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REVIEW ENHANCEMENT OF THERMAL CONDUCTIVITY AND HEAT TRANSFER USING CARBON NANOTUBE FOR NANOFLUIDS AND IONANOFLUIDS

Ail. J. Ali [1,2,*], E.N. Tugolukov [1]

ABSTRACT

This paper attempts to present a clearer picture, a detailed and up to date review of the heat transfer enhancement and thermal conductivity improvement for conventional fluids by adding carbon nanotubes or hybrid carbon nanotubes in the base fluid to obtain nanofluids or ionanofluid. Carbon nanotubes have attracted the interest of different researchers because of their high thermal conductivity that exceeds other equivalent types of nanoparticles. In view of this, the effect of different key factors like concentration, temperature and shape type of nanoparticles on the thermal conductivity improvement in nanofluids were reviewed. Moreover, the effect of surfactant stabilizers on the carbon nanotubes nanofluids distribution was evaluated. The results that have been obtained from the valuable studies have been analyzed and some gaps have been found that need to be re-reviewed by the researchers.

Keywords: *Enhancement, Thermal Conductivity, Carbon Nanotubes, Heat Transfer, Convection, Nano Fluid*

INTRODUCTION

With the development and emergence of new sciences and technology, the researchers have developed conventional heat transfer fluids that are used in various industries like cooling, heating and other applications. The objective was to improve the properties of conventional fluids and thereby enhance production and reduce cost. One of the results of the development and enhancement of the heat-transfer fluid is the appearance of nanofluid. Nanofluids are playing an important role in development and improvement heat transfer, nanofluids differ from conventional fluids in their exciting thermophysical properties that attracted the interest of scientists and the researchers. Nanofluids lead to increasing heat transfer and thermal conductivity, but also in another direction it was noted that the nanofluids have led to increasing the pressure drop when the concentration of the nanoparticles is high in the base fluid, due to the increase in viscosity, where the pressure drop is considered to be an important parameter [1-4]. Most workers have shown that the increase in temperature and concentration would lead to increasing the thermal conductivity and heat transfer [5-7]. One of the problems in nanofluid technology is the agglomeration of nanoparticles after different time periods. Three methods have been used to avoid sedimentation of nanoparticles and to obtain a stable suspension: [8,9].

- A chemical method by adding surfactants.
- A physical method using ultrasonic waves at different frequencies.
- An electrical method by controlling the pH.

Nanofluid is a mixture of the basic liquid and nanoparticles (1–100 nm). The essential liquids are Water, Fat, Ethylene glycol (EG), Engine oil (EO) and others while the nanoparticles are: MWCNT, SWCNT, CuO, Cu, Al, Si, etc. Where each of these nanoparticles has different thermal conductivity and contributes to improving heat transfer [10-12]. But this improvement also depends on several parameters as (volume fraction, Thermal conductivity of nanoparticles and base fluid, size of nanoparticles, shape of the nanoparticles, acidity, temperature, aspect ratio, additives, effect of clustering) [13-22]. As shown in Figures 1 and 2. There are two types of particle shapes investigated in nanofluid research; cylindrical shaped and spherical shaped-nanoparticles. Nanofluids with cylindrical shape nanoparticles such as carbon nanotubes show a larger increase in thermal conductivity in comparison with the nanofluids of spherical shape [23].

In addition to that, the studies show that the pH of the nanofluid significantly impacts the thermal conductivity of the suspension and it was also noted that thermal conductivity enhances with enhancing the pH, where the maximum

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1Department of "Technology and Methods of Nano products Manufacturing", Tambov State Technical University, Tambov, Russia"
2 Department of "Biomedical engineering" University of Technology, Baghdad, Iraq"
** E-mail address: 10678@uotechnology.edu.iq , tugolukov.en@mail.ru*
Orcid id: 0000-0003-0047-8605, 0000-0003-1766-3786
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level of conductivity is reached close to the isoelectric point, after which the thermal conductivity reduces with further increasing the value of pH [24]. The rest of the parameters will be reviewed later in this paper.

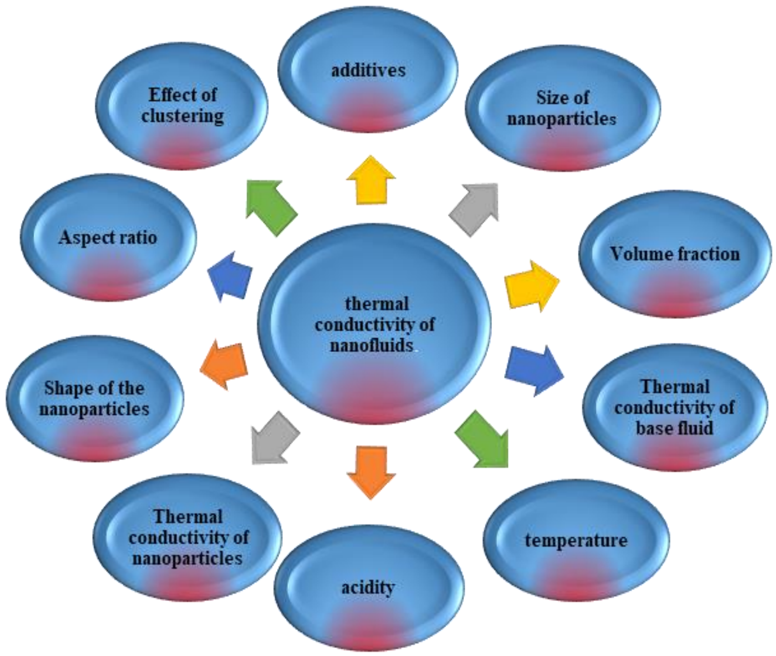

Figure 1. Parameters affecting in thermal conductivity of nanofluids

Carbon nanotubes have unique properties when added to conventional fluids. The heat transfers in carbon nanotubes can be along the axis direction due to the cylindrical shape and this is a feature of carbon nanoparticles and this results in a higher thermal conductivity compared to the other nanoparticles. The points above explain that the carbon nanotubes have better advantages than other nanoparticles in terms of thermal conductivity, shape and aspect ratio. [25-27]. Therefore, there are numerous numerical and experimental studies concentrated on using CNT-nanofluids. Ghadikolaei et al. [28] experimentally investigated for squeezing flow of CNTs/ EG in a rotating channel with nonlinear thermal radiation. Also, Ghadikolaei et al. [29] numerically investigated the influence of heat transfer and magneto hydrodynamic flow of MWCNTs and SWCNTs as a micro-polar dusty fluid affected by Joule heating and nonlinear thermal radiation.

Sobamowo et al. [30] investigated the influence of thermo-fluidic parameters on the nonlinearity dynamic behaviors of SWCNTs conveying fluid utilizing the homotopy perturbation method. The objective of the present paper is to review and summarize the data and recent papers that used carbon nanotubes nanofluids to enhance thermal conductivity and heat transfer, as well as the utilization of carbon nanotube in ionanofluids with a quick review of some carbon nanotube properties and its applications.

This paper can be considered as a comprehensive and up-to-date guide. It has been analyzed and some important gaps were found that could be addressed by the researchers in the future and it can open up new horizons in using carbon nanotubes for nanofluids.

