)	SiO ₂ ; CuO; TiO ₂ ; Al ₂ O ₃	Spherical 5 nm; 20 nm; 30 nm; 60 nm	1 wt. %	Two-step	Ultrasonication	Differential scanning calorimetry (DSC), SEM, XRD	71

Ultrasonic treatment [3]-[13], [15], [17]-[22], [24], [26]-[29], [31-49], [51]-[57], [59]-[71] is used to break down the clusters of nanoparticles. There are two types of ultrasonication methods as direct method (using probe) and indirect method (using ultrasonic bath). Sundar et al. [41] prepared nanodiamond (ND)-water nanofluids using two-step method and observed reducing ND particle agglomerations with the ultrasonication bath. The ultrasonication method is generally used with stirring method. Zyla and Fal [57] prepared suspensions of silicon dioxide (SiO₂) nanoparticles in (7-14 nm) ethylene glycol (EG) using mechanical stirring and the sonication with ultrasound wave bath.

The addition of surfactants - dispersants is used to reduce the surface tension of the base fluid and improve wetting behaviour. Therefore dispersants improve the stability and thermophysical properties of nanofluids. Researchers employed different type of surfactants including sodium dodecylbenzenesulfonate (SDBS) [5], [12], [17], [29], [52] oleic acid [6], [31], [47], [64] and Cetyltrimethylammonium bromide (CTAB) [6, 13, 31-33, 45, 59], gum Arabic (GA) [7] sodium dodecyl sulfate (SDS) [8], [10]-[11], [40], Sodium lauryl sulphate (SLS) [24], chitosan [26], sodium hexametaphosphate (SHMP) [27], carboxymethyl cellulose (CMC-Na) [42], Polyvinylpyrrolidone (PVP) [45], N-hydroxysuccinimide (NHS) [46], ammonium citrate [50].

pH value of nanofluids also influences the stability of nanofluids. Since nanoparticles surface charge depends on pH values of the suspension, optimal pH value can reduce the agglomeration with increasing repulsive forces between nanoparticles. Ding et al. [7] experimentally investigated the heat transfer behaviour of aqueous suspensions of multi-walled carbon nanotubes (CNT) nanofluids flowing through a horizontal tube. Their results showed that CNT nanofluids were found to be very stable for months without visually observable sedimentation after a preparation process including sonication for over 24 hours, adding Gum Arabic dispersant, adjusting the suspension to a preset pH level and treating the mixture with the high shear homogeniser for 30 min.

Various characterization techniques of nanofluids have been developed. TEM and SEM are widely used microscopic techniques to determine the shape, size and distribution of nanoparticles. XRD is employed to determine the crystal structure of crystalline materials. FT-IR spectroscopy is done to study the nanoparticle. DLS analysis is performed to estimate the average disperse size of nanoparticles in the base liquid media. Zeta potential measurement is one of the most critical tests to validate the quality of the nanofluids stability via a study of its electrophoretic behavior. Zeta potential is the potential difference between the dispersion medium and the stationary layer of fluid attached to the nanoparticle. The rising electrostatic repulsive forces between nanoparticles leads to an increase in the value of zeta potential which indicates better stability of nanofluids. Since zeta potential analysis is applicable only for the certain viscosity of fluid, UV-vis-spectrophotometer is commonly utilized to determine the stability of nanofluids including all base fluids. On the other hand, the sedimentation photograph capturing

method is easy and cheap method and the formation of sediments is detected by capturing photographs at equal intervals of time using a camera. The visual investigation of sedimentation of nanofluids is also performed by centrifugation method which is a much faster method compared to the photograph capturing method.

Hajjar et al. [35] estimated the characteristics of graphene oxide (GO) nanosheets-water mixture which was stirred and sonicated using an ultrasonic washing machine. The size and morphological characterization of the GO nanosheets (GONs) were examined by using SEM and XRD and UV-vis-spectrophotometer were used to investigate the structure of GONs. Said et al. [36] used the ultrasonicator, high pressure homogenizer and pH control to dissolve Al₂O₃ (13 nm) and TiO₂ (21 nm) nanoparticles into water. The mean nanoparticle diameters were studied by DLS technique, and the nanofluid Field emission scanning electron microscopy (FESEM) and TEM were used to achieve the morphological characterization of the the nanoparticles. In order to determine the nanofluid stability, a zetasizer Nano instrument was used by measure zeta potential of the nanoparticles in water.

