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Chapter 9

Nanofluids Based on Carbon Nanostructures

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Abstract

A nanofluid consists in a liquid suspension of nanometer-sized particles. These fluids may contain (or not) surface-active agents to aid in the suspension of the particles. Nanometer-sized particles have higher thermal conductivity than the base fluids. Oxides, metals, nitrides, and nonmetals, like carbon nanotubes, can be used as nanoparticles in nanofluids. Water, ethylene glycol, oils, and polymer solutions can be used as base fluids. In this chapter, we summarize the recent studies of using CNTs and graphene to improve the thermal conductivity of nanofluids. Moreover, we refer to the studies about the effect of using magnetic fields on enhancing the thermal conductivity of nanofluids. Too much discrepancy about thermal conductivity of nanofluids can be found in the literature. For carbon nanofluids, unfortunately, no significant improvements on thermal conductivity are observed using low concentrations. Different improvement percentages have been reported. This variation in the thermal conductivity can be attributed to many factors, such as particle size temperature, pH, or zeta potential. We believe that more research efforts need to be made in order to, first, improve the thermal conductivity of nanofluids and, second, assess the effect of the different parameters and conditions on the thermal conductivity of nanofluids.

Keywords: CNTs, graphene, nanofluids, thermal conductivity, alignment and magnetic field

1. Introduction

The enhancement of the efficiency of heat transfer fluids has been of great interest to scientists and engineers for the past two decades. Conventional heat transfer fluids, such as mineral oil, water, and ethylene glycol (EG), have poor heat transfer properties, compared to solids. In recent years, nanofluids have been investigated as potential heat transfer fluids [1–11].

The conventional coolants/fluids used in radiators and engines have poor heat transfer properties and contain millimeter- or micrometer-sized particles to improve the heat transfer properties that can clog new cooling technologies that include microchannels. The use of fluids with better heat transfer can allow engines to run at optimal temperatures and allow the use of smaller and lighter radiators, pumps, and other components. Smaller radiators allow a smaller front end of large vehicles, such as trucks. Fluids with better heat transfer can also lead to the production of lighter vehicles with better fuel economy, since less pumping power is needed. Although many factors such as pH, particle size, and zeta potential can affect the thermal conductivity (TC) of nanofluids, they are not promising to improve thermal conductivity values [12–16].

Wensel et al. [17] found that using low concentrations of the nanoparticles do not enhance the TC effectively. For example, using of 4–5 vol.% metal oxides increases the thermal conductivity by 10–20% only, which is not the significant increase that is needed.

2. Carbon-based nanomaterials

In this chapter, two carbon-based nanomaterial nanofluids will be discussed: carbon nanotube (CNT) and graphene-based nanofluids and their thermal conductivity.

2.1. Carbon nanotubes

Carbon nanotubes (CNTs) have attracted significant attention since they were discovered by Iijima in 1991 [18]. The sp^2 carbon–carbon bond in the plane of the graphene lattice is the strongest among of all chemical bonds. CNTs can be obtained with different numbers of walls, including single-walled CNTs, double-walled CNTs, and multiwall CNTs. They have very good thermal conductivity along the length of the tubes. It has been shown that the thermal conductivity of CNTs is unusually high (e.g., 3000 W/mK) for MWNTs [19] and even higher for SWCNTs (6000 W/mK). The thermal conductivity of CNTs is more than seven times higher than that of copper, which is well known for having a good thermal conductivity of 385 W/Mk [19–22]. Because of their remarkable thermal, electrical, mechanical properties, and low density, carbon nanotubes are ideal materials for reinforcement in composites [23–27], sensors [28], and many other applications, such as thermal managements [29–31].

2.1.1. Carbon nanotubes and carbon nanotubes metal oxide-based nanofluids

Due to the high thermal conductivity of CNTs, researchers started to use them to prepare nanofluids in order to improve the heat transfer. CNTs tend to aggregate into groups due to the large surface energy (strong van der Waals attractions between individual tubes) [32]. Therefore, a variety of approaches has been introduced to decrease the nanotubes agglomeration, namely, the modification of their chemistry through noncovalent adsorption using surfactants [33–36], covalent (functionalization) by chemical modification [37–42], and metal coating (like Ni-coated SWNTs). **Table 1** summarizes the work carried out so far dealing with the use of CNTs in nanofluids. Xie et al. [52] investigated the functionalized carbon nanotubes and found out that the thermal conductivity enhancement increased with the increase in nanotubes loading. In addition, it was found that the thermal conductivity decreased with the increase in thermal conductivity of the base fluid. Chen et al. [46] studied the effect of MWNTs on the thermal conductivity enhancement of ethylene glycol-based nanofluid and found that the enhancement reached up to 17.5% at 0.01 volume fraction. Ding et al. [49] observed a significant enhancement of the convective heat transfer in comparison with pure water as the working fluid, which depends on the flow condition, CNT concentration, and the pH level (although the latter is small). Grag et al. [44] studied the effect of ultrasonication on the thermal conductivity of MWCNT fluids and found that the thermal conductivity was enhanced by 20% when the ultrasonication was used for 40 min in 1 wt.% MWCNT concentration, in a 130 W, 20 kHz ultrasonication environment.

Reference	Material	Base fluid	Concentration	Characterization	TC improvement	Stabilizing agent	Stability
Phuoc et al. [43]	MWCNTs	Water	1.43 vol.%	Density and sound analyzer	13%	Chitosan	Stable for 45 days
Garg et al. [44]	MWCNTs	Water	1 wt.%	TEM,	20%	Gum Arabic	Stable
Meng et al. [45]	MWCNTs	EG	4 wt.%	TEM, UV-VIS	24.3%	Functionalization	Stable
Chen et al. [46]	MWCNTs	Water	1 vol.%	TEM,	17.5%	NA	Stable for many months
Chen and Xie [47]	SWCNTs	Water	0.2 vol.%	TEM	15.6%	Functionalization	Stable
	DWCNTs				14.2%		
	MWCNTs				12.1%		
Choi et al. [12]	MWCNTs	PAO	1.0 vol.%	TEM	160%	NA	Stable
Assael et al. [48]	MWCNTs	Water	0.6 vol.%	HR-TEM	38 %	Sodium dodecyl sulfate (SDS)	Stable
Ding et al. [49]	MWCNTs	Water	0.6 vol.%	TEM, SEM	79%	SDS, gum Arabic	Stable
Shaikh et al. [50]	CNT	PAO	1.0%	SEM	161%	Functionalization	Stable
	EXG	PAO	1.0%	SEM	131%		Stable
	HTT	PAO	1.0%	SEM	104%		Stable
Baby and Sundara [51]	Ag/ (MWCNT-HEG	EG	0.04 vol.%	SEM, XRD	8%	NA	Stable

PAO: poly (α-olefin) oil.

Table 1. Current research of carbon nanomaterials-based nanofluids.