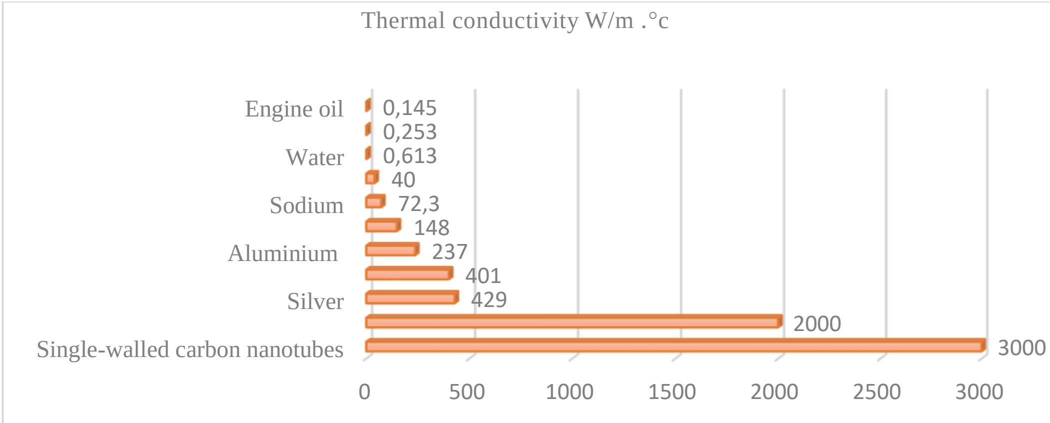

Figure 2. Thermal conductivities of different liquids and solids in room temperature [25-27].

CARBON NANOTUBES

Carbon Nanotubes Types

Carbon nanotubes (CNT) – have a cylindrical shape and are considered as the best type in improving conventional heat transfer fluids where they can be added in small volume fractions to improve the thermophysical properties of fluids. CNTs exist as single (SWCNTs), multi-walled (MWCNTs) structures and hybrid CNTs, as shown in Figure 3. There are several properties of CNTs, like aspect ratio, unique structure, tremendous strength, high thermal conductivity, light weight and remarkable electronic properties that range from metallic to semi-conducting and these lead to some unique applications. [31-34]. The researchers exhibited that the enhancement of thermal conductivities of different nanofluids that contain CNTs would be increased in comparison to base fluids by ten times or hundreds of times. [35-37]. But like other nanoparticles, the problem of agglomeration also appears in carbon nanoparticles after an indefinite period of time in the base fluid, therefore it was treated in two ways either mechanically using ultrasonication or chemically using surfactants and CNT-functionalization using acids, electrically or all. Carbon nanotubes have a thermal conductivity higher than metallic or nonmetallic solids, reaching up to 3500 W/m.c° [38,39].

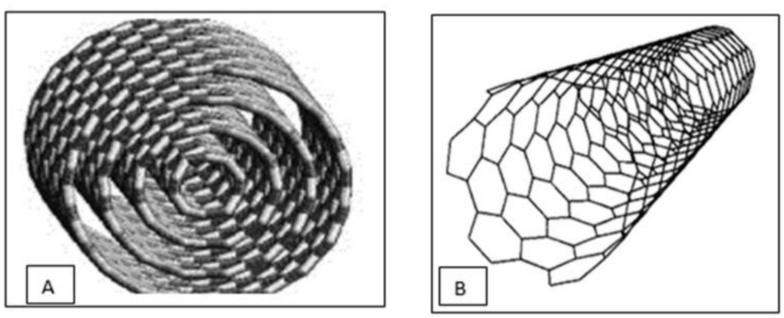

Figure 3. (a) MWCNTs, (b) SWCNTs

ADVANTAGES AND DISADVANTAGES CARBON NANOTUBES

Advantages

- CNTs have the strongest robust design, among the materials detected in terms of tensile strength and elasticity coefficient respectively [40].
- CNTs can be used as a semiconductor like silicon or as a conductor like copper, depending on the chirality [40,41].
- Higher thermal conductivity than all known materials [42].
- The chemical modification of nanotubes is proving to be valuable in a wide range of fields [43].

Disadvantages

- Numerous studies on the possible toxicity of carbon nanomaterials are currently underway. Despite the fact that reliable data on the toxicity of these materials have not been obtained, the risk of long-term exposure to carbon nanomaterials on the human body cannot be completely excluded. [44,45].
- High price compared to other Nanoparticles.

EFFECT ASPECT RATIO IN CARBON NANOTUBE ON THERMAL CONDUCTIVITY

There are many investigators that have examined the effects of aspect ratio (length/diameter ratio) in the nanoparticle. Carbon nanotubes (SWNT or MWCNT) have a high aspect ratio which is larger than other nanoparticles. In addition, the proportion of diameter to length in carbon nanotubes results in increasing the thermal conductivity of the nanofluids. Moreover, contradictory results that have been observed in the studies proved the increase of thermal conductivity with the increase in particle size. This hypothesis agrees with the effect of the size of nanoparticles in enhancing thermal conductivity for CNTs nanoparticles. Due to the fact that the thermal conductivity of CNTs is significantly higher compared to the thermal conductivity of base fluids, an increase in the length of carbon nanotubes with a constant diameter will enhance the additive thermal conductivity of nanofluids, as illustrated in Figure 7. Researchers believe that the aspect ratio is an important factor affecting the improvement of thermal conductivity in nanofluids, but both chemical functionalization and mechanical methods may reduce the aspect ratio mean value of the nanotubes, due to the treating CNTs with acids at high temperature and leading to damage in the structure sidewall of CNTs. Therefore, proper treatment of CNTs should be performed to minimize damages in the aspect. [46-51].

MECHANISMS OF THE ENHANCEMENT OF THERMAL CONDUCTIVITY IN NANOFLUIDS CONTAINING CNT

Like the other nanofluids containing another nanoparticle, Brownian motion (BM) of nanoparticles, molecular-level layering at the liquid/particle interface, nanoparticle clustering, dispersion, surface charge state and coupled transport play an obvious role in the enhancement of the influence of thermal conductivity of base fluids, due to nanoparticle suspension. For example, the mixing influence created by BM of the nanoparticles is one of the reasons for the thermal conductivity enhancement of nanofluids, due to diffusion and random walk motion. [52-55]. The researchers observed that the thermal conductivity of (CNT) in an axial direction is higher compared to that in the horizontal direction. This feature has provided high performance of carbon nanoparticles in enhancing the thermal conductivity in nanofluid compared to other nanoparticles. Also, carbon nanotubes are hydrophobic in nature except if they were functionalized with chemical groups [56,57]. Xie et al. [58] observed that the hydrophobicity of carbon nanotubes surface significantly affects the hydrodynamic behavior (pressure drop) of water flow in the carbon nanotubes. Also, it was found that the contact angle reduced from 155° to 40° indicating the transition from hydrophobic to hydrophilic states. A quick review was carried out, about influence factors to improve the thermal conductivity mechanisms in nanofluids containing CNT in this paper. A review of these factors is recommended.

