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Journal of Composites and Compounds

Thermal conductivity, viscosity, and heat transfer process in nanofluids: A critical review

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A B S T R A C T

Heat transfer efficiency has always been at the center of attractions for many researchers and industries, and demand for higher efficiency methods and materials are increased in the last decades. Among the different methods of heat transfer enhancement, using nanofluids has proven to be an effective technique. In the present paper, the properties of nanofluids including viscosity, thermal conductivity as well as convective heat transfer are discussed and useful conclusions about the reported results by different researchers are presented. The effect of volume fraction, temperature, size and shape of particles, base fluid properties, and other factors on viscosity, and thermal conductivity of nanofluids are reviewed. Also, in the present manuscript, the methods of stable nanofluid preparation, and the effective factors on the stability of nanofluids are exhibited in detail. Besides, a summarized number of experimental and mathematical studies on the properties, and stability of nanofluids are listed, compared, and analyzed. The works about the Nusselt number in fluids and nanofluids are presented in detail to determine the future challenges of nanofluids.

A R T I C L E I N F O R M A T I O N

Article history:
Received 29 August 2020
Received in revised form 03 November 2020
Accepted 12 December 2020

Keywords:
Nanofluid
Heat transfer
Convection
Thermal conductivity

Table of contents

1. Introduction

The rising energy demands and concerns about environmental pollutions have motivated the engineers to utilize new sources of energy such as solar, wind, and biogas [1–4]. The optimization of thermal systems is inevitable to increase the efficiency and reduce the cost and air pollution [2, 5–9]. The energy-efficient systems are obtained by enhancing the heat transfer rate using different passive or active methods [10, 11]. Active methods benefit the external energies such as electric or magnetic field, vibrating surface, or a mechanical mixer. However, the passive methods don't need external sources and the heat transfer enhancement is obtained by a change in geometry or fluid properties [12, 13]. The miniaturization of the channels, using the fins, or utilizing nanofluids are some common passive methods [11, 14–17]. In the last decades, due to the developments of miniaturized devices, such as computer electronic components, the old techniques of cooling became inadequate [15, 18–20]. Besides, the evolutions in technology have created an urgent demand for new and efficient cooling methods to maintain the device temperatures below the critical area. This need for new methods has motivated the researchers to study and find a profitable way. Nanofluid, which is the mixture of nano-sized particles in the base fluid, proved to be a novel heat transfer method in heat transfer issues [21].

Nanofluids are known as a new generation of fluids with hidden and unknown thermal capabilities.

Choi [22, 23] introduced nanofluids and claimed that they showed better heat transfer characteristics than their base fluids. Adding nanoparticles to the base fluid is a passive method for improving heat transfer processes [24]. The volume fraction of the nanoparticles as well as their size and type are significant factors that result in the mentioned improvements. Also, the working temperature and type of fluid play role in enhancement [25, 26].

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DOR: 20.1001.1.26765837.2020.2.5.3.7
https://doi.org/10.29252/jcc.2.4.3

Nomenclature

A	Area (m2)	vol	Volume fraction
c_p	Heat capacity (J/kg.K)	wt	Weight fraction
CTAB	Cetyltrimethylammonium bromide		
d	Diameter (m)	*Greek Letters*	
EG	Ethylene glycol	α	Thermal diffusivity
EO	Engine oil	β	A constant
GA	Gum Arabic	μ	Dynamic viscosity (Pa.s)
h	Convective heat transfer coefficient (W/m2 K)	ρ	density (kg/m^3)
k	Thermal conductivity (W/m.K)	σ	A constant
L	Length (m)	ϕ	Particle volume fraction
n	Shape factor	ψ	Sphericity
Nu	Nusselt number		
PG	Propylene glycol	*Subscripts*	
Pr	Prandtl number	bf	Base fluid
PVP	Polyvinyl pyrrolidone nanofluids	c	Critical
R	Thermal resistance (m² K/W)	eff	Effective
r	Radius (m)	l	Laminar
Re	Reynolds number	p	Particle
SDBS	Sodium dodecylbenzene sulfonate	t	turbulent
SDS	Sodium dodecyl sulfate		
T	Temperature (K)		

Nowadays, nanofluids have been used in many fields of industries such as electronic, nuclear, medicine, and transportation systems [27].

Nanofluids preparation, stability, characterizations, thermal features, conduction, and convection heat transfer processes have been studied widely by the researchers [28]. For the first time, Choi [22] dispersed the nano-sized particles in a base fluid and called the mixture as nanofluid. After introducing nanofluids, Lee et al. [29], Eastman et al. [30], Yu et al. [31], and many other researchers investigated the thermal behavior of nanofluids, and heat transfer rate enhancement by use of nanofluids was proved. It was also shown that the unique behavior of nanofluids may originate from some mechanisms such as the Brownian motion of nanoparticles and decreases in the thermal boundary layer [32].

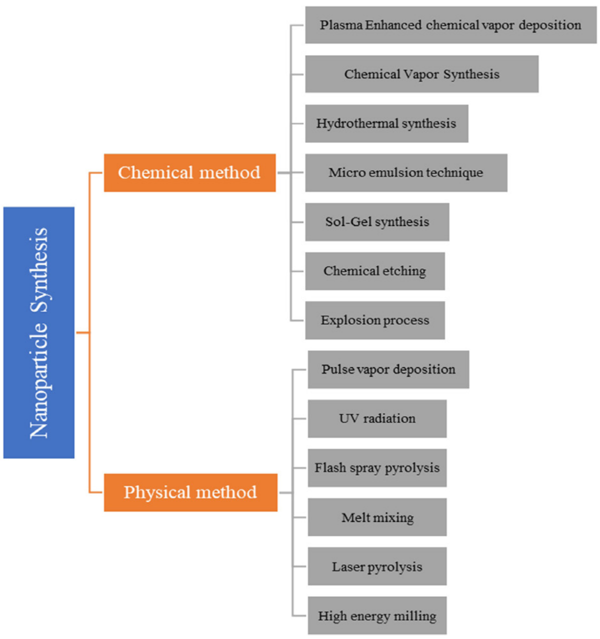

Fig. 1. Synthesizing methods of nanoparticles [21].