Phuoc et al. [43] studied the thermal conductivity, viscosity, and stability of nanofluids made of MWCNT dispersed in water. The nanotubes have an outside diameter of 20–30 nm, inside diameter of 5–10 nm, length of 10–30 mm, and average density of 2.1 g/cm^3. Different weight ratio of Chitosan surfactant, namely, 0.1, 0.2, and 0.5 wt.%, was used to disperse MWCNTs in water. It was found that Chitosan dispersed and stabilized MWNTs in water efficiently; as only 0.1 wt.% Chitosan surfactant could disperse and stabilize 3 wt.% MWCNTs in water. The thermal conductivity of nanofluids containing 0.5–3 wt.% MWCNTs was enhanced from 2.3 to 13%. However, the enhancement of the thermal conductivity was independent of viscosity of the base fluid, which shows that the particle velocity does not have a significant effect on the thermal conductivity. **Figure 1** shows the dispersion behavior of the MWCNTs in deionized (DI) water (DW).

Figure 1. Nanofluid prepared by dispersing MWCNTs in deionized water (A) shows that MWNTs deposited at the bottom of the container and (B) shows that MWNTs maintain good dispersion: From Ref. [43].

Garg et al. [44] reported that 1 wt.% MWCNT increased the thermal conductivity up to 20% at 35°C. Gum arabic was used as a surfactant to stabilize the nanofluids. The study revealed that the thermal conductivity of CNT nanofluids increased considerably after 24°C. Meng et al. [45] found a 25.4% enhancement of the thermal conductivity of CNT glycol nanofluids with 4.0% mass fraction at room temperature. **Figure 2** shows that the transmittances from 200 to

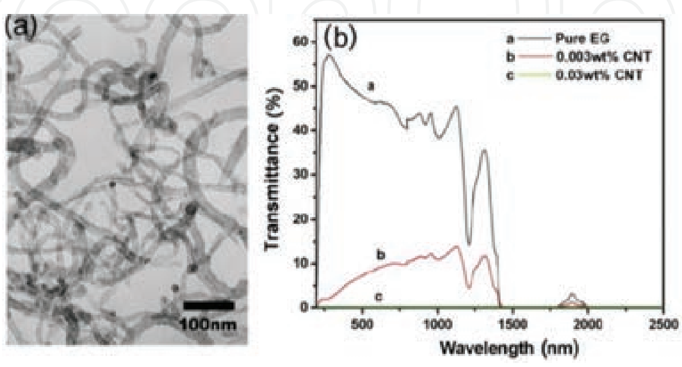

Figure 2. TEM image of HNO_3-treated CNTs (A) and UV–Vis–NIR transmittance spectra (B) of the CNTs glycol nanofluids. From ref. [45].

1500 nm, the values drop from 50% to about 10%, indicating that a small amount of CNTs results in significant absorption enhancement of light.

Chen et al. [46] reported that 1 vol.% of MWCNTs without surfactant, placed in ethylene glycol-based nanofluid, yielded an enhancement of 17.5%. A mechano-chemical reaction method was used to enhance the MWCNTs dispersibility for producing a CNT nanofluid. **Figure 3** shows the thermal conductivities of nanofluids as a function of nanotube loadings in two different fluids: deionized water and ethylene glycol. The enhancement using ethylene glycol as fluid and without surfactant at 1 vol.% of MWCNTs is higher than the enhancement using DW as fluid and at 1 vol.% of MWCNTs.

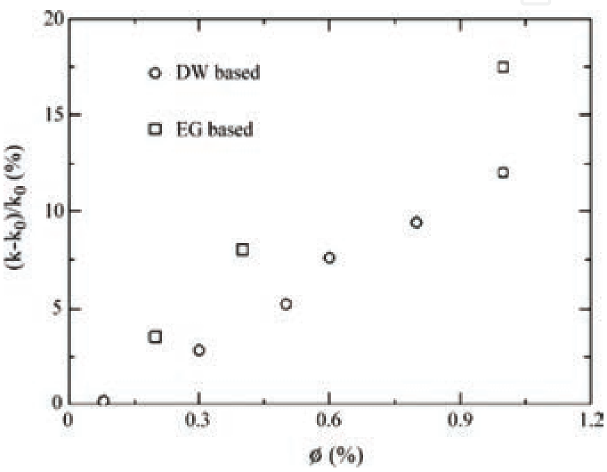

Figure 3. Thermal conductivities of nanofluids as a function of nanotube loadings. From ref. [47].

Chen and Xie [47] investigated nanofluids made of SWCNTs and DWCNTs in water-based fluids, respectively. Those CNTs were functionalized by a wet-mechano-chemical reaction method in order to obtain a stable dispersion. The study revealed that the thermal conductivity enhancement was 15.6, 14.2, and 12.1% for SWCNT, DWCNT, and MWCNT at a volume fraction of 0.2%, respectively.

Choi et al. [12] reported that the enhancement of thermal conductivity at a 1% volume fraction of MWCNTs in poly (α-olefin) (PAO) oil was 160%, compared to the base fluid at room temperature.

Assael et al. [48] found a 38% enhancement of the thermal conductivity in 0.6 vol.% MWNTs nanofluids in which water was a base fluid and SDS surfactant was used to stabilize the nanofluids. Ding et al. [49] confirmed that 1.0 vol.% of MWCNT dispersed in water, with SDBS surfactant, lead to an enhancement of 79% at 30°C. Shaikh et al. [50] prepared nanofluids by dispersing CNTs, exfoliated graphite (EXG), and heat-treated nanofibers (HTT) in PAO oil. The thermal conductivity for 1% CNTs, EXG, and HTT was enhanced by 161, 131, and 104 %, respectively. Baby and Sundara [51] reported on the synthesis of silver nanoparticle decorated MWCNT-graphene mixture and dispersed the (Ag/(MWNT-HEG)) composite in ethylene glycol without surfactant. They found that only 0.04 vol.% of the nanoparticles enhanced the thermal conductivity by ~8% at 25°C.

2.2. Graphene

Graphene, the first ever stable two-dimensional (2D) honeycomb lattice of sp^2-bonded carbon atoms, has attracted the interest of many researchers and is very promising for a wide range of applications due to its spectacular electronic, mechanical, and optical properties. Since few layers of graphene were isolated for the first time from graphite, using a tape in 2004 [53], the graphene production rate has increased rapidly in order to synthesize large-area and high-quality graphene films, compatible with various applications. Actually, the history of graphene dates back to the 1960s, when single-atom plane of graphite, termed as graphite layer, was isolated. For several decades, the existence of 2D atomic structures remained as an unaccepted concept. Now the term of graphene, the basic block of graphite, is widely used to describe the 2D monolayer of carbon atoms with a honeycomb structure. Graphene lattice consists of repetitive two identical carbon atoms, A and B, that together form one unit cell (**Figure 4**). The distance between each carbon atom and its neighbors is 1.42 Å [54]. **Figure 5** shows first Brillouin zone and band structure of graphene using tight binding approximation. *K* and *K*′ are Dirac points, the transition between the valence and the conduction band.