EXPERIMENTAL STUDIES OF THERMAL CONDUCTIVITY

The thermal conductivity of nanofluid carbon nanotubes loading has made great success and kinds of carbon nanotubes have attracted the researchers. A carbon nanotube is one of the most promising nanoparticles at this time. This review showed that the effect of shape, temperature, size and concentration of carbon nanoparticles on thermal conductivity of nanofluids. The number of experimental publications in this paper about the improvement of thermal conductivity and heat transfer in nanofluids by using carbon nanotube for each year as shown in Figure 4.

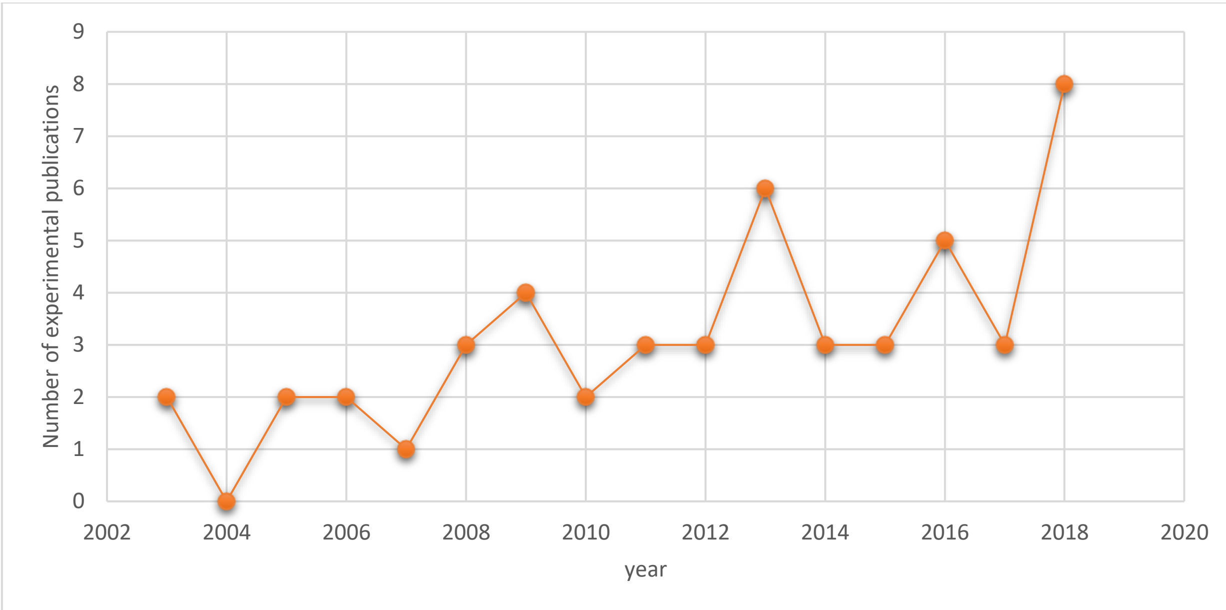

Figure 4. A number of experimental publications that deal with thermal conductivity and heat transfer in nanofluids by using carbon nanotube per year (according to this review)

Effect of Volume Concentration

Xie et al. [59] have studied the thermal conductivity of TCNT in DE, EG and DW at 1.0 vol. %volume fractions. Observed an increasing thermal conductivity that was 7.0 %, 12.7% and 19.6% for TCNT when added to DW, EG and DE respectively. Without surfactant for DW and EG the stable nanofluid was obtained. DE suspension a stable nanofluid was obtained from the little amount of oleylamine. The thermal conductivity improvement of alumina nanoparticle suspensions was less than TCNT suspensions at the same concentration. Abdallah et al. [60] have researched the effects of pristine carbon nanotubes and MWCNTs-PEG using Fischer esterification approach to show their dispersion in aqueous media with different concentrations of 0.01,0.05 and 0.1 wt.% weight fraction without using any surfactants. The maximum enhancement of thermal conductivity was 5.77% and 19% enhancement at 1 wt.% loading of pure CNT and functionalized MWCNTs respectively. Esfe et al. [61] have examined the thermal conductivity of FSWCNTs -EG at various concentrations (0.02, 0.05, 0.075, 0.1, 0.25, 0.5, 0.75 vol.%) where the maximum enhancement of thermal conductivity was found to be about 45% at 0.75 concentration loading at 50ºC. As observed in this investigation, thermal conductivity was a nonlinear function of temperature and concentration and also thermal conductivity was increased with concentrations and temperature. Furthermore, it was noticed from the experiment that functionalizing CNT with COOH was the best in dispersing the nanotubes in the base fluid. Therefore, it is not necessary to use a surfactant for obtaining a stable suspension. A similar trend could also be observed where Jiang et al. [63] have observed thermal conductivity enhancement of CNT/water nanofluid with various CNT volume fractions (0.22–1 vol.%) at (30–90 °C). In this paper, it was found that thermal conductivity was increased nonlinearly with CNT volume fractions. The model used in this study shows the upper and lower limits of MWCNT-based nanofluid thermal conductivity. In another study carried by Jana et al. [64] have shown that the enhancement in thermal conductivity of (0.3 vol.% CuNP suspension and 0.8 vol.% CNT suspension) nanoparticles, were decreased every five minutes due to the effect of sedimentation and agglomeration. It is noted that in 5-minute interval, thermal conductivity enhancement was reduced from (30% to 5%, 2% and 1%) for CNT and from (74% to 30%, 16% and 10%) for CuNP. Amrollahi et al. [65] have reported that the maximum improvement in thermal conductivity of the SWNTs–water nanofluids were found to be 30% enhancement at 1 wt.% loading at 25ºC. In this experimental study SDS and GA were used as a surfactant and gave better dispersion and stability.

A summary of thermal conductivity improvement K (%) for CNTs in the base fluid of (EG-water) is included in this paper, as shown in Figure 5. In addition to that, a number of contributions vs base fluids are presented in Fig 6. It was observed that the water was used more compared to other base fluids in nanofluids.

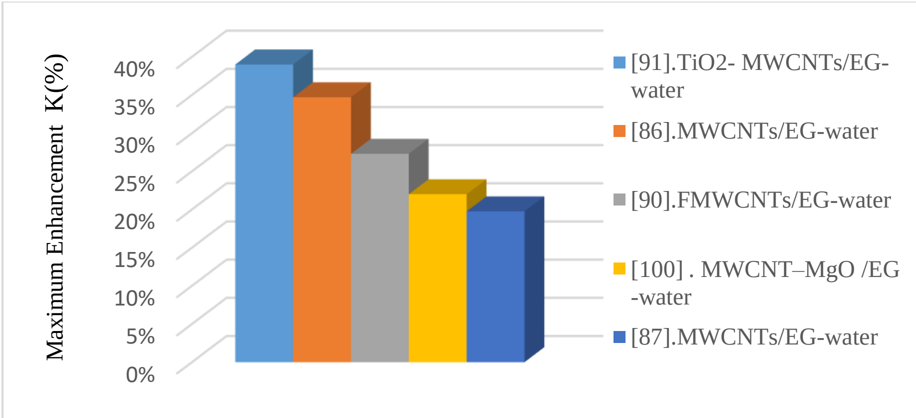

Figure 5. Thermal conductivity enhancement K (%) for MWCNTs and MWCNTs vs. Base fluid (EG-Water) (according to this review)