As mentioned above, the stability of nanofluids is a crucial factor that determines the applicability of nanofluids. Researchers always looking for stable nanofluids. So, many stability tests have been accomplished and the results showed the three main different methods to prepare a stable suspension, that is surfactants, ultrasonic bath, and pH control [33–35]. Also, there are other factors such as viscosity that are critically related to the pumping power of nanofluid. Although there are a lot of experimental studies of the nanofluids behavior, numerical methods are still a strong tool to obtain detailed information about the investigated phenomenon and have wide applications in heat and mass transfer, bio-mechanics, and solid mechanics [36, 37, 46, 38–45].

In the present paper, a critical review of the preparation, characterization, and heat transfer enhancement nanofluids has been done. We are attempting to provide a comprehensive review of the factors that affect the thermos-physical properties of nanofluids. Also, the experimental correlations and results have been compiled. The present review mainly aims to summarize the recent researches on thermophysical properties and the stability of nanofluids and applications of nanofluids in various industries and devices.

2. Nanofluids

2.1. Preparation methods

Nanofluids are recognized with their unique thermal properties, such as viscosity, thermal conductivity, and many other properties, compared to common fluids. Many types of nanoparticles are used for synthesizing nanofluids including carbon nanotubes, metals, metal oxides, ceramics, etc. metals generally have considerably high thermal conductivities than fluids, however, some types of advanced ceramics offer interestingly high thermal conductivities even more than common metal, such as ZrB_2 [47, 48, 57–66, 49, 67–76, 50, 77–86, 51, 87–96, 52, 97–102, 53–56], TiB_2 [103, 104, 113–121, 105–112], SiC, AlN [122–125], TiC [126, 127, 136, 128–135], and HfB_2 [137]. These ceramics have proved remarkable thermos-mechanical behaviors in different branches of industry [138, 139, 148–157, 140, 158–164, 141–147]. One of the important factors,

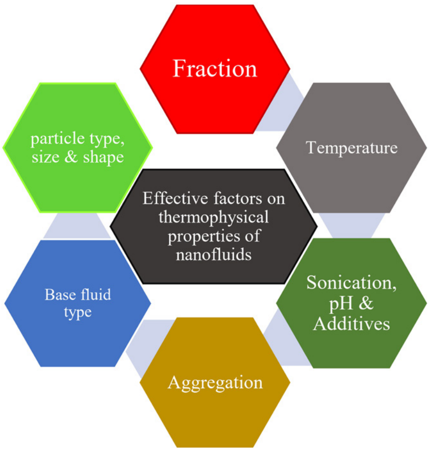

Fig. 2. Effective parameters on thermophysical properties of nanofluids.

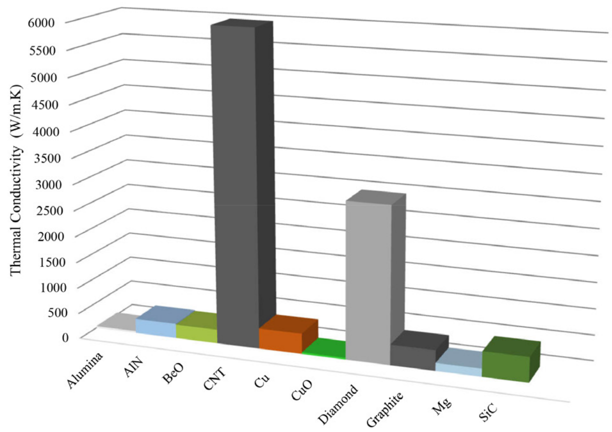

Fig. 3. Thermal conductivity of various materials at 25°C [211].

which affects the final properties od nanofluids, is the preparation of the nanoparticles [165]. Some of the synthesizing methods of nanoparticles are presented in Fig. 1.

Also, there are various methods for analyzing nanoparticles. The most common methods are Transmission Electron Microscope (TEM), Scanning Electron Microscope (SEM), Optical spectroscopy, X-ray Diffraction (XRD), Infrared and Raman Spectroscopy [166].

The synthesis of a nanofluid is a key role task in researches. The main goal of preparing nanofluids is to obtain a stable suspension without any agglomeration in a specified period and temperature. The agglomeration of nanoparticles in a nanofluid is a significant problem in all nanofluid investigations. Two main methods involved with preparing nanofluids are One-step and Two-step methods [167]. The purpose of the mentioned methods is to generate good nanoparticle suspensions. The unique heat transfer improvements by using nanofluids directly depend on the quality of the suspension. The quality of nanofluid is a function of the synthesis method and the homogeneity of nanoparticles in the base fluid [166]. Overcoming the mentioned problems has become more important in higher nanoparticle concentrations [168].

In the One-step method, in a single process, the nanoparticles are formed and dispersed in the base fluid. In the Two-step method, nanoparticles are prepared in the first step and after that, in the second step, the prepared particles are dispersed in a fluid [167]. From an economical point of view, the Two-step method takes lower costs [169]. In the two-step method, nanoparticles can be synthesized and dispersed in base fluid chemically or mechanically [170]. In chemical dispersion, surfactants are commonly are added to the fluid, whereas in mechanical dispersion, sonication is often employed to disperse nanoparticles [171]. Besides, there are other significant factors that have remarkable effects on a suspension's quality. According to various studies such as Sonawane et al. [172], and Buonomo et al. [173], particle size and sonication time are

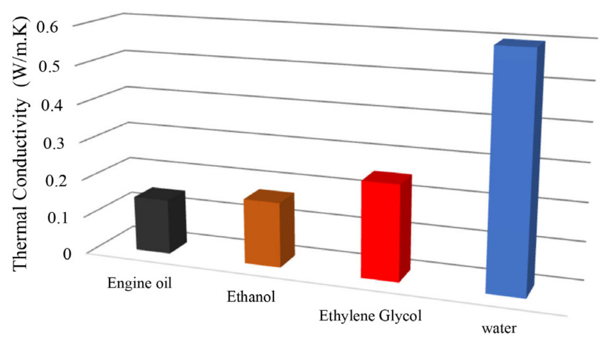

Fig. 4. Thermal Conductivity of various fluids at 25°C [211].