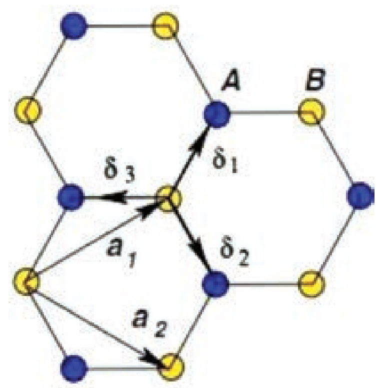

Figure 4. Graphene lattice.

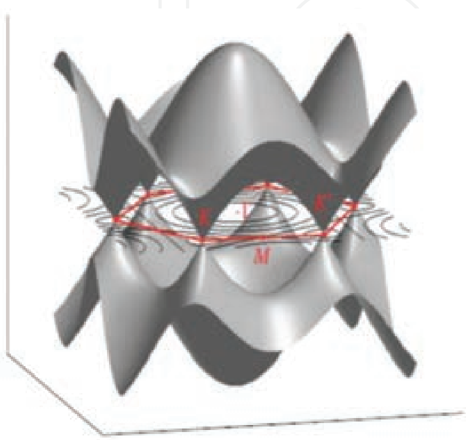

Figure 5. First Brillouin zone and band structure of graphene using tight binding approximation. *K* and *K*′ are Dirac points, the transition between the valence and the conduction band. Reproduced from [54].

2.2.1. Graphene and graphene metal oxide-based nanofluids

The high thermal conductivity of graphene encouraged researchers to use it to prepare nanofluids with super high thermal conductivity. Yu et al. [55] made stable nanofluids by dispersing graphene oxide nanosheets in ethylene glycol and found out that the thermal conductivity of the nanofluids was higher than that of the ethylene-glycol base fluid. The thermal conductivity of the nanofluids was enhanced up to 61.0% at 5.0 vol.% of graphene nanosheets (GNs), and almost constant for 7 days, indicating that the hydrophilic surfaces allow graphene oxide nanosheets to have good compatibility with ethylene glycol. Yu et al. [56] used a facial technique to prepare ethylene glycol-based nanofluids containing graphene nanosheets. They found that the thermal conductivity of the graphene nanofluids increased by 86% at 5.0 vol.% graphene, showing that the extensive presence of saturated sp^3 bonds and oxygen atoms made graphene oxide nonconducting, hindered the thermal transport, and promoted phonon scattering. Mehrali et al. [57] prepared stable nanofluids by mixing graphene nanoplatelets and water using a tip ultrasonicator. In this study, four concentrations were prepared: 0.025, 0.05, 0.075, and 0.1 wt.% for three different specific surface areas of 300, 500, and 750 m^2/g. It was found that the highest thermal conductivity was 27.64% for a concentration of 0.1 wt.%, with a specific surface area of 750 m^2/g. Aravind and Ramaprabhu [58] adopted a simple thermal treatment method to prepare graphene nanosheets (GNs)-based nanofluids. The procedure was carried out without surfactant and harsh chemical treatments, which reduced the alkaline pH of graphite oxide suspension in ethylene glycol (EG) and deionized (DI) water-based fluids. It was found that the thermal conductivity at 25°C and 0.14% volume fraction of GN in EG and DI water is enhanced by 6.5 and 13.6%, respectively. Ijam et al. [59] prepared a glycerol-water-based nanofluid containing graphene oxide nanosheets. The mixture was stable for up to 5 months. The thermal conductivity of the prepared nanofluid with different temperatures (25–45°C) and weight fractions (0.02–0.1 wt. %) revealed an enhancement of thermal conductivity of 4.5% at 25°C for a weight fraction of 0.02 and 11.7% for a weight fraction of 0.1 wt.% and 45°C, respectively. Kole et al. [60] studied the thermal and electrical conductivity of stable and well dispersed functionalized graphene-ethylene glycol. High purity graphite powder was used to make Graphene nanosheets. Then the Hummers' method [61] was followed, and exfoliation and reduction by hydrogen gas were used to obtain hydrogen-exfoliated graphene (HEG), which was functionalized with acid. The material was dispersed in distilled water nanofluids with volume concentration between 0.041 and 0.395 vol.%. It was found that the thermal conductivity at 0.395 vol.% was enhanced by 15%, and the thermal conductivity of both the base fluid and the prepared nanofluid increased linearly with temperature. However, the thermal conductivity ratios (TC of the nanofluids over the TC of base fluids) were nearly independent of temperature. The study also showed that the electrical conductivity of the f-HEG nanofluids had a significant enhancement of 8620% at 0.395 vol.% loading of f-HEG, in a base fluid of 70:30 mixture of EG and distilled water. Hajjar et al. [62] studied the thermal conductivity of graphene oxide nanofluids, which comprised of graphene oxide obtained by the Hummers' method and water. They found that 0.25 wt.% of graphene oxide could enhance the thermal conductivity by 33.9% at 20°C and up to 47.5% at 40°C. Ghozatloo et al. [63] investigated the stability and thermal conductivity behavior of the nanofluids made of graphene- and water-based fluids. They also analyzed the influence of time and temperature on the effective thermal conductivities for different concentrations of graphene that was functionalized in mild conditions by potassium persulfate. The thermal conductivity for 0.05 wt.% of the functionalized graphene is enhanced around 14.1% at 25°C and 17% at 50°C compared with water. Liu et al. [64] studied the thermodynamic properties (including thermal conductivity, viscosity, specific heat, and density) of graphene-dispersed nanofluids for temperatures ranging from room temperature to around 200°C. The studied nanofluids were made out of graphene and the ionic liquid 1-hexyl-3-methylimidazolium tetra fluoroborate ((HMIM)BF4). The work showed that the thermal conductivity of the nanofluid containing 0.06 wt.% graphene increased by 15.2–22.9% at the tested temperature range (25–200°C). Viscosity, specific heat, and density decreased, respectively, by 4.6–13.1, 3, and 2.8%, compared to (HMIM)BF4.

3. Effect of the alignment of the carbon nanostructures on the thermal conductivity of nanofluids

Many researchers have studied the effect of the alignment of iron oxide nanoparticles and carbon nanomaterials on the thermal, electrical, and mechanical properties of fluids and polymers. **Table 2** summarizes most work about the effect of the alignment of iron oxide nanoparticles and carbon nanomaterials on the thermal conductivity of nanofluids.