Elias et al. [62] prepared Al₂O₃ (13 nm) nanoparticles 50:50% by weight of ethylene glycol-water mixture by using an ultrasonic homogenizer. The stability of the nanofluid was been checked with sedimentation photograph capturing method. Also, Moghaddam et al. [67] fabricated graphene-glycerol nanofluids with the help of a sonicator. After the preparation, the morphology and structure of the graphene sheets were characterized by nine methods, namely TEM, high resolution transmission electron microscopy (HRTEM), SEM, Raman spectroscopy, FT-IR spectroscopy, energy-dispersive X-ray (EDX) analysis, powder X-ray diffraction, Boehm's titration, and N₂ adsorption-desorption technique.

III. THERMOPHYSICAL PROPERTIES OF NANOFLUIDS

Suspension of nanomaterials in the base fluids results in the modification of thermophysical properties such as thermal conductivity, viscosity, density and specific heat. A detailed summary of the available experimental studies on thermophysical properties of various nanofluids is presented in Table 2.

The thermal conductivity of nanofluids is measured by different methods such as the transient hot wire, temperature oscillation and steady-state parallel plate. The transient hot wire method is widely used for measuring thermal conductivity due to low uncertainty with a short measurement time. The methods to measure the rheological characteristics of the nanofluids are mainly divided into two groups including the flow type such as capillary and orifice (cup) viscometers and the drag type such as rotational, falling object and vibrational/oscillating viscometers.

The parameters related to the enhancement of thermophysical properties are base fluid type, nanoparticle type, size, shape and concentration, temperature, adding surfactants, pH value of base fluids and sonication time.

Table 2. An outline of previous studies on thermophysical properties of nanofluids

Researcher	Measurement methods	Temperature range	k enhancement (%)	μ enhancement (%)	ρ enhancement (%)	C_p enhancement (%)	Reference
Masuda et al. (1993)	Transient hot wire, viscometer	27–72 °C	32% increase with 4.3 vol.% at 32 °C.	245% increase with 4.3 vol.% at 72 °C.	-	-	2
Wang et al. (1999)	Steady-state parallel-plate, viscometer	Room temperature	55% increase with 9.6 vol.% at room temperature.	85% increase with 5 vol.% at room temperature.	-	-	3
Putra et al. (2003)	Temperature oscillation technique (Polyoxymethylene, cylindrical block and thermocouples)	20–50 °C	36% increase with 4 vol.% at 50 °C.	-	-	-	4
Wen et al. (2004)	Copper tube with a silicon rubber flexible heater and thermocouples	22 °C	9.8% increase with 1.6 vol.% at 22 °C.	-	-	-	5
Murshed et al. (2005)	Transient hot wire	Room temperature	Near to 33% and 30% increase for rod and spherical shapes particles at 5 vol.% respectively.	-	-	-	6
Ding et al. (2006)	Transient hot wire, Bohlin CVO rheometer	20, 25, 30 °C	80% increase with 1 wt.% at 30 °C.	-	-	-	7
Hwang et al. (2006)	Transient hot wire	-	Up to 11.3% increase with 1 vol.%.	-	-	-	8
He et al. (2007)	Transient hot wire	22 °C	5% increase with 2 vol.% at 22 °C.	Approximately 11% increase with 2 vol.% at 22 °C.	-	-	9
Hwang et al. (2007)	Transient hot wire	Room temperature	7% increase with 1 vol.% at room temperature.	-	-	-	10
Zhang et al. (2007)	The transient short hot wire	23 °C	42% increase with 0.9 vol.% at 23 °C.	-	-	-	11
Li et al. (2008)	Hot Disk Thermal Constants Analyser	25–30 °C	Nearly 18% increase with 0.8 w.t.% at 25-30 °C.	-	-	-	12
Murshed et al. (2008)	Transient hot wire, controlled rate rheometer	20–60 °C	12% increase with 1 vol.% at 60 °C.	82% and 84% increase with 5 vol.% and 4 vol.% for Al ₂ O ₃ and TiO ₂ respectively.	-	-	13
Nguyen et al. (2008)	The piston-type viscometer (ViscoLab450 model)	22–75 °C	-	5.47% increase with 12.9 vol.% at 22 °C.	-	-	14
Duangthongsuk and Wongwises (2009)	Transient hot wire, Bohlin rotational rheometer	15–35 °C	8% increase with 2 vol.% at 15 °C.	17% increase with 2 vol.% at 35 °C.	-	-	15
Mintsa et al. (2009)	Transient hot wire	Room temperature	19% increase with 3.1 vol.% at 38.5 °C.	-	-	-	16
Zhu et al. (2009)	Transient plane source (TPS)	25–30 °C	10.1% increase with 0.15 wt.% at 25–30 °C.	-	-	-	17
Beck et al. (2010)	The transient hot wire	23–137 °C	14% increase with 4 vol.% at 76 °C	-	-	-	18
Chandrasekar et al. (2010)	Transient hot wire, Brookfield cone and plate viscometer	Room temperature	10% increase with 3 vol.% at room temperature.	136% increase with vol. 5% at room temperature.	-	-	19
Godson et al. (2010)	Transient hot wire, reverse-flow viscometer	50-90 °C	129% increase with 0.9 vol. % at 90 °C.	44% increase with vol. 0.9% at 90 °C.	-	-	20
Teng et al. (2010)	Transient hot wire	10–50 °C	14.6% increase with 2 wt.% at 50 °C.	-	-	-	21