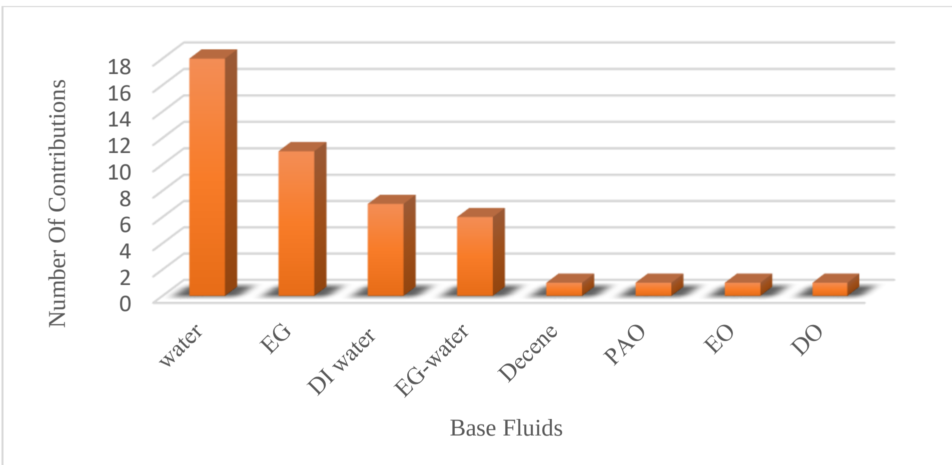

Figure 6. A number of contributions vs. Base fluids (according to this review)

Effect of Temperature

In the literature, nanofluid thermal conductivity depends on temperature and increases thermal conductivity with increasing temperature [68-70]. Sundar et al. [71] have studied the effects of temperature on nanofluid (MWCNT–Fe3O- water) and noted 0.3 vol.% loading which improved the thermal conductivity by 13.88%. at 20°C. while the increase of thermal conductivity was 28.46% at the same concentration at 60°C was higher compared to the thermal conductivity of base fluid. Other researchers Xie et al. [72] have investigated the influence and dependence of temperature on thermal conductivity and noted a weak dependence. Baby et al. [73] have found that thermal conductivity of the hybrid nanostructure (f-HEG+f-MWCNT) of functionalized (f- HEG) and (f- MWCNT) respectively in DI water was increased with the temperature by 9% at 30°C and 12% at 50 °C at the same volume fraction. A similar trend was observed for (f-HEG+f-MWCNT) in EG where thermal conductivity was increased with the temperature at the same volume fraction. Naddaf et al. [74] have investigated the influence of temperature (5,20,40,60,80,100) °C of nanofluid (MWCNT- Diesel oil) with surfactant oleic acid (OA) and covalent with hexylamine (HA). It was noted that the thermal conductivity of nanofluid (OA-MWCNT/DO, HA-MWCNT/DO) and MWCNT/DO containing concentrations 0.05wt.%, 0.1wt.%, 0.2wt. % and 0.5wt.% augmented for all concentrations with the temperature augmentation. Also, thermal conductivity compared with the pure diesel oil was augment of all nanofluids in all concentrations at the constant temperature.

Effect of Carbon Nanotube Types

Previous studies indicated the length of CNTs and number of walls significantly affect the thermal conductivity of CNTs-nanofluid. Therefore, the researchers have studied this criterion with care. Xing et al. [75] have studied the influences of three kinds of nanotubes (S-SWNTs), (L-SWNTs) and (MWNTs) with different concentrations ranging from 0.48 to 0.05 vol. % and also with different aspect ratios at temperatures of 10-60 °C. The observed thermal conductivity in this study was dependent on the temperature, aspect ratio and concentration where the maximum enhancement of 0.48 vol.% reaches 5.0%, 16.2% and 8.1% for MWCNTs, L-SWCNTs and S-SWCNTs nanofluids respectively. Hexadecyltrimethylammonium bromide (CTAB) was used as a surfactant.

In addition to, Fig. 7 shows the thermal conductivity improvement of three types of CNTs-nanofluids with 0.24 vol.% loading at 30°C. It is observed that thermal conductivity improvement are 2.75%, 3.33% and 7.54% for "MWNTs, S-SWNTs, and L-SWNTs" nanofluids, respectively. As a result, longer length and the smaller outer diameter (single wall), higher aspect ratio, are advantageous to the thermal conductivity improvement. We conclude that the L-SWNTs nanofluids have enhanced thermal conductivity more than MWCNTs nanofluid and S-SWCNTs.

In a previous study of the same author Xing et al. [76] the thermal conductivity of the three models has been measured, based on the experimental results of temperature, aspect ratio, and concentration. Considering the more comprehensive influencing factors, the Deng model is more in line with the experimental results than the other models.

In addition, a summary of experimental investigation results on the thermal conductivity of various CNT-nanofluids is given in Table 1 and Fig 8.

Also, as can be seen, the rate of carbon nanotubes diameters used in the researches (according to this review) is presented, as shown in Figure 9. Furthermore, the effect of surfactant stabilizers on the distribution of carbon nanotubes by various researchers was evaluated, as seen in Table 2. Thereby making the paper quite comprehensive concerning the use of carbon nanotubes-nanofluid in enhancing thermal conductivity.

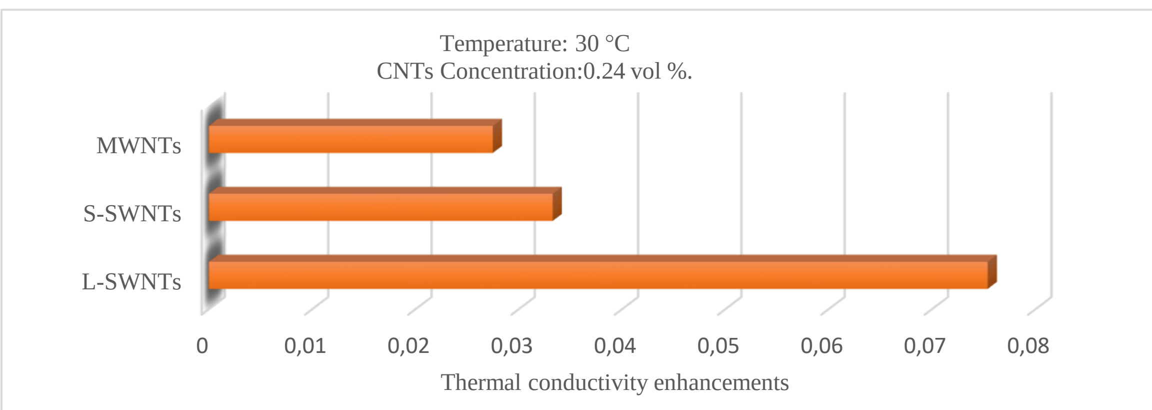

Figure 7. The effect of carbon-nanotubes types (aspect ratio) on thermal conductivity