Reference	Material	Base fluid	Concentration	Characterization	TC improvement		Stabilizing agent	Stability
					No MF	With MF		
Hong et al. [65]	CNTs $+Fe_2O_3$	Water	0.01 wt.% CNTs, 0.02 wt.% Fe_2O_3	SEM	15%	52%	Sodium dodecylbenzenesulfonate (NaDDBS)	Stable
Wensel et al. [17]	CNTs $+Fe_2O_3$	Water	0.02 wt.%	Optical microscopy	10 %	50%	NaDDBS	Stable
Wright et al. [66]	Ni-CNTs	Water	0.01 wt.%	NA	NA	75%	NA	Stable
Horton et al. [67]	Ni-CNTs	PAO	0.05 wt.%	TEM, Optical microscopy	NA	11%	NA	Stable
Hong et al. [68]	SWCNT, Fe_2O_3	Water	0.017 wt.% SWNT, 0.017 wt.% Fe_2O_3	TEM, Optical microscopy		MF 0.62 kG applied for 30 min 123%	NaDDBS	Stable
Younes et al. [69]	Fe_2O_3	Water	0.4 vol.%	TEM, Optical microscopy	18%	81%	NA	Stable

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Reference	Material	Base fluid	Concentration	Characterization	TC improvement	Stabilizing agent	Stability
Younes et al. [70]	SWCNT-COOH	Water	0.016 wt.%	Optical microscopy	NA 41%	NA	Stable
	SWCNT-SO_2OH	Water			40%		Stable
	SWCNT-PABS	Water			12%		Stable
	SWCNT-CONH2	Water			17%		Stable
	SWCNT-PEG	Water			14%		Stable
Younes et al. [30]	CNFs	Water	0.02 wt.%	Optical microscopy	10% 20%	NaDDBS	Stable
Philip et al. [71]	Fe_3O_4	Water	6.3 vol.%	Optical microscopy	300%	NA	Stable

Table 2. Current research of the effect of the alignment of iron oxide nanoparticles and carbon nanomaterials on the thermal conductivity of nanofluids.

Hong et al. [65] studied the effect of the alignment on the thermal conductivity of nanofluids under an external magnetic field and obtained the thermal conductivity and microscopic images taken with and without magnetic field, shown in **Figures 6** and **7**.

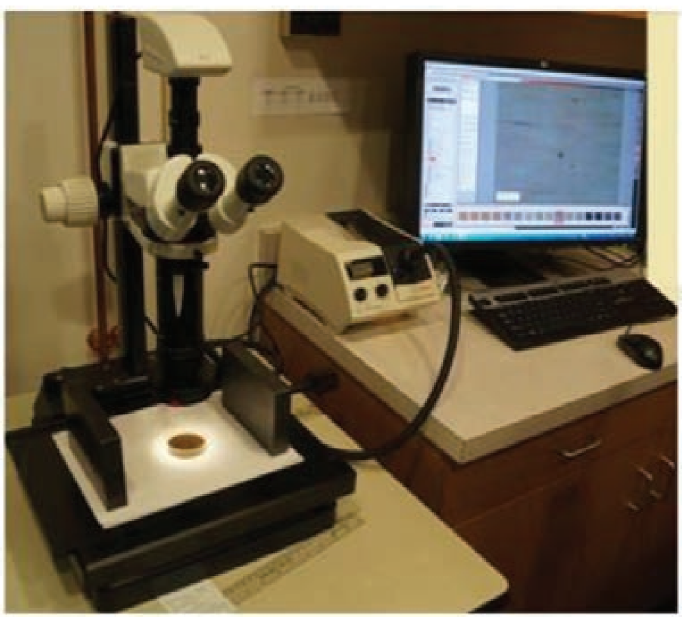

Figure 6. Experimental setup for taking optical microscopy images using the optical microscope, Leica Z16 APO under application of a magnetic field. From Ref. [70].

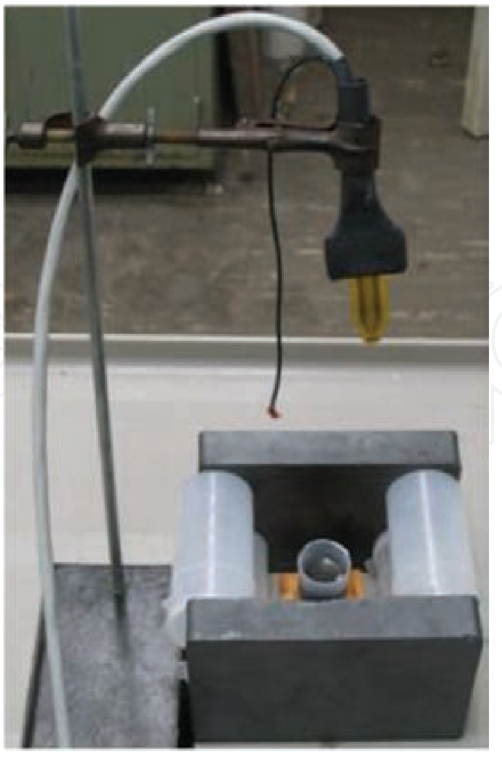

Figure 7. Experimental setup for measuring TC under application of a magnetic field. From Ref. [70].

Figure 8 shows that the nanotubes align very well in the magnetic field direction.

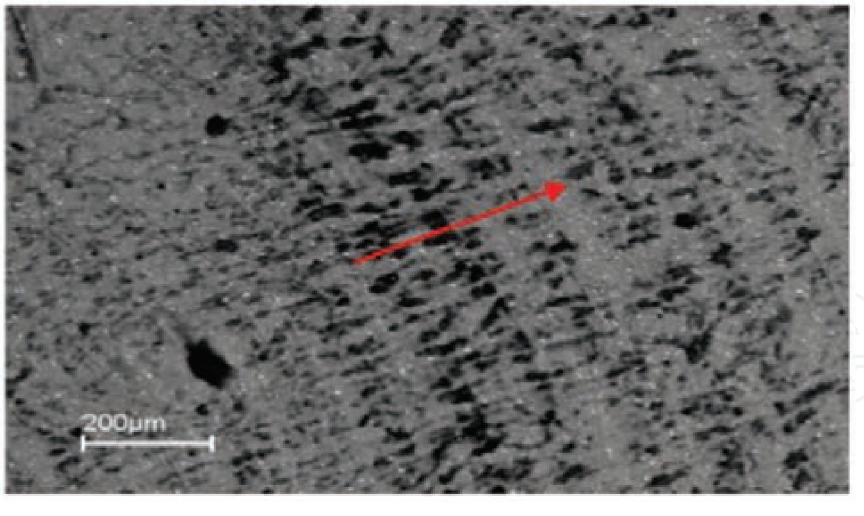

Figure 8. SEM picture of 0.01 wt.% carbon nanotube + 0.02 wt.% Fe_2O_3 with magnetic field. From Ref. [65].

The heat transfer of nanofluids containing carbon nanotubes and magnetic-field-sensitive nanoparticles of Fe_2O_3 was enhanced when a magnetic field was applied for some time. The enhancement was attributed to the formation of aligned chains of Fe_2O_3 under the applied magnetic field and to the fact that chains help to connect the nanotubes. Wensel and Wright [17, 66] found that the thermal conductivity of nanofluids containing 0.02 wt.% was enhanced by 10% under a magnetic field. That was attributed to the aggregation of metal oxide particles on the surface of nanotubes by electrostatic attraction, which forms the aggregation chain along the nanotubes. Horton et al. [67] investigated the thermal conductivity of nanofluids containing magnetic-metal-coated carbon nanotubes (Ni-coated SWCNTs), which significantly enhanced by 60% under a magnetic field. **Figure 9** shows a color online microscope image of 0.05 wt.% Ni-coated SWCNT in DI water, before (A) and after the magnetic field (B) was applied (H = 0.62 kG).