Table 1.
Some of the reported synthesis studies of nanofluids

Synthesis method	Authors	Publish year	Nanoparticle/Base fluid	Particle size (nm)	Fraction (Vol% or wt%)
One-Step	Eastman et al. [30]	2001	Cu/EG	10	0.3
	Hong et al. [174]	2005	Fe/EG	10	0.55
	Liu et al. [175]	2006	Cu/Water	75~100	0.1
	Paul et al. [176]	2012	Ag/Water	-	1
	De Robertis et al. [177]	2012	Cu/EG	-	-
Two-Step	Choi et al. [178]	2001	CNT/Poly oil	25*50000	2
	Murshed et al. [179]	2005	TiO_2/Water	15	5
	Meibodi et al. [180]	2010	CNT/Water	1-4	0.12
	Lee et al. [181]	2011	SiC/Water	<100nm	0.001-3
	Singh et al. [182]	2012	Al_2O_3/EG&Water	130,211,300	0.25-1
	Fazeli et al. [183]	2012	SiO_2/Water	18	3.5-5
	Zeinali Heris et al. [184]	2015	MWCNT/Water	10*20000	0.55
	Choudhary et al. [185]	2016	Al_2O_3/Water	40	0.1-2
	Irani et al. [186]	2018	GO/Water+MDEA	-	0.1 & 0.2

other critical factors that affect the dispersion level of nanoparticles and lead to better thermophysical properties of nanofluids. Some of the synthesized nanofluids utilizing one-step and two-step methods reported in various articles are presented in Table 1.

2.2. Stability of nanofluids

Synthesizing a stable and durable homogenous nanofluid has always been challenging for researchers due to the agglomeration of nanoparticles as a result of the van der Waals forces [187]. To avoid particle agglomeration, some physical and chemical methods have been proposed and investigated [165]. The most common method that researchers use while confronting agglomerations is adding surfactants which is a chemical method [188]. The addition of surfactants makes hydrophobic materials disperse in an aqueous suspension better than normal situations [189]. There are many types of surfactants such as Gum Arabic, CTAB, SDS, SDBS, NADDBS, CMC, HCTAB, TX-100, etc. [190]. Besides, the fraction of surfactants that are used for making a suspension stable is very important. If used less than the limit, causes inadequate stability and if overused, causes agglomeration of nanoparticles in the suspension due to the osmotic pressure [191].

Also, there are other methods that enhance the stability of nanofluid. Li and Xuan [192] suggested the ultrasonic waves for increasing the stability of nanofluids in addition to surfactants. Peng et al. [193] defined and studied the important factors of the preparation of stable nanofluids. They showed that the dispersion method, volume fraction of nanoparticles, the viscosity of the base fluid, the value of pH, density of nanofluid, type of nanoparticles, and size of nanoparticles in conjunction with ultrasonic waves affect the stability of nanofluids.

The main purpose of all methods is to prevent particle clustering by changing the surface properties of particles, which results in a stable nanofluid. An ultrasonic bath, which is used widely by researchers [35], is a powerful instrument for breaking the agglomerations. A conclusion of researches, which has utilized an ultrasonic bath to prepare stable nanofluids, is presented Table 2.

The stability of an aqueous nanofluid directly depends on electro-kinetic properties. The high surface charge density of the nanoparticles may result in strong repulsive forces and consequently, bring up better dispersion of nanoparticles in suspensions [35].

In the isoelectric point (IEP), the concentration ions that play a role in zeta potential is zero. In the isoelectric point, surface charge density is equal to electron charge density and because of that, the zeta potential is zero. The pH value has to be considered to attain the isoelectric point [206]. It has been observed that pH control makes a nanofluid to be stable for a long time [207]. By controlling the repulsive force between nanoparticles, the zeta potential is decreased to zero at a particular pH value at the isoelectric point and it is a negative problem for the stability of nanofluids [35]. The pH deviation of a prepared suspension from the isoelectric point increases the stability of colloidal particles and causes the changes in the thermal conductivity of the nanofluid [208]. Jorge et al. [209] investigated the MWCNT/water nanofluid at pH values of 2 and 5.5 and reported that the mentioned nanofluids were stable because of the deposition of amines on the MWCNT surface. Zareei et al. [210] evaluated the stability of Al_2O_3/water nanofluid at various pH values and showed that the Al_2O_3/water nanofluid had the highest stability at pH=4 while pH=10 showed less stability. Each type of nanoparticle became stably dispersed at its optimized pH value that leads to optimum thermal properties. At an optimum pH, the repulsive force between nanoparticles increases and prevents the sedimentations and agglomerations [211].

Among the various methods to evaluate the stability of nanofluids the most common techniques are: zeta potential, absorbency, stratification observing, sedimentation observing, and particle size-changing [212]. When almost all of the particles have high zeta potential values, there is no tendency for agglomeration and consequently, the suspension becomes stable [213]. In the zeta potential method, a Laser Doppler Velocimetry (LDV) records the movement of nanoparticles under an electrical field. Nowadays most of the investigations about the stability of nanofluids are done with the zeta potential method [181]. The acceptable values of zeta potential are shown in Table 3 [214]