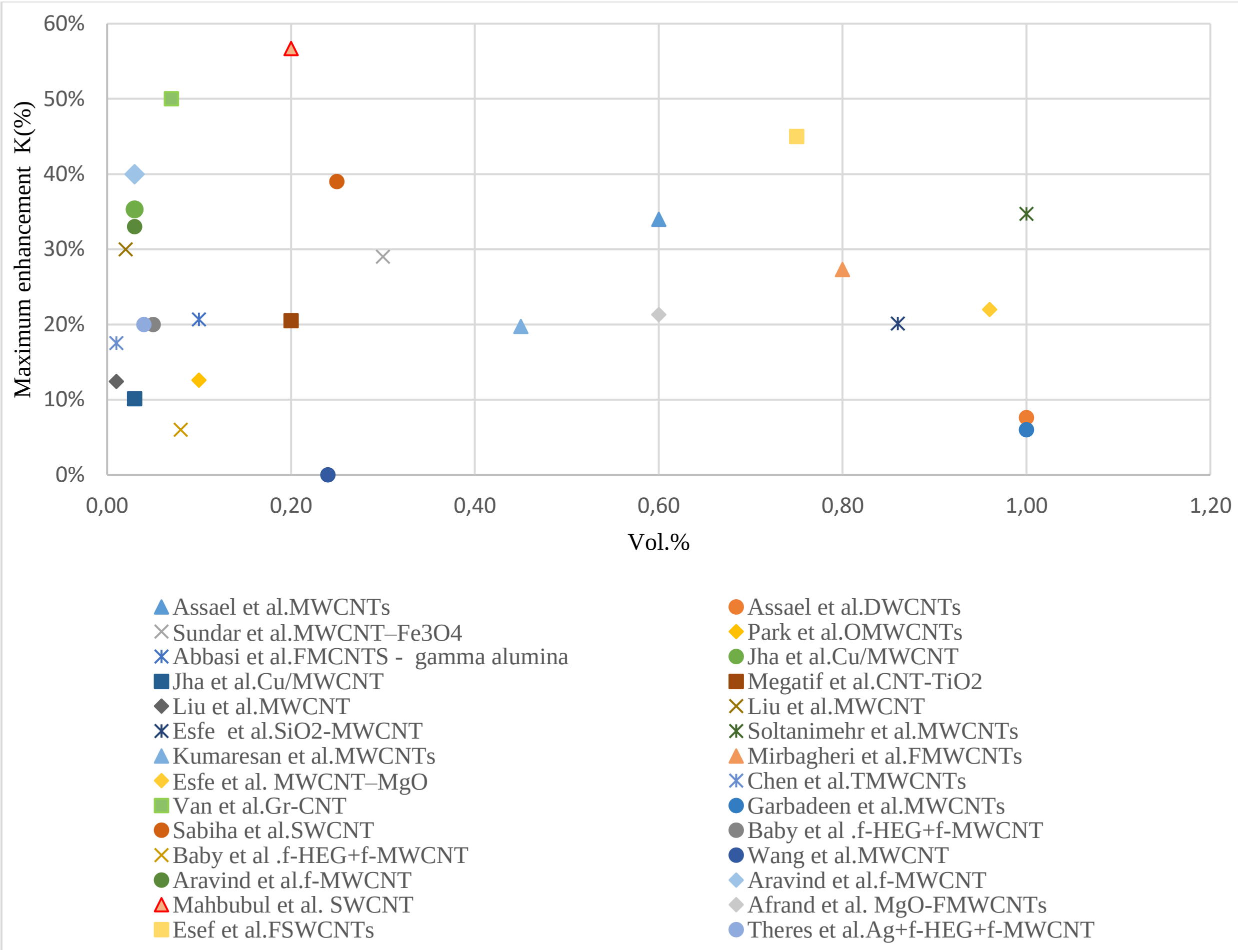

Figure 8. Thermal conductivity enhancement of MWCNTs, DWCNTs and hybrid MWCNTs vs. volume fraction (according to this review)

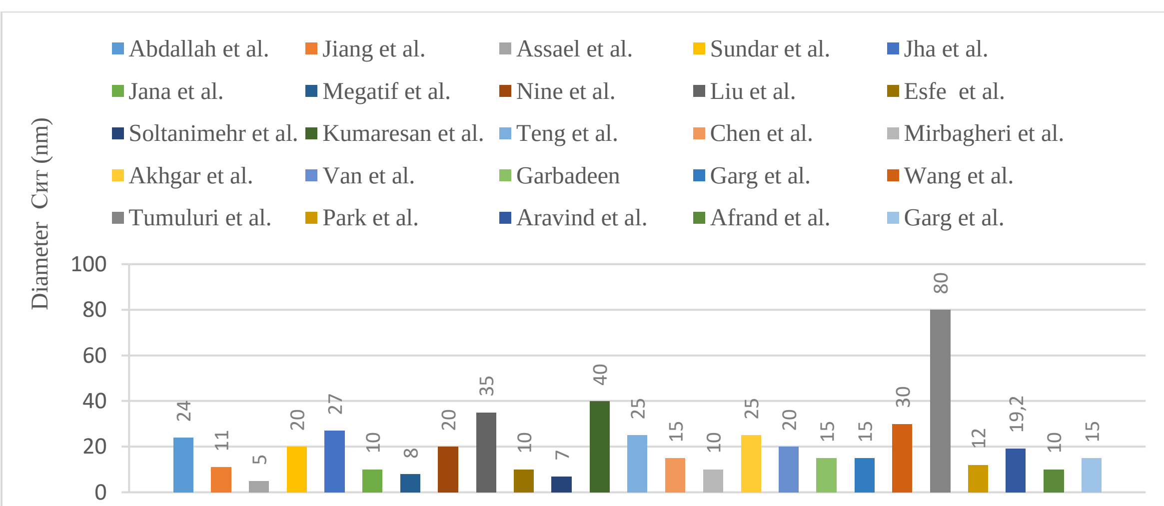

Figure 9. The rate of carbon nanotube diameter used in research (according to this review)

Table 1. Summary of an experimental investigation results on thermal conductivity of various CNT-nanofluids

Investigator	Particles Hybrid Particles	Base fluids	Diameter СИТ(nm)	Concentration (%)	Maximum enhancement K(%)	Temperature	Ref
Manasrah et al.	PCNT CNTs+PEG	water	24	0.01-0.1 wt.% 0.01-0.1 wt.%	5.77% 19%	25–65 °C 25–65 °C	[60]
Esfe et al.	FSWCNTs	EG	2	0.02- 0.75vol.%	45%	30 - 50°C	[61]
Jiang et al.	MWCNTs	water	11	0.22–1 vol.%	-	30–90°C	[63]
Jana et al.	CNTs	DI Water	10	0.8 vol.%	34%	25°C	[64]
Amrollahi et al.	SWCNTs	water	1–4	1wt.%	30%	20 -25°C	[65]
Garg et al.	MWCNT	DI water	10–20	1 wt.%	20%	35 °C	[66]
Assael et al.	MWCNTs DWCNTs	Water water	100-250 5	0.6 vol.% 0. 1vol.%	34% 7.6%	Ambient temperature Ambient temperature	[67]
Sundar et al.	MWCNT–Fe3O4	water	10–30	0.1 -0.3 vol.%	29%	20 -60 °C	[71]
Baby et al.	(f-HEG+f-MWCN") (f-HEG+f-MWCNT)	DI water EG	30–40	0.05 vol. % 0.08 vol.%	20% 6%	30°C 50 °C	[73]
Manasrah et al.	CNTs Fe2O3-CNT	Water Water	24	0.01 - 0.10 wt.% 0.01 - 0.10 wt.%	5.77% 16.4%	25–65 °C	[77]

Table 1. Summary of an experimental investigation results on thermal conductivity of various CNT-nanofluids (cont.)