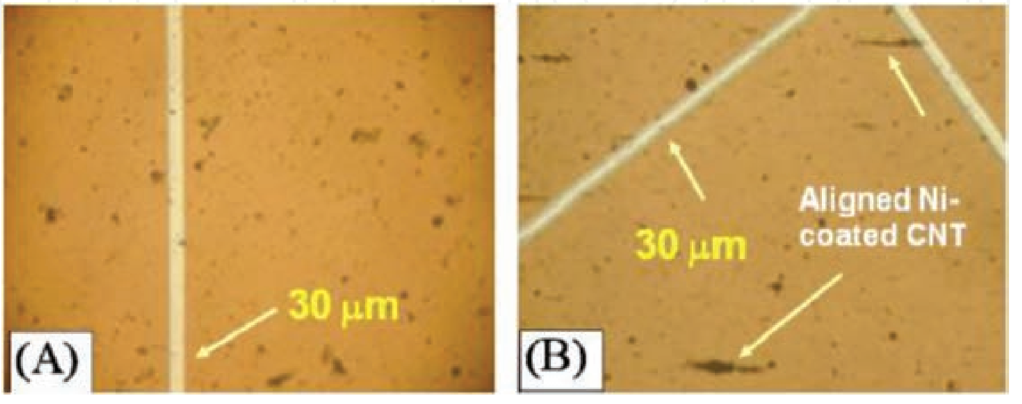

Figure 9. Color online microscope image of 0.05 wt.% Ni-coated SWCNT in DI water. (A) Before magnetic field and (B) after magnetic field (H = 0.62 kG). From Ref. [66].

Figure 10 shows TEM images of carbon nanotubes. (A) As received, uncoated CNTs, the image shows that the wall of one CNT is clear and nothing adhere to it. (B) Ni-coated CNTs, the image shows that the wall of the CNTs has been modified with some Ni adhered to the surface of the CNTs and (C) shows that the wall of the Ni-coated CNTs after applying the magnetic field experiment. It can be seen that the density of the Ni coated has decreased due to the effect of sonication and the magnetic field experiment.

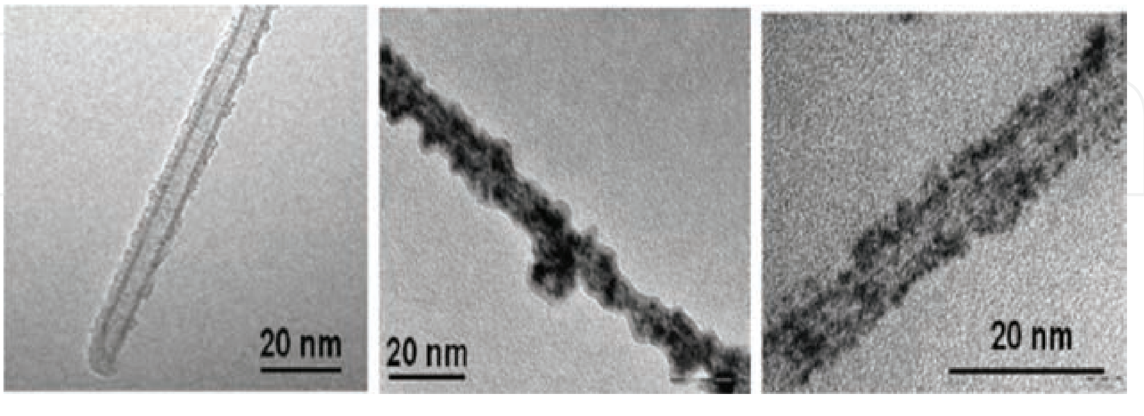

Figure 10. TEM images of carbon nanotubes. (A) As received, uncoated. (B) Ni-coated nanotube before the magnetic field experiment, and (C) after the experiment. From Ref [67].

Hong et al. [68] studied the thermal conductivity of nanofluids containing CNTs and magnetic-field-sensitive nanoparticles of Fe_2O_3 with NaDDBS surfactant and found that an electrostatic attraction among the nanotubes, the surfactant, and the metal oxide caused aggregation. NaDDBS surfactant with a negative charge attracted Fe_2O_3, which had positive zeta potential charge. When a cationic surfactant, cetyltrimethyl ammonium bromide (CTAB), replaced the anionic surfactant NaDDBS, no alignment was found because both the surfactant and Fe_2O_3 have the same positive charge. **Figure 11** shows that the nanotubes align very well in the direction of the magnetic field, either in scale bar 100 μm (A) or 10 μm (B).

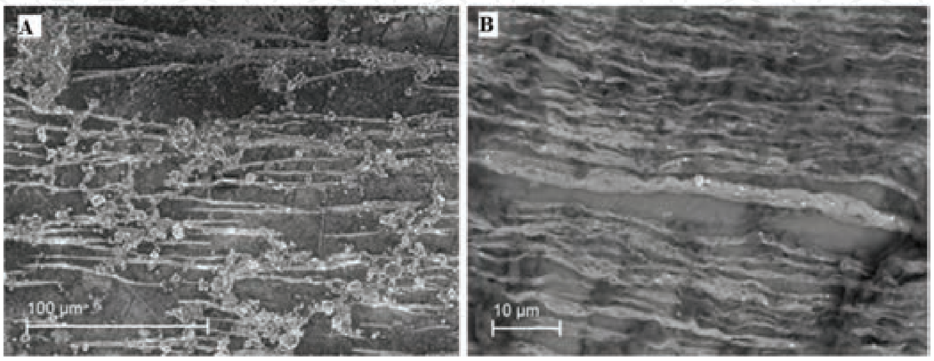

Figure 11. Electron SEM images of 0.017 wt.% SWCNT, 0.017 wt.% Fe_2O_3, and 0.17 wt.% NaDSSB with magnetic field. (A) Scale bar 100 m, and (B) scale bar 10 m. From Ref. [68].

Younes et al. [27, 70] studied the alignment of different functionalized SWCNTs using Fe_2O_3 nanoparticles under an external magnetic field. These authors found that, even in the absence of NaDDBS as surfactant, some functionalized SWNTs, i.e., SWNT-SO_2OH and SWNT-COOH, could disperse well in water and showed a clear alignment under an external magnetic field. **Figure 12** shows microscopy image of 0.016 wt.% SWNT-COOH and 0.016 wt.% Fe_2O_3 in DI water. This microscope image of 0.016 wt.% SWNT-COOH and 0.016 wt.% γ-Fe_2O_3 in DI water was obtained using a high-speed microscope video system. Magnetic field (H = 0.14 kG) was applied with an internal reference of 30 μm. As shown in **Figure 12**, it is clearly seen that the randomly dispersed SWNT-COOH/γ-Fe_2O_3 forms large and long lines, indicating that SWNT-COOH/γ-Fe_2O_3 nanoparticle mixture aligns under the external magnetic field.

Figure 12. Microscopy image of 0.016 wt.% SWNT-COOH, 0.016 wt.% Fe_2O_3 in DI water. At 8 min, the internal reference is 30 μm. From Ref. [70].