2.3. Thermophysical properties of nanofluids

The main idea of the synthesis of nanofluids is to enhance the thermophysical behavior of the base fluids. Thermal properties of the working fluid play an essential role in the heat transfer rate of a thermal system. The working fluid commonly has weak thermal properties, therefore the improvements of these properties increase the efficiency of thermal devices, reduce costs, and results in more compact and miniaturized devices [20]. The properties of some of the base fluids that are utilized commonly in various investigations are presented in Table 4 [187, 215–218]. The dispersion of nanoparticles in the base fluid is one of the attractive methods in the enhancement of the fluid properties. Many factors affect the thermophysical properties of nanofluids that are presented in Fig. 2 [219]. Kolade et al. [220] investigated the effect of

Table 2.
Investigations of nanofluid stability

Authors	Publish year	Nanoparticles/Base fluid	Particle size(nm)	Fraction (vol% or wt%)	Sedimentation	surfactant
Patel et al. [194]	2005	Al_2O_3/Water	11	0.8	-	-
Lee et al. [195]	2006	CuO/Water	25	0.3	-	-
Zhu et al. [189]	2007	Graphite/Water	20	0.5	-	PVP
Li et al. [188]	2008	Cu/Water	25	0.1	-	SDBS
Chen et al. [196]	2009	Titanate NT/EG	10*100	0.5-8	>2 months	-
Yu et al. [197]	2010	Fe_3O_4/Kerosene	15	0.1-2	-	Oleic acid
Chandareskar [198]	2010	Al_2O_3/Water	43	033-5	-	-
Aravind et al. [199]	2011	MWCNT/Water	-	0.005-0.03	-	-
Shanbedi et al. [200]	2012	MWCNT/Water	15*10000	0-1.5	>6 months	-
Shanbedi et al. [201]	2013	MWCNT/Water	15*10000	0-1	>6 months	GA
Amiri et al. [202]	2015	Graphene/Water	3.74*3000	0-0.1	1 month	SDBS
Mustafizur [203]	2016	SiO_2/Methanol	5-15	0.005-0.05	24 hours	-
Cacua et al. [204]	2017	Al_2O_3/Water	-	0.1-0.5	30 days	SDBS-CTAB
Krishnan et al. [205]	2019	MgO/Water-EG	-	0.05-0.6	20 days	-

Table 3.
The acceptable values of zeta potential [70]

Zeta potential (mv)	Stability
0	No stability or little stability
15	Some stability but settling lightly
30	Moderate stability
45	Good stability with settling possibility
60	Excellent stability

the particle fraction on the effective thermal conductivity of Al_2O_3-water and MWCNT-water nanofluids and reported 6% and 10% enhancement at 2% and 0.2% fractions, respectively. Das et al. [221] reported that temperature increment results in higher thermal conductivity of nanofluids. Also, Shou et al. [222] indicated that an increase in thermal conductivity had a linear proportion with temperature. Chon et al. [223] studied the effect of nanoparticles size on the thermal conductivity of nanofluids for spherical nanoparticles with the size of 10-50 nm and showed that the thermal conductivity of nanofluids increased with a decrease in particles size.

2.3.1. Thermal conductivity

In the last decades, the thermal conductivity of the fluids containing nanoparticles has become a point of attraction for many researchers and various numerical and experimental studies have done about nanofluids [220]. The results of various studies show that the thermal conductivity of nanofluids improves by diverse factors like volume fraction, nanoparticle type and size, the thermal conductivity of nanoparticles and base fluid, temperature, viscosity, Brownian motion, pH value, and the quality of dispersion[224]

The Brownian movement of nanoparticles at nano-sized levels and molecular scales plays a key role in the thermal behavior of solid-fluid suspensions including nanofluids. The increases in thermal conductivity of nanofluids are related to local convections that caused by Brownian motions of nanoparticles [225].

Solid materials have generally higher thermal conductivities than fluids. Metals possess considerably high thermal conductivity, however, some types of advanced ceramics offer considerable thermal conductivities such as ZrB_2, AlN, BeO, and TiB_2 [226–231]. Since the thermal conductivity of solid nanoparticles is very higher than fluids, it is expected that dispersing nanoparticles in a base fluid enhances the thermal conductivity and the heat transfer functions of the fluid. The approximate thermal conductivity of some materials and base fluids is shown in Fig. 3 and Fig. 4, respectively [211].

The experimental studies exhibited that nanofluids do not conform with general correlations and the thermal conductivity of nanofluids depends on many factors that some of them are still unknown. Jana et al. [232] studied various nanofluids and showed that the Cu-water nanofluid brings up to 74% enhancement in thermal conductivity. Xie et al. [233] investigated the effect of using CNT, CuO, and Al_2O_3 nanoparticles in a base fluid and showed that regardless of the type of the base fluid, Carbon nanotube suspensions demonstrated better thermal conductivity values in the same volume fractions [233]. Wang et al. [234] compared the diverse data for Al_2O_3 and CuO nanoparticles by considering water, vacuum pump fluid, engine oil, and ethylene glycol as base fluids and showed that the thermal conductivity of nanofluids increased with a decrease in nanoparticle size. Abareshi et al. [235] investigated the thermal conductivity of Fe_3O_4-water nanofluid and highlighted that the thermal conductivity of nanofluids improved with increment in temperature due to the increases in the activity of molecules to transfer energy. Lai et al. [236] and Zhu et al. [237] claimed that the pH value is very effective on the thermal conductivity of suspensions. In Table 5 found., the thermal

Table 4.
Thermophysical properties of common base fluids that utilized in nanofluids [187, 215–218]

Base fluid	cp (J/kg.K)	k (W/m.K)	ρ (kg/m³)	μ (N.s/m²)
Distilled water	4184	0.599	998	1.00E-04
Ethylene Glycol	2383	0.25	1117	2.20E-02
Engine oil	1881	0.145	888	8.40E-01
Propylene glycol	4019	0.34	1036	4.20E-02
EG + water (X=0.5)	3473	0.316	1094	28.00E-04

conductivity enhancement reported by some researchers is presented.

Many studies reported the enhancement of thermal conductivity by utilizing and dispersing nanoparticles in the base fluid [220]. Although the researchers presented many models to predict the thermal conductivity of nanofluids, however, comparing the experimental data with theoretical models shows the need for more investigations to explain the abnormal improvements in the thermal conductivity of nanofluids.