Table 2. An outline of previous studies on thermophysical properties of nanofluids (*continued*)

Researcher	Measurement methods	Temperature range	k enhancement (%)	μ enhancement (%)	ρ enhancement (%)	C_p enhancement (%)	Reference
Yeganeh et al. (2010)	Transient hot wire	30–50 °C	9.8 % increase with 3 vol.% at 50 °C.	-	-	-	22
Gandhi et al. (2011)	Transient hot wire	30–50 °C	27 % increase with 0.2 vol.% at 50 °C.	-	-	-	23
Suresh et al. (2011)	Transient hot wire, Brookfield cone and plate viscometer (LVDV-I PRIME C/P)	Room temperature	12 % increase with 2 vol.% at room temperature.	103 % increase with 2 vol.% at room temperature.	-	-	24
Aladag et al. (2012)	A stress controlled rheometer	2–10 °C	-	26% decrease with 1 wt.% when the temperature increased from 2 to 10 °C.	-	-	25
Hung and Chou (2012)	Transient hot wire, viscometer	Room temperature	8.9 % increase with 1.5 wt.% at room temperature.	235 % increase with 1.5 wt.% at room temperature.	-	-	26
Suganthi and Rajan (2012)	Viscometer (LVDV II+ PRO)	35–55 °C	-	18 % increase with 1.5 vol.% at 35 °C.	-	-	27
Yiamsawasd et al. (2012)	Transient hot wire	15–60 °C	23 % increase with 8 vol.% at room temperature.	-	-	-	28
Halefadi et al. (2013)	A stress-controlled rheometer	0–40 °C	-	510 % increase with 0.557 vol.% at 10 °C.	-	-	29
Mena et al. (2013)	A Brookfield rheometer, model LVDV-III, with a cone-plate geometry (spindle CPE-40)	20–70 °C	-	Maximum viscosity of 2.45 cP was obtained 4 vol.% at 10 °C.	-	-	30
Reddy and Rao (2013)	Thermal conductivity apparatus with thermocouples	30–70 °C	5%, 12% and 7% increase for water, 40:60 and 50:50 ethylene glycol-water base fluids with 1 vol.% at 70 °C, respectively.	-	-	-	31
Sundar et al. (2013)	Transient hot wire, AR-1000 rheometer (TA Instruments)	20–60 °C	48 % increase with 2 vol.% at 60 °C.	197 % increase with 2 vol.% at 60 °C.	-	-	32
Esfe et al. (2014)	Transient hot wire	24.7–60 °C	25 % increase with 1.13 vol.% at 60 °C.	13 % increase with 1.13 vol.	-	-	33
Ghanbarpour et al. (2014)	TPS, rotating coaxial cylinder viscometer.	20–50 °C	87.5 % increase with 50 wt.% at 20 °C.	300 % increase with 50 wt.% at 50 °C.	-	-	34
Hajjar et al. (2014)	Transient short hot wire	10–40 °C	47.54 % increase with 0.25 wt.% at 40 °C.	-	-	-	35
Said et al. (2014)	Transient hot-wire, Brookfield Viscometer (DV-II+Pro Programmable Viscometer),	25–80 °C	20 % increase with 0.3 vol.% at 80 °C.	5% increase with 0.5 vol.% for Al ₂ O ₃ at 25 °C. 35% increase with 0.5 vol.% for TiO ₂ at 25 °C.	-	-	36
Esfe et al. (2015)	Transient hot wire	An ambient temperature	7% increase with 1 vol.% at an ambient temperature	7% increase with 1 vol.% at an ambient temperature	-	-	37
Afrand et al. (2016)	Transient hot wire	20–55 °C	89% increase with 3 vol.% at 55 °C.	-	-	-	38
Megatiff et al. (2016)	The transient hot wire, a viscometer	25–40 °C	20% increase with 0.2 wt.% at 25 °C.	6% increase with 0.2 wt.% at 25 °C.	1% increase with 0.2 wt.% at 25 °C.	2% decrease with 0.2 wt.% at 25 °C.	39
Said (2016)	The transient hot wire, the Brookfield viscometer (DV-II+Pro Programmable Viscometer), heat flux-type differential scanning calorimeter	20–60 °C	62% increase with 0.5 vol.% at 60 °C.	100% increase with 0.5 vol.% at 60 °C.	-	40% decrease with 0.5 vol.% at 20 °C.	40