Younes et al. [30] studied the effect of the alignment of carbon nanofibers in water and epoxy under an external magnetic field on the thermal conductivity of nanofluids. They found that the magnetic field aligned the nanofibers, not only in water but also in epoxy, as clearly seen in **Figure 13**. Adding 0.02 wt.% of carbon nanofibers to water enhanced the thermal conductivity by 10%. The addition of an external magnetic field enhanced the thermal conductivity around 20%.

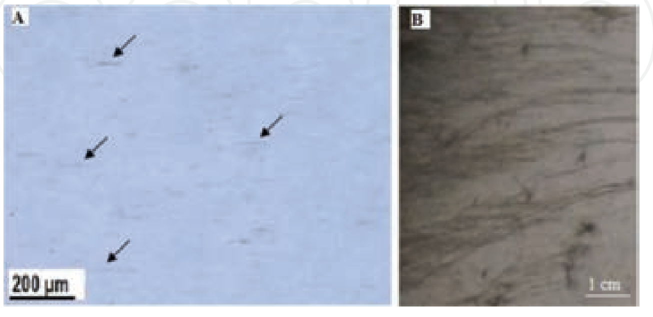

Figure 13. Alignment of CNFs in epoxy. (A) Optical microscopy images for 0.002 wt.% CNFs, 0.002 wt.% Fe_2O_3, and 0.02 wt.% NaDDBS in epoxy after 48 h. (B) Digital camera image of 0.02 wt.% CNFs, 0.02 wt.% Fe_2O_3, and 0.2 wt.% NaDDBS in epoxy after 2 h. Magnetic field (H = 1.2 kG) was applied. From Ref. [30].

Christensen et al. [26] studied the effect of nonionic surfactant on the dispersion and alignment of carbon nanotubes in the presence of Fe_2O_3. Gum arabic and Triton X-100 were used as nonionic surfactants. Gum arabic did not allow good dispersion or alignment in aqueous fluid. Triton X-100 allowed dispersion and alignment of both Fe_2O_3 and SWNT in an aqueous base

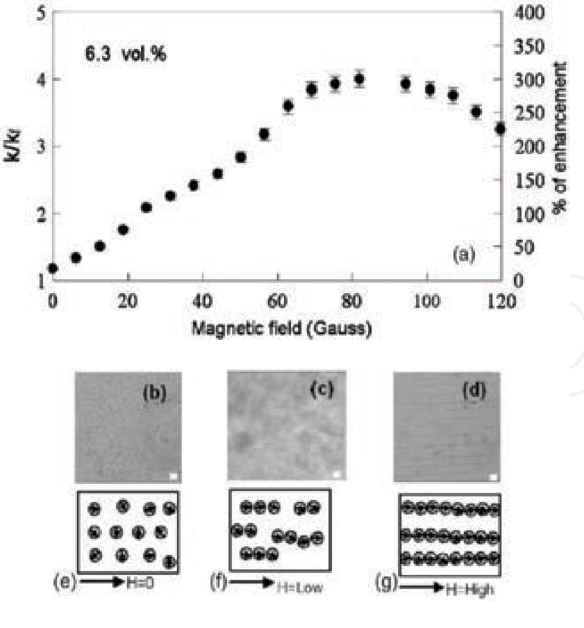

Figure 14. (a) Thermal conductivity ratio k/k_f and the corresponding percentage of enhancement as a function of applied magnetic field for 6.3 vol.% of Fe_3O_4. (B)–(D) Micrographs of ferrofluid emulsion of 200 nm, (B) without, (C) with low, and (D) with high magnetic field. (E)–(G) Schematic alignment of particles under the above three cases. From Ref. [71].

fluid. Due to the partial negative charge of Triton X-100, alignment did occur, but the alignment was slower, when compared to surfactants or functional groups containing stronger charges.

Glover et al. [72] prepared a nanofluids that consisted of water and 0–0.5 wt.% of sulfonated carbon nanotubes. The electrical conductivity of the prepared nanofluids was measured. The study found that the electrical conductivity increased by 13 times when only 0.5 wt.% of functional sulfonated carbon nanotubes was used. Philip et al. [71] observed a dramatic enhancement of thermal conductivity in a nanofluid containing magnetic particles of Fe_3O_4 (of 6.7 nm diameter) under a magnetic field (see **Figure 14**). The maximum enhancement in thermal conductivity was 300% ($k/k_f = 4.0$) for a particle loading of 6.3 vol.%.

4. Conclusions

The main focus of this chapter is to summarize the recent studies using CNTs and graphene to improve the thermal conductivity of nanofluids. Moreover, this chapter summarizes the investigation about the effect of using magnetic fields on enhancing the thermal conductivity of nanofluids. Too much discrepancy about thermal conductivity of nanofluids can be found in the literature. For carbon nanofluids, unfortunately, no significant improvements on thermal conductivity are observed using low concentrations. The thermal conductivity increased by approximately 10–20% when 1 vol.% SWCNT was used. However, at these high concentrations, the viscosity is greatly increased and the nanofluid becomes "mud-like," which are the difficulties reported in the literature. This variation in the thermal conductivity can be attributed to many factors, such as particle size, temperature, pH, or zeta potential. Finally, we believe that more efforts need to be done in order to improve the thermal conductivity of nanofluids and study the effect of the different parameters in thermal conductivity. In addition, more investigation about the use of magnetic field to align magnetic sensitive nanoparticles is required.

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References

[1] Altan CL, Elkatmis A, Yüksel M, Aslan N, Bucak S. Enhancement of thermal conductivity upon application of magnetic field to Fe3O4 nanofluids. Journal of Applied Physics. 2011;110(9):093917.

[2] Leong K, Saidur R, Kazi S, Mamun A. Performance investigation of an automotive car radiator operated with nanofluid-based coolants (nanofluid as a coolant in a radiator). Applied Thermal Engineering. 2010;30(17):2685–2692.

[3] Srikant R, Rao D, Subrahmanyam M, Krishna VP. Applicability of cutting fluids with nanoparticle inclusion as coolants in machining. Proceedings of the Institution of Mechanical Engineers, part J. Journal of Engineering Tribology. 2009;223(2):221–225.

[4] Kulkarni DP, Vajjha RS, Das DK, Oliva D. Application of aluminum oxide nanofluids in diesel electric generator as jacket water coolant. Applied Thermal Engineering. 2008;28(14):1774–1781.

[5] K.K. Kuo, G.A. Risha, B.J. Evans, E. Boyer, Potential Usage of Energetic Nano-sized Powders for Combustion and Rocket Propulsion, MRS Online Proceedings Library Archive, 800 (2003) AA1.1 (12 pages).

[6] Prasher R, Phelan PE, Bhattacharya P. Effect of aggregation kinetics on the thermal conductivity of nanoscale colloidal solutions (nanofluid). Nano Letters. 2006;6(7):1529–1534.

[7] Wen D, Lin G, Vafaei S, Zhang K. Review of nanofluids for heat transfer applications. Particuology. 2009;7(2):141–150.

[8] Saidur R, Leong K, Mohammad H. A review on applications and challenges of nanofluids. Renewable and Sustainable Energy Reviews. 2011;15(3):1646–1668.