Maxwell [251] for the first time presented a mathematical model to determine the thermal conductivity of a solid-fluid suspension by assuming spherical shape for all solid particles as follow:

$$k_{eff} = \frac{k_p + 2k_{bf} + 2(k_p - k_{bf})\phi}{k_p + 2k_{bf} - (k_p - k_{bf})\phi} k_{bf} \quad (1)$$

where φ is the volume fraction and k_{bf} and k_p are the thermal conductivity of the fluid and particles, respectively.

Researchers also developed various mathematical models by considering different parameters that affect thermal conductivity. Hamilton and Crosser [252] considered the shape of the particles and justified the Maxwell model as below:

$$k_{eff} = \frac{k_p + (n-1)k_{bf} + (n-1)(k_p - k_{bf})\phi}{k_p + (n-1)k_{bf} - (k_p - k_{bf})\phi} k_{bf} \quad (2)$$

where n is the shape factor given as

$$n = \frac{3}{\psi} \quad (3)$$

ψ is defined as the sphericity of the solid particles. A series of mathematical models considering the different involving factors are presented by several researchers. A conclusion of various presented models suggested by researchers is shown in Table 6.

2.3.2. Viscosity

The viscosity is a significant and important characteristic of all types of fluids that shows the resistance of a fluid flow against shear stress. Because of that, the viscosity has a great effect on the rheological and thermal behaviors of nanofluids as a special type of fluids. The viscosity affects the friction between the fluid molecules and the contact surface of nanoparticles and plays a key role in fluid flow and heat transfer phenomena. The pumping power and convective heat transfer rate are directly related to the value of viscosity [267].

The viscosity depends on various factors such as dispersing method, nanoparticle diameter, nanoparticle type, temperature, and nanoparticle concentration which the effect of concentration is more than other factors [268, 269]. Ghazvini et al. [270] showed that the viscosity of nanofluids increased by up to 20% in high nanoparticle concentrations. Ding et al. [271] investigated the viscosity of carbon nanotube-water nanofluid as a function of shear stress and indicated that the viscosity of

Table 5.
The overview of the result of some studies on the thermal conductivity of nanofluids

Authors	Publish year	Particle/Base fluid	Fraction (vol% or wt%)	Particle size (nm)	Additives	Enhancement (%)
Xuan & Li [192]	2000	Cu/water	2.5-7.5	100	Laurate salt	22-75
Xie et al. [238]	2002	Al_2O_3/water	1.8-5	60.4	-	7-21
Patel et al. [239]	2003	Ag/water	0.001	60-70	-	3% at 30°C 4% at 60°C
Das et al. [221]	2003	Al_2O_3/water	1-4	38.4	-	2-9% at 21°C 10-24% at 51°C
Wen & Ding [240]	2004	Al_2O_3/water	0.19-1.59	42	SDBS	1-10
Hong et al. [174]	2005	Fe/EG	0.2-0.55	10	-	13-18
Putnam et al. [241]	2006	Au/ethanol	0.01-0.07	4	Alkanrthiolate	0.3-1.3
Lee et al. [195]	2006	CuO/water	0.03-0.3	25	-	4-12% at pH=3 2-7% at pH=6
Li et al. [188]	2008	Cu/water	0.02-1 wt%	25	SDBS	10.7
Godson et al. [242]	2010	Ag/water	0.3-0.9	60	-	10-30% (50 to 90°C)
Kole & Dey [243]	2010	Al_2O_3/water	0.001-0.035	50	Oleic acid	10.5%
Colla et al. [244]	2012	Fe_3O_4/water	5-20 wt%	67	-	0-7% at 10°C 1-10% at 30°C 5-11% at 50°C 3-15% at 70°C
Manna et al. [245]	2012	SiC/water	0.01-0.1	60	-	7.5-11.5%
Teng [246]	2013	Al_2O_3/water	0,0.5,1,3	20	Chitosan	1-9% decrease
Amiri et al. [202]	2015	Geraphene/water	0.025-0.1 wt%	3.74*3000	SDBS	Up to 26.2
Sinha et al. [247]	2017	ZnO/water	0.1-5	-	-	33
Micali et al. [248]	2018	CuO-water	2.5	-	-	Up to 18
Ranjbarzadeh et al. [249]	2019	SiO_2/water	0.1-3	-	-	Up to 38.2
Riahi et al. [250]	2020	Al_2O_3/water	0.7	9	-	8.6

nanofluids increases with increments in concentration on the one hand and also, decrements in temperature on the other hand. Zeinali Heris et al. [272] showed that the viscosity value of CuO-water nanofluid is greater than Al_2O_3-water nanofluid because of the bigger size of CuO nanoparticles.

Nguyen et al. [273] investigated the effect of temperature, concentration, and size of nanoparticles on the dynamic viscosity of Al_2O_3-water and CuO-water nanofluids. The results showed that the viscosity of prepared nanofluids was a function of temperature and volume fraction of nanoparticles.

A conclusion of experimental researches about the viscosity of nanofluids is presented in Table 7. Also, there are some mathematical correlations for predicting the effective viscosity of nanofluids. A summary of the significant viscosity correlations is presented in Table 8.

2.4. Convective heat transfer process in nanofluids

Using nanofluids in various devices is an effective method to reach high efficiencies in the cooling procedure. In the previous sections, the synthesis and some thermophysical properties of nanofluids have been explained, however, convective heat transfer needs many studies about the flow regime, heat transfer process, and other significant factors [295]. The convective heat transfer coefficient of nanofluids increases with increment in conductive heat transfer rate, intensification of turbulence, stopping the growth of the boundary layer, etc. [24]. A decrease in the thermal boundary layer can lead to the stimulation of the particles around the wall and migration of the particles toward the center of the duct and this subject will decrease the viscosity near the wall [296]. Numerous studies have been performed to investigate the convective heat transfer using nanofluids. A constant heat flux or constant wall temperature is usually considered as the boundary condition for studying the heat transfer of nanofluids [297].