Table 2. An outline of previous studies on thermophysical properties of nanofluids (*continued*)

Researcher	Measurement methods	Temperature range	k enhancement (%)	μ enhancement (%)	ρ enhancement (%)	C_p enhancement (%)	Reference
Sundar et al. (2016)	The transient hot wire, A&D-vibro viscometer	20–60 °C	23% increase with 1 vol.% at 60 °C.	30 % increase with 1 vol.% at 20 °C.	-	-	41
Huminic et al. (2017)	The transient hot wire	20–50 °C	18% increase with 1 wt.% at 50 °C.	40% increase with 1 wt.% at 20 °C.	-	-	42
Bouguerra et al. (2018)	THW (The transient hot wire)-LI liquid thermal conductivity system, a stress controlled rheometer (TA HR-2)	25 °C	23% increase with 2 vol% at 25 °C.	50% increase with 2 vol.% at 25 °C.	-	-	43
Gao et al. (2018)	The transient hot wire	-20-50 °C	7% increase with 0.15 vol.% at 40 °C.	-	-	-	44
Heyhat and Irannezhad (2018)	The transient hot wire	25-55 °C	6%, 7.2%, 27% increase for Ag, SiC, and GO respectively, at temperature range between 25 °C and 55 °C.	-	-	-	45
Liu et al. (2005)	Modified transient hot wire	Room temperature	30.3% increase with 2 vol.% at room temperature.	-	-	-	46
Chopkar et al. (2006)	The transient hot wire	Room temperature	27% increase with 2.5 vol.% at room temperature.	-	-	-	47
Chen et al. (2007)	The transient hot wire, Bolin CVO rheometer	20–60 °C	15% increase with 1.8 vol.% at 40 °C	23% increase with 1.8 vol.%	-	-	48
Yu et al. (2009)	Transient short hot wire, LV DV-II Brookfield viscometer	10–60 °C	27% increase with 5 vol.% at 30 °C	-	-	-	49
Moosavi et al. (2010)	The transient hot wire, Ostwald viscometer	10-50 °C	10.5% increase with 3 vol.% at 25 °C.	27% increase with 0.6 vol.% for ethylene glycol base fluids at 25 °C.	-	-	50
Paul et al. (2011)	The transient hot wire	30-70 °C	103% increase with 0.1 vol.% at 70 °C.	-	-	-	51
Yu et al. (2011)	The transient short hot wire	10-60 °C	86% increase with 5 vol.% at 60°C	-	-	-	52
Yu et al. (2011a)	The transient short hot wire, a viscometer (LV DV-II+ Brookfield Programmable Viscometer)	10-60 °C	39% and 40% increase for ethylene glycol and propylene glycol base fluids, respectively, with 10 vol.% at 60 °C.	138% and 123% increase for ethylene glycol and propylene glycol base fluids, respectively, with 9 vol.% at 20 °C.	-	-	53
Gallego et al. (2014)	The transient hot wire, Schott rotational viscometer, vibrating tube densimeter	10-70 °C	45% increase with 6.9 vol.% at 70°C	38% increase with 4.7 vol.% at 10 °C	0.9-4% increase within volume concentration range from 0.6 to 3 for the temperature range of 10 °C to 70 °C	-	54
Aklu et al. (2017)	The transient hot wire, rotational rheometer	25-60 °C	17% increase with 2 vol.% at 60°C	80% increase with 2 vol.% at 40°C	-	-	55
Zyla (2017)	The transient hot wire, HAAKEMARS2 rheometer	Room temperature	33% increase with 7.2 vol.% at 25°C	81% increase with 7.2 vol.% at 25°C	-	-	56
Zyla and Fal (2017)	The transient hot wire, HAAKEMARS2 rheometer	25 °C	3% increase with 2.6 vol.% at 25°C	39% increase with 2.6 vol.% at 25°C	-	-	57
Ahmadi et al. (2018)	-	10-60 °C	17% increase with 2 vol.% at 40°C	-	-	-	58