[9] Pastoriza-Gallego M, Lugo L, Legido J, Piñeiro M. Enhancement of thermal conductivity and volumetric behavior of FexOy nanofluids. Journal of Applied Physics. 2011;110(1):014309.

[10] Yu W, France DM, Routbort JL, Choi SU. Review and comparison of nanofluid thermal conductivity and heat transfer enhancements. Heat Transfer Engineering. 2008;29(5): 432–460.

[11] Sidik NAC, Mohammed H, Alawi OA, Samion S. A review on preparation methods and challenges of nanofluids. International Communications in Heat and Mass Transfer. 2014;54:115–125.

[12] Choi S, Zhang Z, Yu W, Lockwood F, Grulke E. Anomalous thermal conductivity enhancement in nanotube suspensions. Applied Physics Letters. 2001;79(14):2252–2254.

[13] Keblinski P, Eastman JA, Cahill DG. Nanofluids for thermal transport. Materials Today. 2005;8(6):36–44.

[14] Wang X, Xu X, Choi SU. Thermal conductivity of nanoparticle-fluid mixture. Journal of Thermophysics and Heat Transfer. 1999;13(4):474–480.

[15] Wen D, Ding Y. Experimental investigation into the pool boiling heat transfer of aqueous based γ-alumina nanofluids. Journal of Nanoparticle Research. 2005;7(2–3): 265–274.

[16] Anoop K, Sundararajan T, Das SK. Effect of particle size on the convective heat transfer in nanofluid in the developing region. International Journal of Heat and Mass Transfer. 2009;52(9):2189–2195.

[17] Wensel J, Wright B, Thomas D, Douglas W, Mannhalter B, Cross W, et al. Enhanced thermal conductivity by aggregation in heat transfer nanofluids containing metal oxide nanoparticles and carbon nanotubes. Applied Physics Letters. 2008;92(2):023110.

[18] Iijima S. Helical microtubules of graphitic carbon. Nature. 1991;354(6348):56–58.

[19] Biercuk M, Llaguno MC, Radosavljevic M, Hyun J, Johnson AT, Fischer JE. Carbon nanotube composites for thermal management. Applied Physics Letters. 2002;80(15): 2767–2769.

[20] Berber S, Kwon Y-K, Tománek D. Unusually high thermal conductivity of carbon nanotubes. Physical Review Letters. 2000;84(20):4613.

[21] Nan C-W, Liu G, Lin Y, Li M. Interface effect on thermal conductivity of carbon nanotube composites. Applied Physics Letters. 2004;85(16):3549–3551.

[22] Spitalsky Z, Tasis D, Papagelis K, Galiotis C. Carbon nanotube–polymer composites: chemistry, processing, mechanical and electrical properties. Progress in Polymer Science. 2010;35(3):357–401.

[23] Hongtao L, Hongmin J, Haiping H, Younes H. Tribological properties of carbon nanotube grease. Industrial Lubrication and Tribology. 2014;66(5):579–583.

[24] Abueidda DW, Dalaq AS, Al-Rub RKA, Younes HA. Finite element predictions of effective multifunctional properties of interpenetrating phase composites with novel triply periodic solid shell architectured reinforcements. International Journal of Mechanical Sciences. 2015;92:80–89.

[25] Abueidda DW, Al-Rub RKA, Dalaq AS, Younes HA, Al Ghaferi AA, Shah TK. Electrical conductivity of 3D periodic architectured interpenetrating phase composites with carbon nanostructured-epoxy reinforcements. Composites Science and Technology. 2015;118:127–134.

[26] Christensen G, Younes H, Hong H, Smith P. Effects of solvent hydrogen bonding, viscosity, and polarity on the dispersion and alignment of nanofluids containing Fe_2O_3 nanoparticles. Journal of Applied Physics. 2015;118(21):214302.

[27] H. Younes, Carbon Nanomaterials and Metal Oxide Nanoparticles and Their Applications Toward Grease and Nanofluids, South Dakota School of Mines and Technology, Rapid City2013.

[28] Sofela SO, Younes H, Jelbuldina M, Saadat I, Al Ghaferi A, editors. Carbon nanomaterials based TSVs for dual sensing and vertical interconnect application. Interconnect Technology Conference and 2015 IEEE Materials for Advanced Metallization Conference (IITC/MAM), 2015 IEEE International; 2015.

[29] Younes H, Christensen G, Li D, Hong H, Ghaferi AA. Thermal conductivity of nanofluids: Review. Journal of Nanofluids. 2015;4(2):107–132.

[30] Younes H, Christensen G, Liu M, Hong H, Yang Q, Lin Z. Alignment of carbon nanofibers in water and epoxy by external magnetic field. Journal of Nanofluids. 2014;3(1):33–37.

[31] Rahmana M, Younes H, Ni G, Zhang T, Al Ghaferi A. Synthesis and optical characterization of carbon nanotube arrays. Materials Research Bulletin. 2016;77:243–252.

[32] Rahman MM, Younes H, Subramanian N, Ghaferi AA. Optimizing the dispersion conditions of SWCNTs in aqueous solution of surfactants and organic solvents. Journal of Nanomaterials. 2014;2014:145.

[33] Cui S, Canet R, Derre A, Couzi M, Delhaes P. Characterization of multiwall carbon nanotubes and influence of surfactant in the nanocomposite processing. Carbon. 2003;41(4):797–809.

[34] Yurekli K, Mitchell CA, Krishnamoorti R. Small-angle neutron scattering from surfactant-assisted aqueous dispersions of carbon nanotubes. Journal of the American Chemical Society. 2004;126(32):9902–9903.

[35] Rosca ID, Watari F, Uo M, Akasaka T. Oxidation of multiwalled carbon nanotubes by nitric acid. Carbon. 2005;43(15):3124–3131.

[36] Velasco-Santos C, Martínez-Hernández AL, Fisher FT, Ruoff R, Castano VM. Improvement of thermal and mechanical properties of carbon nanotube composites through chemical functionalization. Chemistry of Materials. 2003;15(23):4470–4475.

[37] Saini RK, Chiang IW, Peng H, Smalley R, Billups W, Hauge RH, et al. Covalent sidewall functionalization of single wall carbon nanotubes. Journal of the American Chemical Society. 2003;125(12):3617–3621.

[38] Kong H, Gao C, Yan D. Functionalization of multiwalled carbon nanotubes by atom transfer radical polymerization and defunctionalization of the products. Macromolecules. 2004;37(11):4022–4030.

[39] Peng H, Alemany LB, Margrave JL, Khabashesku VN. Sidewall carboxylic acid functionalization of single-walled carbon nanotubes. Journal of the American Chemical Society. 2003;125(49):15174–15182.

[40] Shen J, Huang W, Wu L, Hu Y, Ye M. The reinforcement role of different amino-functionalized multi-walled carbon nanotubes in epoxy nanocomposites. Composites Science and Technology. 2007;67(15):3041–3050.

[41] Jeong G-H. Surface functionalization of single-walled carbon nanotubes using metal nanoparticles. Transactions of Nonferrous Metals Society of China. 2009;19(4):1009–1012.