By using nanofluids, complicated behaviors such as Brownian motion, rotation of the particles, and micro-displacements of nanoparticles emerge [297]. These mechanisms make it necessary to find new correlations to cover the convective heat transfer of the nanofluids.

Jung et al. [298] investigated the Al_2O_3-water nanofluid in a microchannel with considering the laminar flow regime and showed a 32% increase in the convective heat transfer coefficient in comparison with used base fluids. Zeinali heris et al. [299] investigated the Cu-water nanofluids in a tube with a laminar flow regime at constant wall temperature condition as a boundary condition and indicated that with increases in volume fraction, the convective heat transfer coefficient values improved as 45% at 2% volume fraction. Faulkner et al. [300] investigated the convective heat transfer in a microchannel by utilizing CNT-water. The results showed that the convective heat transfer coefficient improves with an increase in volume fraction. Aravind et al [199] synthesized the CNT-water nanofluids at 0.005% and 0.03% volume fractions and showed that the convective heat transfer coefficient increases with an increase in Reynolds number and volume fraction. Naraki et al. [301] investigated the CuO-water nanofluid in a car radiator and presented an 8% enhancement in the heat transfer rate.

Several mathematical correlations are presented by researchers for predicting the Nusselt number of single-phase fluids in a tube at laminar and turbulent flow regimes. A conclusion of some correlations for the Nusselt number is shown in Table 9.

2.5. Future Challenges

As the researches about nanofluid progress over time, many chal-

Table 6.
A conclusion of models proposed for thermal conductivity of nanofluids

Reference	Year	Correlation	Dependent Parameters
Maxwell et al [251]	1890	$k_{eff}=\frac{k_p+2k_{bf}+2(k_p-k_{bf})\phi}{k_p+2k_{bf}-(k_p-k_{bf})\phi}k_{bf}$	Volume fraction
Bruggeman [253]	1937	$k_{eff}=\frac{1}{4}[(3\phi-1)k_p+(2-3\phi)k_{bf}]+\frac{k_{bf}}{4}\sqrt{\Delta}$ $\Delta=\left[(3\phi-1)^2\left(\frac{k_p}{k_{bf}}\right)+(2-3\phi)^2+2(2+9\phi-9\phi^2)\left(\frac{k_p}{k_{bf}}\right)\right]$	Volume fraction
Hamilton & Crosser [252]	1962	$k_{eff}=\frac{k_p+(n-1)k_{bf}+(n-1)(k_p-k_{bf})\phi}{k_p+(n-1)k_{bf}-(k_p-k_{bf})\phi}k_{bf}$	Volume fraction Shape factor
Wasp [254]	1977	$k_{eff}=\frac{k_p+2k_{bf}-2(k_{bf}-k_p)\phi}{k_p+2k_{bf}+(k_{bf}-k_p)\phi}k_{bf}$	Volume fraction
Lu and Lin [255]	1996	$k_{eff}=\left[1+\frac{k_p}{k_{bf}}\phi+\frac{k_p-k_{bf}}{k_p+2k_{bf}}\phi^2\right]k_{bf}$	Volume fraction
Yu and Choi [256]	2003	$k_{eff}=\frac{k_{pe}+2k_{bf}+2(k_{pe}-k_{bf})(1+\beta)^3\phi}{k_{pe}+2k_{bf}-(k_{pe}-k_{bf})(1+\beta)^3\phi}k_{bf}$ $k_{pe}=\frac{[2(1-\gamma)+(1+\beta)^3(1+2\gamma)\gamma]}{[-(1-\gamma)+(1+\beta)^3(1+2\gamma)]}k_p$	Interfacial layer Volume fraction
Nan [257]	2003	$\frac{k_{eff}}{k_{bf}}=\frac{3+\phi(\frac{k_p}{k_{bf}})}{3-2\phi}$	Volume fraction
Wang et al [258]	2003	$k_{eff}=\frac{(1-\phi)+3\phi\int_0^\infty\frac{k_{c1}(r)n(r)}{k_{c1}(r)+2k_{bf}}dr}{(1-\phi)+3\phi\int_0^\infty\frac{k_{bf}(r)n(r)}{k_{c1}(r)+2k_{bf}}dr}k_{bf}$	Size effect Surface adsorption
Kumar et al [259]	2004	$k_{eff}=k_{bf}+c\frac{2k_BT}{\pi\nu d_p^2}\frac{\phi r_b}{k_{bf}(1-\phi)r_p}k_{bf}$	Temperature, Density, Specific heat capacity, Viscosity, Radius of nanoparticle, Volume fraction
Xie et al [260]	2005	$k_{eff}=\left(1+3\Theta\phi_T+\frac{3\Theta^2\phi_T{}^2}{1-\Theta\phi_T}\right)k_{bf}$ $\Theta=\frac{\beta_{1b}[(1+\gamma^3)-\frac{\beta_{p1}}{\beta_{b1}}]}{(1+\gamma)^3+2\beta_{p1}\beta_{b1}}$	Interfacial nanolayer Volume fraction
Prasher [261]	2005	$\frac{k_{eff}}{k_{bf}}=1+64.7\phi^{0.746}(\frac{d_{bf}}{d_p})^{0.369}(\frac{k_p}{k_{bf}})^{0.7476}\times\mathrm{Pr}^{0.9955}\times\mathrm{Re}^{1.2321}$	Reynolds number Prandtl number Particle size Volume fraction
Murshed [262]	2006	$\frac{k_{eff}}{k_{bf}}=\frac{[1+0.27\phi^{1.3}\left(\frac{k_p}{k_{bf}}-1\right)][1+\frac{0.52\phi}{1-\phi^{0.3}}\left(\frac{k_p}{k_{bf}}-1\right)}{1+\phi^{1.3}\left(\frac{k_p}{k_{bf}}-1\right)\left(\frac{0.52}{1-\phi^{0.3}}+0.27\phi^{0.3}+0.27\right)}$	Volume fraction