Table 2. An outline of previous studies on thermophysical properties of nanofluids (*continued*)

Researcher	Measurement methods	Temperature range	k enhancement (%)	μ enhancement (%)	ρ enhancement (%)	C_p enhancement (%)	Reference
Keyvani et al. (2018)	The transient hot wire	25-50 °C	22% increase with 2.5 vol.% at 50°C.	-	-	-	59
Namburu et al. (2007)	LV DV-II Brookfield programmable viscometer	-35–50 °C	-	4.6% increase with 6.12 vol.% at -30°C.	-	-	60
Sahooli and Sabbaghi (2013)	The transient hot wire	20-95 °C	66% increase with 0.045 wt.% at 70°C	-	-	-	61
Elias et al. (2014)	The transient hot wire, a Brookfield programmable viscometer (LVDV-III ultra), portable density meter, differential scanning calorimeter	10–50 °C	8% increase with 1 vol.% at 50°C.	151% increase with 1 vol.% at 50°C.	3% increase with 1 vol.% at 50°C	11% decrease with 1 vol.% at 50°C	62
Sundar et al. (2014)	The transient hot wire, AR-1000 rheometer	20–60 °C	32%, 31% and 27% increase for 20:80, 40:60 and 60:40 ethylene glycol-water base fluids with 1.5 vol.% at 60 °C, respectively.	37% , 175% and 158% increase for 20:80, 40:60 and 60:40 ethylene glycol-water base fluids with 1.5 vol.% at 0 °C, respectively.	4% increase for 20:80, 40:60 and 60:40 ethylene glycol-water base fluids with 1.5 vol.% at 20 °C.	1% decrease for 20:80, 40:60 and 60:40 ethylene glycol-water base fluids with 1.5 vol.% at 20 °C.	63
Kole and Dey (2011)	Brookfield programmable viscometer (model: LVDV-II-Pro)	10–80 °C	-	Nearly 200% increase with 1.5 vol.% at 0 °C.	-	-	64
Dudda and Shin (2013)	Modulated differential scanning calorimeter (MDSC)	150-450 °C	-	-	-	8%, 12% and 19% increase for 5 nm, 10 nm and 60 nm, respectively.	65
Lu and Huang (2013)	Differential scanning calorimetry (DSC, Model Q20, TA Instrument, and Model 7020 of EXSTAR)	290–335 °C	-	-	-	14% decrease with 4.6 vol.% at 335 °C.	66
Moghaddam et al. (2013)	Brookfield viscometer (LV DV-II + Pro EXTRA	20–60 °C	-	401.49% increase with 2 mass fractions% at 20 °C.	-	-	67
Rashin and Hemalatha (2013)	Brook Field LVDVE viscometer	35–55 °C	-	27.6% increase with 2.5 wt.% at shear rate of 3.67 s ⁻¹ at 35°C.	-	-	68
Tiznobaik and Shin (2013)	MDSC	150–500 °C	-	-	-	The average enhancements of specific heat capacity are 23–28% in the solid phase and 22–26% in the liquid phase, respectively.	69
Manikandan et al. (2014)	Rotational viscometer (LVDV-II+Pro, Brookfield Engineering)	29–140 °C	41% increase with 2 vol.% at 10°C	23% increase with 1 vol.% at 140°C.	-	-	70
Sang and Liu (2017)	Simultaneous Thermal Analyzer (STA-449F3, NETZSCH)	500–540 °C	-	-	-	79.9–113.7%, 50.6–73.9%, 31.1–56.5% and 50.6–66.5% increase for SiO ₂ , CuO, TiO ₂ , Al ₂ O ₃ in the range of 500–540 °C, respectively.	71