[42] Zhang L, Kiny VU, Peng H, Zhu J, Lobo RF, Margrave JL, et al. Sidewall functionalization of single-walled carbon nanotubes with hydroxyl group-terminated moieties. Chemistry of Materials. 2004;16(11):2055–2061.

[43] Phuoc TX, Massoudi M, Chen R-H. Viscosity and thermal conductivity of nanofluids containing multi-walled carbon nanotubes stabilized by chitosan. International Journal of Thermal Sciences. 2011;50(1):12–18.

[44] Garg P, Alvarado JL, Marsh C, Carlson TA, Kessler DA, Annamalai K. An experimental study on the effect of ultrasonication on viscosity and heat transfer performance of multi-wall carbon nanotube-based aqueous nanofluids. International Journal of Heat and Mass Transfer. 2009;52(21–22):5090–5101.

[45] Meng Z, Wu D, Wang L, Zhu H, Li Q. Carbon nanotube glycol nanofluids: photo-thermal properties, thermal conductivities and rheological behavior. Particuology. 2012;10(5):614–618.

[46] Chen L, Xie H, Li Y, Yu W. Nanofluids containing carbon nanotubes treated by mechanochemical reaction. Thermochimica Acta. 2008;477(1–2):21–24.

[47] Chen L, Xie H. Surfactant-free nanofluids containing double- and single-walled carbon nanotubes functionalized by a wet-mechanochemical reaction. Thermochimica Acta. 2010;497(1–2):67–71.

[48] Assael M, Metaxa I, Arvanitidis J, Christofilos D, Lioutas C. Thermal conductivity enhancement in aqueous suspensions of carbon multi-walled and double-walled nanotubes in the presence of two different dispersants. International Journal of Thermophysics. 2005;26(3):647–664.

[49] Ding Y, Alias H, Wen D, Williams RA. Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids). International Journal of Heat and Mass Transfer. 2006;49(1–2):240–250.

[50] Shaikh S, Lafdi K, Ponnappan R. Thermal conductivity improvement in carbon nanoparticle doped PAO oil: An experimental study. Journal of Applied Physics. 2007;101(6):064302.

[51] Theres Baby T, Sundara R. Synthesis of silver nanoparticle decorated multiwalled carbon nanotubes-graphene mixture and its heat transfer studies in nanofluid. AIP Advances. 2013;3(1):012111.

[52] Xie H, Lee H, Youn W, Choi M. Nanofluids containing multiwalled carbon nanotubes and their enhanced thermal conductivities. Journal of Applied Physics. 2003;94(8):4967.

[53] Novoselov KS, Geim AK, Morozov SV, Jiang D, Zhang Y, Dubonos SV, Grigorieva IV, Firsov AA. Electric field effect in atomically thin carbon films. Science. 2004; 306(5696): 666–669.

[54] Cooper DR, D'Anjou B, Ghattamaneni N, Harack B, Hilke M, Horth A, Majlis N, Massicotte M, Vandsburger L, Whiteway E, Yu V. Experimental review of graphene. ISRN Condensed Matter Physics. 2011;2012:1–56.

[55] Yu W, Xie H, Bao D. Enhanced thermal conductivities of nanofluids containing graphene oxide nanosheets. Nanotechnology. 2009;21(5):055705.

[56] Yu W, Xie H, Wang X, Wang X. Significant thermal conductivity enhancement for nanofluids containing graphene nanosheets. Physics Letters A. 2011;375(10):1323–1328.

[57] Mehrali M, Sadeghinezhad E, Latibari ST, Kazi SN, Mehrali M, Zubir MNBM, et al. Investigation of thermal conductivity and rheological properties of nanofluids containing graphene nanoplatelets. Nanoscale Research Letters. 2014;9(1):1–12.

[58] Aravind SJ, Ramaprabhu S. Surfactant free graphene nanosheets based nanofluids by in-situ reduction of alkaline graphite oxide suspensions. Journal of Applied Physics. 2011;110(12):124326.

[59] Ijam A, Golsheikh AM, Saidur R, Ganesan P. A glycerol–water-based nanofluid containing graphene oxide nanosheets. Journal of Materials Science. 2014;49(17):5934–5944.

[60] Kole M, Dey T. Investigation of thermal conductivity, viscosity, and electrical conductivity of graphene based nanofluids. Journal of Applied Physics. 2013;113(8):084307.

[61] Hummers Jr WS, Offeman RE. Preparation of graphitic oxide. Journal of the American Chemical Society. 1958;80(6):1339.

[62] Hajjar Z, Morad Rashidi A, Ghozatloo A. Enhanced thermal conductivities of graphene oxide nanofluids. International Communications in Heat and Mass Transfer. 2014;57:128–131.

[63] Ghozatloo A, Shariaty-Niasar M, Rashidi AM. Preparation of nanofluids from functionalized graphene by new alkaline method and study on the thermal conductivity and stability. International Communications in Heat and Mass Transfer. 2013;42:89–94.

[64] Liu J, Wang F, Zhang L, Fang X, Zhang Z. Thermodynamic properties and thermal stability of ionic liquid-based nanofluids containing graphene as advanced heat transfer fluids for medium-to-high-temperature applications. Renewable Energy. 2014;63:519–523.

[65] Hong H, Wright B, Wensel J, Jin S, Ye XR, Roy W. Enhanced thermal conductivity by the magnetic field in heat transfer nanofluids containing carbon nanotube. Synthetic Metals. 2007;157(10):437–440.

[66] Wright B, Thomas D, Hong H, Groven L, Puszynski J, Duke E, et al. Magnetic field enhanced thermal conductivity in heat transfer nanofluids containing Ni coated single wall carbon nanotubes. Applied Physics Letters. 2007;91(17):173116.

[67] Horton M, Hong H, Li C, Shi B, Peterson G, Jin S. Magnetic alignment of Ni-coated single wall carbon nanotubes in heat transfer nanofluids. Journal of Applied Physics. 2010;107(10):104320.

[68] Hong H, Luan X, Horton M, Li C, Peterson G. Alignment of carbon nanotubes comprising magnetically sensitive metal oxides in heat transfer nanofluids. Thermochimica Acta. 2011;525(1):87–92.

[69] Younes H, Christensen G, Luan X, Hong H, Smith P. Effects of alignment, pH, surfactant, and solvent on heat transfer nanofluids containing Fe2O3 and CuO nanoparticles. Journal of Applied Physics. 2012;111(6):064308.

[70] Younes H, Christensen G, Hong H, Peterson G. Alignment of different functionalized single wall carbon nanotubes using Fe2O3 nanoparticles under external magnetic field. Journal of Nanofluids. 2013;2(1):4–10.

[71] Philip J, Shima P, Raj B. Enhancement of thermal conductivity in magnetite based nanofluid due to chainlike structures. Applied Physics Letters. 2007;91(20):203108.

[72] Glover B, Whites KW, Hong H, Mukherjee A, Billups WE. Effective electrical conductivity of functional single-wall carbon nanotubes in aqueous fluids. Synthetic Metals. 2008;158(12):506–508.