Investigator	Particles Hybrid particles	Base fluids	Diameter CИT(nm)	Concentration (%)	Maximum enhancement K(%)	Temperature	Ref
Aravind et al.	f-MWCNT f-MWCNT	Water EG	-	0.005,0.03 vol.% 0.005,0.03 vol.%	33% 40%	30 -70°C	[78]
Wang et al.	MWCNT	water	20 - 30	0.05 -0.24 vol. %	10%	20 -50 °C	[80]
Park et al.	OMWCNTs	water	10-15	0.1 vol.%	12.6%	10-90 °C	[87]
Abbasi et al.	FMCNTS- gamma alumina	DI water	-	0.1 vol.%	20.68%	-	[88]
Jha et al.	Cu/MWCNT Cu/MWCNT	DI water EG	25-30	0.03 vol. % 0.03 vol. %	35.3 % 10.1%	27-48°C	[89]
Baghbanzadeh et al.	Silica Nano sphere/ MWCNT Silica Nano sphere/ MWCNT	water	D lower than 10 nm	0.1- 1.0 wt. %	16.7% 12.3%	40 ◦C 27◦C	[90]
Megatif et al.	CNT-TiO2	water	8	0.1-0.2vol.%	20.5%	25°C	[91]
Nine et al.	Al2O3-MWCNTs	Water	20	1 -6 wt. %	12%	25°C	[92]
Liu et al.	MWCNT	EG EO	20–50	0.01vol.% 0.02 vol.%	12.4 % 30%	room temperature. room temperature.	[94]
Esfe et al.	SiO2-MWCNT	EG	5–15	0.025 -0.86 vol.%	20.1%	30 -50°C	[95]

Table 1. Summary of an experimental investigation results on thermal conductivity of various CNT-nanofluids (cont.)

Investigator	Particles Hybrid particles	Base fluids	Diameter CИT(nm)	Concentration (%)	Maximum enhancement K(%)	Temperature	Ref
Yang et al.	MWCNT	PAO	-	0.3-8 wt. %	-	-	[96]
Soltanimehr et al.	MWCNTs	EG-water	5–15	0.025-1.0 vol.%	34.7%	25-50°C	[97]
Kumaresan et al.	MWCNTs	EG-water	30–50	0.15 -0.45 vol.%	19.75%	40 °C	[98]
Teng et al.	MWCNTs-NC	EG-water	20–30	0.1 -0.4 wt.%	49.6%	80–95 °C	[99]
Chen et al.	TMWCNTs	EG	15	0.01 vol.%	17.5%	5-65°C	[100]
Mirbagheri et al.	FMWCNTs	EG-water	5–15	0.025- 0.8 vol.%	27.3%	25 °C	[101]
Akhgar et al.	TiO2-MWCNTs	EG-water	20 -30	0.05-1 vol.%	38.7%	20-50°C	[102]
Van et al.	Gr-CNT	EG	20	0.0175 -0.07 vol.%	50%	50 °C	[103]
Garbadeen et al.	MWCNTs	water	10–20	0–1 vol.%	6%	27 °C	[104]
Sabiha et al.	SWCNT	water	1–2	0.05–0.25 vol.%	36.39%	20-60 °C	[105]

Table 1. Summary of an experimental investigation results on thermal conductivity of various CNT-nanofluids (cont.)

Investigator	Particles Hybrid particles	Base fluids	Diameter CИТ(nm)	Concentration (%)	Maximum enhancement K(%)	Temperature	Ref
Tumuluri et al.	MWCNT	water	60–100	1.12 wt.%	8.5%	32 °C	[106]
Theres et al.	Ag+f-HEG+f-MWCNT	EG	-	0.04vol.%	20%	50 °C	[107]
Aravind et al.	sG+ f-MWCNT sG+ f-MWCNT	DI Water EG	19.2	0.04 vol.% 0.04 vol.%	87.9% 24%	50°C 50°C	[108]
Ali et al.	FCNT	Water	-	0.05 wt.%	11.6 %	40°C	[110]
Esfe et al.	MWCNT–MgO	water–EG	5–15	0.015-0.96vol.%	22%	30–50 °C	[111]
Afrand et al.	MgO-FMWCNTs	EG	5–15	0–0.6 vol.%	21.3%	25 -50 °C	[112]

EFFECT OF SURFACTANT STABILIZERS ON THE DISTRIBUTION OF CARBON NANOTUBES BY VARIOUS RESEARCHES

There are many research papers displaying the influence of various surfactants such as (CTAB, SDS, and SDBS) on the stability of nanofluids. The researchers have investigated the effects of dispersion methods on thermal conductivity and nanofluid stability. The stability of nanofluids was confirmed by using surfactant or ultrasonicator in an aqueous medium [81-84]. In addition to that, the surfactant plays a marked role in the improvement of the thermal conductivity in nanofluids in some researches [85,86].

Table 2. Combinations of various nanofluids and surfactants

Nanofluids	Thermal Conductivity Measurement Techniques	Stability period and Sample preparation techniques	Surfactants and Homogenization Time	Ref
Treated CNTs+ water Treated CNTs+ EG Treated CNTs+ DE	THW	2 months	- - oleylamine	[59]
PCNT CNT+PEG	Mathis Instruments Ltd modified THW	For long periods of time -	Using ultra sonicator for 30 min	[60]
FSWCNTs -EG	KD2 pro principle is based on THW	- -	Magnetic stirring is used for 2 h+ ultrasonic processor is used for 6 h	[61]
MWNTs- water	THW	- 2-step method	Using polyvinylpyrrolidone and magnetic force agitation 30 min.+ ultra-sonication, for 1 h	[63]
SWNTs- water	KD2	For more than a month 2-step	GA and SDS and for 30 min ultrasonic disruptor	[65]

Table 2. Combinations of various nanofluids and surfactants (cont.)

Nanofluids	Thermal Conductivity Measurement Techniques	Stability period and Sample preparation techniques	Surfactants and Homogenization Time	Ref
MWCNTs- DI water	KD 2	1 month -	GA * As shown in below	[66]
MWCNTs -Water DWCNTs- Water	THW	- -	CTAB+ AQ and the Ultrasonic was used at different time intervals (10-120) min	[67]
MWCNT- water.	3ω method	- 2-step	TritonX− SDBS	[80]
MWCNTs- water	KD2 Pro	- -	SDBS Made mechanical stirring for 2 times with 30 mint	[6]
OMWCNTs-water	THW	- -	two hours' ultrasonic	[87]
hybrid MCNTS + gamma alumina- DI water	KD2 Pro	45 days 2-step	Arabic Gum	[88]
Silica Nano sphere/ MWCNT- water	KD2	1 month 2-step	SDBS "For 2 min then for 20 min in two stages: each stage took 10 min and there was 5 min stop between them".	[90]
MWCNT- water	KD2	more than a month	Arabic gum+ SDBS	[93]

Table 2. Combinations of various nanofluids and surfactants (cont.)