Masuda et al. [2] reported an experimental study on various water-based nanofluids containing Al_2O_3 (13 nm), SiO_2 (12 nm) and TiO_2 (27 nm). The maximum enhancement in thermal conductivity of 32% and the maximum enhancement of viscosity of 245% with 4.3% particle volume concentration were observed for Al_2O_3 -water mixture at 32 °C and 72 °C, respectively.

Wang et al. [3] studied thermal conductivity and viscosity of Al_2O_3 (28 nm) and CuO (23 nm) nanoparticles dispersed in water, vacuum pump fluid, engine oil, and ethylene glycol. They found that the thermal conductivity of nanoparticle–fluid mixtures increased with increasing volume fraction at room temperature. The maximum thermal conductivity and viscosity enhancement were 55% and 85% for CuO-ethylene glycol mixture with 15% volume concentration and Al_2O_3 water-mixture with 5% volume concentration at room temperature, respectively.

Murshed et al. [6] investigated effect of the shape of TiO_2 nanoparticles containing spherical (15 nm) and rod-shaped ($\varnothing 10 \text{ nm} \times 40 \text{ nm}$) on the augmentation of the thermal conductivity of water-based nanofluids using the transient hot-wire method. They showed that the enhancement of thermal conductivity was near to 33% and 30% for rod and spherical shapes particles with 5% volume fraction at room temperature, respectively.

Godson et al. [20] considered the influence of volume concentration and temperature on thermal conductivity and viscosity for silver (60 nm) - water nanofluid. They observed that the thermal conductivity increased with the increase in temperature and particle concentrations whereas the viscosity decreased with the increase in temperature and increased with the increase in particle concentrations. They also concluded that thermophoresis played a vital role in the enhancement of thermal conductivity rather than Brownian motion. The maximum thermal conductivity and viscosity enhancement of 129% and 44% were observed 0.9% of volume concentration at 90 °C, respectively.

Halelfadl et al. [29] considered the influence of particle volume fraction varying between 0.0055% and 0.55% and temperature range 0 to 40 °C on viscosity for water-based nanofluids containing carbon nanotubes (CNT) with large aspect ratio using a stress-controlled rheometer. They found that the viscosity of the nanofluid increased with increasing volume fraction and it was 6 times higher than the viscosity of the base fluid for nanoparticles volume fraction of 0.55%. The nanofluids were shown to behave as a shear thinning material at high particle content due to the shear viscosity decreasing when the shear rate increasing, but at lower particle content, the nanofluids behaved in Newtonian manner. It was also reported that the viscosity of nanofluids decreased with increasing temperature, whereas the relative viscosity of nanofluids at high shear rate was independent of temperature.

Besides the thermal conductivity and viscosity of nanofluids, other thermophysical properties of specific heat and density should be evaluated. Specific heat which is

defined as ratio of the quantity of heat required to raise the system temperature by one degree, influences the heat transfer rate of nanofluids.

Said et al. [40] measured thermal conductivity, viscosity, and specific heat of water based nanofluids containing single-walled carbon nanotubes (SWCNTs) with diameter of 1-2 nm and length of 500 nm by using transient hot wire method, the Brookfield viscometer and a heat flux-type differential scanning calorimeter for a temperature range of 20-60 °C and 0.1, 0.25 and 0.5% volume fractions. The results indicated that the thermal conductivity and viscosity increased but the specific heat decreased with the increase of volume concentrations. However, the thermal conductivity increased but the viscosity and specific heat reduced with rising temperature. The maximum enhancement of the thermal conductivity and viscosity were 62% and 100% for 0.5 volume concentration at 60 °C, respectively. The maximum reduction in the specific heat was 40% for 0.5 volume concentration at 20 °C.