Continuation of Table 5

Reference	Year	Correlation	Dependent Parameters
Li [263]	2008	$k_{eff}=k_{static}+k_{Brownian}$ $k_{static}=\frac{k_p+2k_{bf}+2(k_p-k_{bf})\phi}{k_p+2k_{bf}-(k_p-k_{bf})\phi}k_{bf}$ $k_{Brownian}=50000\phi(\rho c_p)_{bf}\sqrt{\frac{k_B T}{\rho_p d_p}}g(T,\phi,d_p)$ $g(T,\phi,d_p)=(a+b\ln(d_p)+c\ln(\phi)+d\ln(\phi)\ln(d_p)$ $+e\ln(d_p)^2)\ln(T)+(g+h\ln(d_p)+i\ln(\phi)+j\ln(\phi)\ln(d_p)+k\ln(d_p)^2)$	Brownian motion Particle diameter Temperature Volume fraction
Vajjha [264]	2010	$k_{eff}=\frac{k_p+2k_{bf}-2(k_{bf}-k_p)\phi}{k_p+2k_{bf}(k_{bf}-k_p)\phi}k_{bf}+5\times10^4\beta\phi\rho_{bf}c_{pf}\sqrt{\frac{kT}{\rho_p d_p}}f(T,\phi)$	Temperature Nanoparticle type Volume fraction
Suganthi [265]	2014	$\frac{k_{eff}}{k_{bf}}=1+7.926\phi$ $\frac{k_{eff}}{k_{bf}}=1+8.195\phi$	Volume fraction
Gao [266]	2018	$\frac{k_{eff}}{k_{bf}}=\frac{\frac{3+2\eta^2\phi}{k_f(\frac{2R_k}{L}+13.4\sqrt{t})}}{3-\eta\phi}$	Thickness Length Thermal resistance Flatness ratio

Table 7.
A conclusion of experimental studies on the viscosity of nanofluids

Authors	Year	Particles/Base fluid	Fraction	Particle size(nm)	Additives	Viscosity increase
Godson et al. [242]	2010	Ag/water	0.3-0.9	20	-	6-23% at 50°C 10-35% at 70°C 20-43% at 90°C
Aravind [199]	2011	MWCNT/water	0.005-0.03	-	-	3-15% at 40°C 4-20% at 60°C 6-11% at 40°C 4-16% at 60°C
Colla et al. [244]	2012	Fe_2O_3/water	5-20 wt%	67	-	21-36% at 10°C 24-49% at 30°C 21-36% at 50°C 32-72% at 70°C
Syam Sundar et al. [274]	2013	Fe_3O_4/water	0.2-2	13	CTAB	6.3-108% at 20°C 1.8-107% at 40°C 10-196.6% at 60°C
Shanbedi et al. [275]	2015	MWCNT/water	0.1 wt%	10*30000	GA SDS CTAB	Temperature increase led to lower viscosity values
Chiam et al. [276]	2017	Al_2O_3/water+EG	0.2-1	-	-	Up to 50%
Yashawantha et al. [277]	2019	Graphite/EG	0.2, 0.8, 2	<50	-	58% decrease by increasing temperature (25°C-60°C)

Table 8.
A conclusion of mathematical correlations for the viscosity of nanofluids

Authors	Year	Correlation	Dependent parameters
Einstein [278]	1906	$\mu_{eff} = (1+2.5\phi)\mu_{bf}$	Volume fraction
Robinson [279]	1949	$\mu_{eff} = \left(1+\frac{c_p\phi}{1-S_r\phi}\right)\mu$	Volume fraction Special heat capacity
Brinkman [279]	1952	$\mu_{eff} = \frac{\mu_f}{(1-\phi)^{2.5}}$	Volume fraction
Eshelby [280]	1957	$\mu_{eff} = \left(1+\frac{7.5(1-\sigma)}{4-5\sigma}\phi\right)\mu_{bf}$ $\sigma = 0.333$	Volume fraction
Krieger [281]	1959	$\mu_{eff} = \mu_{bf}(1-\frac{\phi}{\phi_m})^{-[\eta]\phi_m}$	Volume fraction Shear stress Particle packing
Frankel and Acrivos [282]	1967	$\mu_{eff} = 1.125\left[\frac{\left(\frac{\phi}{\phi_m}\right)^{0.333}}{1-\left(\frac{\phi}{\phi_m}\right)^{0.333}}\right]\mu_{bf}$	Volume fraction
Jeffrey et al [283]	1976	$\mu_{eff} = \mu_{bf}\left(3+\frac{4}{3}\left(\frac{\phi r^2}{\ln\left(\frac{r}{\phi}\right)}\right)\right)$	Volume fraction
Graham [284]	1981	$\frac{\mu_{eff}}{\mu_{bf}} = 1+2.5\phi+\frac{4.5}{\left(\frac{h}{d_p}\right)\left(2+\frac{h}{d_p}\right)\left(1+\frac{h}{d_p}\right)^2}$	Particle diameter Inter-particle spacing
Chow [285]	1993	$\frac{\mu_{eff}}{\mu_{bf}} = \left[\exp\left(\frac{2.5\phi}{1-\phi}\right)+\frac{A\phi^2}{1-A\phi^2\phi_{\max}}\right]$	Volume fraction
Pak and Cho [286]	1998	$\mu_{eff} = (108.2\phi^2+5.45\phi+1)\mu_{bf}$	Volume fraction
Liu [287]	1999	$\frac{\mu_{eff}}{\mu_{bf}} = \left\{\left(\frac{1-\phi}{\phi_{\max}}\right)^2+\left(\frac{k_1-2}{\phi_{\max}}\right)\phi+\left(\frac{k_2-6}{\phi_{\max}^2}\right)\phi^2\right\}$	Volume fraction
Noni [288]	2002	$\frac{\mu_{eff}}{\mu_{bf}} = \left(1+b\left(\frac{\phi}{1-\phi_m}\right)^n\right)$	Volume fraction Bidimensional forces
Orozco and Castillo [289]	2003	$\frac{\mu_{eff}}{\mu_{bf}} = 1+2.5\phi+6.17\phi^2$	Volume fraction
Nguyen [290]	2007	$\frac{\mu_{eff}}{\mu_{bf}} = 0.904^{0.1483\phi}$	Volume fraction
Bobbo [291]	2012	$\frac{\mu_{eff}}{\mu_{bf}} = \left(1+a\phi+b\phi^2\right)$	Volume fraction
Aberoumand [292]	2016	$\frac{\mu_{eff}}{\mu_{bf}} = 1.15+1.061\phi-0.5442\phi^2+0.1181\phi^3$	Volume fraction
Karimipour [293]	2018	$\frac{\mu_{eff}}{\mu_{bf}} = 0.995246-0.000293119T.w+0.125761w$	Weight fraction temperature
Esfe [294]	2019	$\mu_{eff} = 6.35+2.56\phi-0.24T-0.068\phi T+0.905\phi^2+0.0027T^2$	Volume fraction temperature