Nanofluids	Thermal Conductivity Measurement Techniques	Stability period and Sample preparation techniques	Surfactants and Homogenization Time	Ref *[66]
TiO_2- MWCNTs-water-EG	KD2-Prob	- -	CTAB	[102]
SWCNT-water	KD2 Pro	- Two-step	SDS	[105]
MWCNT- DI water	THW	- -	GA and The Ultrasonic was used at different time intervals (20-40)	[106]

"Sample A: 1 wt.% MWCNTs,0.25wt.% GA, ultra-sonicated for 20 min, e=57J/g."

"Sample B: 1 wt.% MWCNTs,0.25wt.% GA, ultra-sonicated for 40 min, e=113J/g."

"Sample C: 1 wt.% MWCNTs,0.25wt.% GA, ultra-sonicated for 60 min, e=188J/g."

"Sample D: 1 wt.% MWCNTs,0.25wt.% GA, ultra-sonicated for 80min, e=290J/g."

EXPERIMENTAL STUDIES OF HEAT TRANSFER

In this review, a study was performed on heat transfer coefficient using CNTs. Manasrah et al. [60] have investigated the influence of different concentrations of pure CNT and PEG-CNT (0.1, 0.05 and 0.01% by weight) loading in aqueous media. The heat transfer increase was observed by 15% at 0.1 wt % loading Pure CNTs. Also, they observed the heat transfer increases with nanofluids containing functionalized CNTs by more than 55% and 33% compared to water and pure nanocarbons respectively. And the measurements have been made in shell and tube heat exchangers at a mass flowrate from 200 kg/h up to 640 kg/h. Hussien et al. [62] have reported the enhancement of forced convective heat transfer with different mass fractions of MWCNTs (0.075, 0.125 and 0.25 wt.%). Also, they observed an improvement in heat transfer coefficient with the increase in mass fraction of MWCNTs in the nanofluid reaching to 23.9% improvement at 0.25 wt.% MWCNTs/water at Re from 200 to 500. Garg et al. [66] have shown that the enhancement in heat transfer coefficient of MWCNTs / DI water has reached up to 32% at a 0.1 wt.% and Re = 600. Researchers have shown that when the water has been utilized as base fluid for comparison purposes at 0.25% Gum Arabic in water led to a low change in the heat transfer coefficient of water in laminar flow conditions and also it is remarkable to see the non-Newtonian Behavior in this experiment. Manasrah et al. [77] have reported the enhancement of convective heat transfer of nanofluids with doped CNTs (Fe_2O_3-CNT) and (CNTs) with various concentrations of 0.01, 0.05, and 0.10 wt.% and also it has added iron oxide nanoparticles loading on the surface of CNTs 1 wt.% and 10.0 wt.%. Observed heat transfer enhancement by 60% with the addition of doped CNTs at 0.1 wt.% and 15% enhancement at 0.1 wt.% with the addition of undoped CNTs. Pressure drop can be neglected because the increases were very small. Also, it was noted that iron nanoparticles were improved in dispersion of the CNTs, increased the thermal conductivity and the heat capacity. Measurements have been made in shell and tube heat exchangers. In another study Aravind et al. [78] the researchers have proposed the role of CNTs in the reduction of the thermal boundary layer thickness and therefore increasing the heat transfer coefficient due to the CNTs migration. There are two directions for the improvement of the heat transfer coefficient, either δt should decrease or improve the thermal conduction coefficient or both. Obtained the maximum enhancement in heat transfer coefficient of about 65%and 180% for 0.03vol.% FMWCNT loading at 70 °C with DI water and EG respectively. Zubir et al. [79] have studied the influence of reduced graphene oxide (RGO) and multi walled carbon nanotube (MWCNT) on heat transfer coefficient and water and as high as 144% improvement in Nu was recorded near the conduit entrance and about 63% at the downstream section and also it was observed that heat transfer coefficient and Nusselt number were enhanced when adding RGO. A similar trend was investigated by (Wang et al). [80] by using a surfactant (TritonX−100 and SDBS) with MWCNT/ distilled water and led to the enhancement of convective heat transfer (190% improvement at 0.24 vol. %) at Re = 120. In a study by Ding et al. [93] multi-walled carbon nanotubes have been added to distilled water and found that the maximum enhancement was 350% for 0.5 wt.% with GA as a dispersant. Abreu et al. [109] have reported the enhancement of convective heat transfer by 47 % and 44 % for the entry and exit regions respectively for 0.5 vol.% MWCNTs in distilled water.

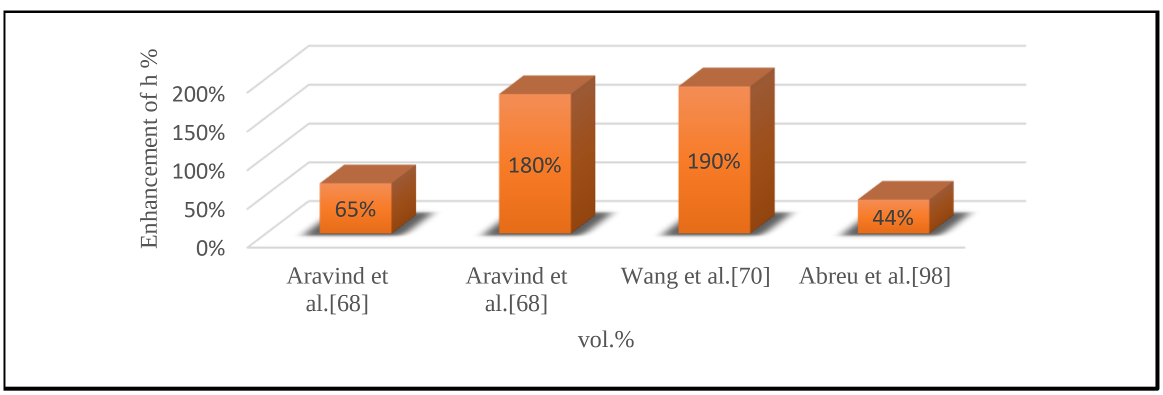

Figure 10. Enhancement of h % vs. vol.% (according to this review)

A summary of some papers on the enhancement of convective heat transfer vs. vol. volume fractions % and wt. weight fraction % have been reviewed, as shown in Figures 10 and 11.

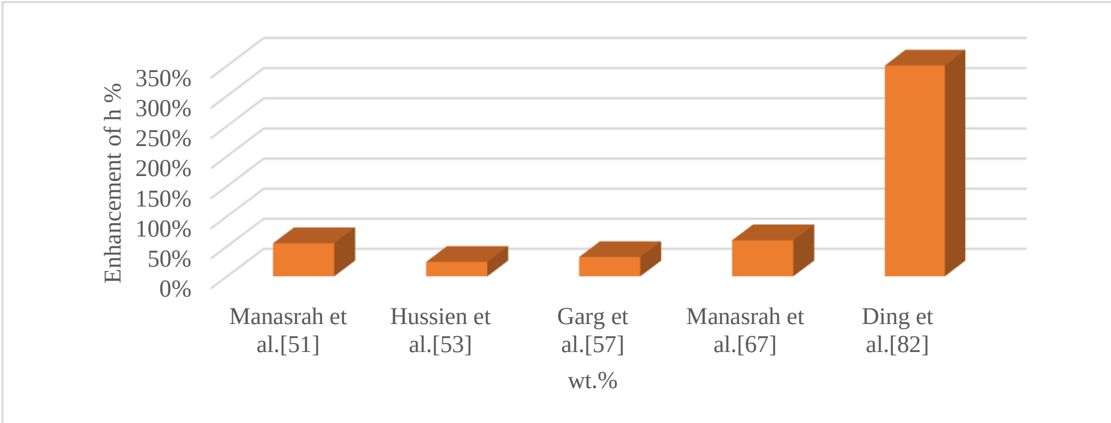

Figure 11. Enhancement of h % vs. wt.% (according to this review)