Paul et al. [51] evaluated the thermal conductivity of mechanically alloyed $\text{Al}_{95}\text{Zn}_{05}$ nanoparticle (10–30 nm) dispersed in ethylene glycol with volume concentrations varied in the range 0.01–0.10% for a temperature range of 30 to 70 °C. They reported that rising temperature and volume fraction increased thermal conductivity of nanofluids but decreased with the increase in crystallite size of the particles. The highest thermal conductivity of 103% was obtained with 0.1 volume fraction at 70 °C.

Moreover, Sundar et al. [63] studied thermal conductivity, viscosity, density and specific heat of Al_2O_3 nanofluids using different base fluids such as 20:80%, 40:60% and 60:40% by weight of ethylene glycol (EG) and water (W) mixtures for volume concentrations between 0.3% and 1.5% in the temperature range 20 °C and 60 °C. It was found that thermal conductivity and viscosity of nanofluids increased with increase of volume concentrations, but thermal conductivity of nanofluids increased and viscosity of nanofluids decreased with increase of temperatures. Among all the nanofluids, maximum thermal conductivity enhancement of 32.26% was observed for 20:80% EG/W nanofluid at 60 °C and the maximum viscosity enhancement of 158% was observed for 60:40% EG/W nanofluid at 0 °C in the volume concentration of 1.5%. Similar to Said et al. [40], Sundar et al. [64] observed that the density and specific heat of nanofluids increased and reduced, respectively, with an increase in particle loadings at 20 °C. The maximum enhancement of density and the maximum reduction of specific heat were 4% and 1%, respectively, for all EG-W mixtures with 1.5% volume fraction at 20 °C.

Dudda and Shin [65] observed the effect of nanoparticle size on the specific heat capacity of SiO_2 (5, 10, 30, and 60 nm)- NaNO_3 - KNO_3 (60:40) nanofluids at 1% concentration by weight in at temperature range between 150 and 450 °C. The specific heat of nanofluids was measured by using a modulated differential scanning calorimeter for both solid and liquid states. They reported that the average enhancement

of specific heat capacity of nanofluids were 3-10% in the solid phase and 8-24% in the liquid phase, respectively.

IV. CONCLUSION

In this paper, previous experimental studies on the preparation, stability and thermophysical properties of nanofluids have been comprehensively reviewed. The main conclusions obtained from experimental results for the referred data ranges are as follows:

- Increasing the stability of nanoparticles in the base fluids is a key point to improve thermophysical properties of nanofluids.
- The maximum thermal conductivity and viscosity enhancement of 129% and 510% were obtained with silver-water [20] and CNT-water [29] nanofluids at 90 °C and 10 °C respectively.
- The maximum density enhancement of 4% was obtained with ethylene glycol based ZnO [54] and ethylene glycol-water (20:80, 40:60 and 60:40 by weight) based Al₂O₃ [63] nanofluids.
- The maximum specific heat enhancement of 116.8% was obtained using ternary carbonates nanofluids of K₂CO₃-Li₂CO₃-Na₂CO₃ (4:4:2 mass ratio) with SiO₂ nano particles at 540 °C [71]. The maximum specific heat reduction of 14% was obtained with the molten salt-based alumina nanofluid at 335 °C [66].
- The data on density and specific heat of nanofluids are insufficient.
- Obtaining optimum enhancement of thermophysical properties depends on many factors including the base fluid type, nanoparticles type, size, shape and concentration, the preparation process, the stability of nanofluids and temperature.

Due to the interaction between thermophysical properties of nanofluids, further experimental research is necessary. Developing new correlations for predicting thermophysical properties of nanofluids by using the experimental data collected in this paper is the subject of an ongoing study. The common functional relationships between the thermophysical properties independent of the preparation methodology, type of the nanoparticles and their sizes - shapes seem to be the first problem to be solved.

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