Table 9.
A summary of correlations presented for Nusselt number

Author	Year	Correlation	Conditions
Dittus-Boelter [302]	1930	$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}$	Turbulent flow n=0.3 for cooling n=0.4 for heating $2500<\mathrm{Re}<1.25\times10^{5}$ $0.6<\mathrm{Pr}<160$
Hausen [303]	1943	$Nu = 3.66 + \frac{0.0668(d/L)\,\mathrm{Re}\,\mathrm{Pr}}{1+0.04[(d/L)\,\mathrm{Re}\,\mathrm{Pr}]^{2/3}}$	Laminar flow Const. wall temperature
Lyon [304]	1952	$Nu = 7 + 0.025(\mathrm{Re}\,\mathrm{Pr})^{0.8}$	Const. heat flux
Lubarsky and Kaufman [305]	1955	$Nu = 0.625\,\mathrm{Re}^{0.4}\,\mathrm{Pr}^{0.4}$	-
Churchill and Ugasi [306]	1972	$Nu^{10} = Nu_l^{10} + \left[\exp\left(\frac{2200-(\mathrm{Re}/365)}{Nu_c^{2}} + \frac{1}{Nu_t^{2}}\right)\right]^{-5}$	-
Notter-Sleicher [307]	1972	$Nu = 5 + 0.015\,\mathrm{Re}^{0.856}\,\mathrm{Pr}^{0.347}$	$0<\mathrm{Pr}<10^{4}$ $10^{4}<\mathrm{Re}<10^{5}$
Pak and Cho [286]	1998	$Nu = 0.021\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.5}$	$10^{4}<\mathrm{Re}<10^{5}$ $6.54<\mathrm{Pr}<12.33$ $0<\phi<3\%$
Maiga et al. [308]	2004	$Nu = 0.086\,\mathrm{Re}^{0.55}\,\mathrm{Pr}^{0.5}$ $Nu = 0.28\,\mathrm{Re}^{0.35}\,\mathrm{Pr}^{0.36}$	Const. heat flux Const. wall temperature
Suresh et al. [309]	2012	$Nu = 0.031(\mathrm{Re}\,\mathrm{Pr})^{0.68}(1+\phi)^{95.73}$	$\mathrm{Re}<2300$ $0<\phi<0.1\%$
Sundar et al. [310]	2012	$Nu = 0.02172\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.5}(1+\phi)^{0.5181}$	$3000<\mathrm{Re}<22000$ $3.72<\mathrm{Pr}<6.5$ $0<\phi<0.6\%$

lenges in nanofluid studies and applications still exist. Firstly, the synthesis of nanofluids must take lower costs on the one hand and give more stable nanofluids on the other hand. So, there is a critical need for more studies about the mechanisms and methods to earn information about the unique behavior of nanofluids and give more stable nanofluids that make them more commercial and applicable.

Secondly, many mathematical and experimental correlations are presented to predict the thermal and rheological properties of nanofluids. Some of them have properly validated, however, all mechanisms involved in the heat transfer of nanofluids are still unknown and unexplored. Considering optimal parameters for prospecting the behavior of nanofluids is very necessary to extract the maximum potential of nanofluids.

From the heat transfer aspect, nanofluids have developed in many heat transfer processes and instruments such as medical sciences, biomechanics, electronics, etc. [311]. Researchers are studying and investigating the various facets of the nanofluids to make nanofluids more reliable and marketable [312].

Nowadays, nanofluids are utilizing in heat transfer and other fields widely. However, this unique type of suspension is still under the investigation to be more applicable. Finding ways to give more stable and high-efficiency nanofluids will lead to a revolution in the heat transfer in industry and many other fields.

3. Conclusion

Cooling performance is a major demand of many industries and because of that, the need for fluids with enhanced thermophysical properties and reliable stability is more vital than the past. The present review gives a piece of summarized information about the nanofluids and heat transfer phenomena in nanofluids and make nanofluids more understanding and displays the recent developments in nanofluids.

Many rheological and thermal properties of nanofluid have taken into account to make nanofluids more applicable. Although, the thermal conductivity, viscosity, stability, and heat transfer processes are reviewed in the present paper. Also, summarized experimental studies and mathematical correlations about the mentioned properties are brought in the present review. The parameters that affect the thermal behavior of nanofluids are particle size, volume and weight fraction, fluid type, nanoparticle type, temperature, viscosity, stability, and preparation method. Nanofluids have a huge potential to be used in many fields and industries but, there is more need for study on the hidden and unknown mechanisms of nanofluids to make them more applicable. Also, more investigations are needed to simplify the preparation methods and enhance the thermos-physical properties of nanofluids.

Acknowledgments

The authors received no financial support for the research, authorship and/or publication of this article.

Conflict of interest

The authors declare that there is no conflict of interest.

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