EFFECT OF CARBON NANOTUBE ON IONANOFLUID

Ionanofluids is a mixture of ionic liquid and nanoparticles, also, it is a new type of heat transfer fluids that showed excellent thermophysical properties leading to high heat capacity and thermal conductivity as well as other features like being non-volatile and designable. However, the high cost of ionanofluid compared to traditional fluids remains a constant problem. The researchers have conducted practical experiments using ionanofluids and reviewed some of the experiments on ionanofluids by using Carbon nanotube [113,114]. De Castro et al. [115] have studied the effect of temperature and concentration of MWCNT on the effectiveness of thermal conductivity of various ionanofluids by current models. Ionanofluids loading at 1 wt% of MWCNTs with base ionic liquids (C4mim] [NTf2]- and [C2mim] [EtSO4]) had maximum enhancement of thermal conductivity that reached .35.5% and 8.5% respectively at room temperature. Another experimental study by França et al. [116] reported the effect of multiwalled carbon nanotubes with ionic liquid between (293 and 343K) and found that ionanofluids containing 0.5 %, 1 %and 3 wt.% of MWCNTs and the thermal conductivity enhancement was between 4 % and 26 %.

APPLICATIONS OF CARBON NANOTUBE NANO FLUIDS

CNT-nanofluids have distinct thermophysical properties, where the addition of CNT to conventional fluids has played a major role in improving their properties. In general, CNT-nanofluid has many important applications. The solar thermal applications enhance the performance of solar harvesting used for volumetric solar collectors [117-119]. As well as in the solar desalination system [120]. It was used also in the medical applications where there are several researches in this field such as a drug carrier in the treatment of cancer [121,122]. Also, in the design of medical devices [1123,124]. CNT-nanofluids have a role in contributing to industrial applications and heat exchangers. Where CNT-nanofluid increases the heat transfer area and this leads to more efficient heat exchangers and higher cooling rates than the rest of the heat transfer fluids [60,77]. As in using CNT -nanofluids in electronics cooling, where nanofluids are utilized as the working fluid in thermosyphons and heat pipes, which can be used for compact device cooling [125,126] and other applications such as a domestic refrigerator [127, 128]. Also, there are many applications in the military and space areas that can't be addressed in this review. The potential for using CNT-nanofluids remains high because it possesses high thermophysical properties that enter many applications.

CONCLUSION

The purpose of this paper is to review the modern scientific literature about the enhancement of thermal conductivity and heat transfer in conventional fluids, which contain nanoparticles especially the carbon nanotubes that are characterized by high thermal conductivity and aspect ratio larger than other nanoparticles. The researchers have observed a significant enhancement in thermal conductivity and heat transfer with the addition of carbon nanoparticles to the base fluid to get the nanofluid, hybrid nanofluids or ionanofluid. Increasing thermal conductivity depends on several parameters, these parameters have been studied. It was observed that the enhancement of thermophysical properties has enhanced with increasing the CNT concentration, temperature and shape type of carbon nanotubes. This review analyzed these studies and found some gaps that needed to be reviewed by researchers in the future.

In this review, many studies used the base fluids such as (water, EG, EG-water, DI water, Decene, PAO and EO) but it was observed that most of them used water with less use of other base fluids like silicone oil and refrigerants. Also, it has been found that the studies did not mention the stability period of the nanofluid, while the stability is as important as the enhancement of thermal conductivity and it shows the economic feasibility of the studies.

Surfactants were used like (SDBS, CTAB, AQ, Arabic Gum and SDS) in the experimental studies. It has been noted that there is an effect of surfactants on the stability of nanofluids, as well as the effect of surfactants on the value of the thermal conductivity coefficient in some studies. In this review, there was no consistent trend towards increasing thermal conductivity in nanofluids by adding surfactants.Most researchers in previous experimental studies have used Hybrid MWCNT and MWCNT but a few of them used the other types of carbon nanotubes like (SWCNT, DWCNT, and Hybrid SWCNT). Not indicating the homogenization time of nanofluid in several studies.

Carbon nanotubes of ionanofluids were reviewed and it has been noted that there was a trend toward using them with nanofluids, many times higher than using them with ionanofluids, which could be because of the high cost of the nanofluids.It was observed that L-SWNTs has a higher thermal conductivity than MWNTs and S-SWNTs with the same concentration and temperature, due to the differences in aspect ratio.

The method of preparing nanofluid plays a remarkable role in the amount of enhancement of the thermal conductivity.

Evidently, the addition of surfactant and nanoparticles to base fluids increases the viscosity and the drop pressure. As most of the experimental studies in this review have used low concentrations of nanoparticles in nanofluids. There was no indication of increasing the drop pressure and can be neglected.It was noticed that in some experimental studies in this review, the functionalizing of CNT with COOH was best dispersing the nanotubes in the base fluid. Therefore, it is not necessary to use a surfactant to obtain a stable suspension.

Finally, we conclude from this analysis and results, there is an urgent need for making many experimental studies on the thermal conductivity and the heat transfer of CNT nanofluids, with taking advantage of the gaps that have been found in other papers, where it can address these gaps with the possibility of obtaining valuable and new results, hence, are proposed for future works.

NOMENCLATURE

d_p	Diameter of particles, nm
Bf	Base fluid
k	Thermal conductivity coefficient, W / m. °c
Re	Reynolds number
T	Temperature, °C
h	Heat transfer coefficient, W / m^2. °c
$vol.\%$	Volume fractions
$wt.\%$	Weight fraction
Subscripts	
$SWCNTs$	Refers to single walled carbon nanotubes
$MWCNTs$	Refers to Multi-walled carbon nanotubes
$TMWCNTs$	Refers to treated MWCNTs
$OMWNTs$	Refers to oxidized MWCNTs
THW	Refers to transient Hot-Wire
$MWCNTs-PEG$	Refers to polyethylene glycol functionalized multi-walled carbon nanotubes
$FSWCNTs-EG$	Refers to ethylene glycol functionalized single walled carbon nanotubes
DE	Refers to decene
EG	Refers to ethylene Glycol
EO	Refers to engine oil
PAO	Refers to polyalphaolefin

$DI\ water$	Refers to deionized water
DW	Refers to distilled water
$Gr - CNT$	Refers to graphene-carbon nanotube
$DWCNTs$	Refers to double wall carbon nanotubes
$SG + f - MWCNTs$	Refers to the hydrophobic solar graphene- functionalization of MWCNTS
$KD2\ Pro$	Refers to Thermal Properties Analyzer
$PCNT$	Refers to pristine carbon nanotubes
$HEG + f - MWCNTs - DI$	Refers to the hybrid nanostructure of functionalized (f- HEG) and (f- MWCNT) Respectively

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