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Thermal Conductivity of Nanofluids – Experimental and Theoretical[1]

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The thermal conductivity of nanofluids has been studied experimentally using the transient hot-wire method, and it is shown that a significant increase can be obtained. Existing methods for the prediction and correlation of the thermal conductivity are discussed. It is shown that a lot of work still needs to be done in this area.

KEY WORDS: carbon nanotubes; heat transfer; nanofluids; thermal conductivity.

1. INTRODUCTION

The fluids that have been traditionally used for heat transfer applications have a rather low thermal conductivity, taking into account the rising demands of modern technology. Thus, there is a need to develop new types of fluids that will be more effective in terms of heat exchange performance. In order to achieve this, it has been recently proposed [1–4] to disperse small amounts of nanometer-sized solids in the fluid. The resulting "nanofluid" is a multiphase material that is macroscopically uniform. It is noted that the term thermal conductivity refers to the property of a single-phase system. In this paper, for practical purposes, this term is used to describe the effective property of the multiphase assembly.

The study of nanofluids has gained considerable interest recently because they are likely to be used in various applications [1–7]. The dispersion of copper (Cu) nanoparticles and alternatively carbon

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nanotubes (C-NTs) has provided the most promising results so far, with reported thermal conductivity enhancements of up to 40% and 160%, respectively, in relation to the base fluid [2–5]. There is thus, a need to prepare stable nanofluids with the desired characteristics and to measure their properties. Furthermore, a great challenge is to understand the mechanisms responsible for the unique thermal behavior of nanofluids and to predict these properties. This work follows our previous studies [3, 4, 8] and is an attempt to get a more comprehensive perspective on the subject.

2. THERMAL CONDUCTIVITY MEASUREMENTS

The thermal conductivity of the nanofluids was studied by our group, and it was measured with the transient hot-wire method. An instrument was built for this purpose, and it was operated with a standard uncertainty of better than 2% as described in an earlier publication [3]. Ethylene glycol and water were selected as the primary base fluids, because they are widely used in heat-transfer applications. The particular interest in water is noted, because of its presence in biological systems. Spherical Cu nanoparticles and carbon multi-walled nanotubes (C-MWNTs) were employed as the dispersed phase in most cases, since they are more likely to be used for a number of applications of nanofluids for increased heat transfer, due to their enhanced thermal conductivity. Moreover, several dispersants were used to aid the formation of homogeneous and stable suspensions.

A summary of the thermal conductivity measurements of nanofluids conducted by our group is shown in Table I.

2.1. Nanosphere Suspensions

As was aforementioned, the suspensions of spherical nanoparticles studied in our previous work [8] involved mainly the dispersion of Cu nanoparticles. Other types of nanospheres have been also employed, showing interesting results [8–12].

2.1.1. Suspensions of Cu Nanoparticles

The Cu nanospheres were dispersed in ethylene glycol, both provided by MER Corporation U.S.A., with the aid of ultrasonic homogenization for 60 min (Bandelin Electronics Model HD 2200) [8]. The results obtained for the thermal conductivity enhancement of suspensions with various nanoparticle concentrations are shown in Fig. 1, as a ratio of the thermal conductivity of the dispersion λ over the thermal conductivity of the base fluid λ_0. Attempts were made to prepare stable suspensions of Cu nanoparticles in vacuum oil TKO-19Ultra, provided by MER Corporation

Table I. Thermal Conductivity Measurements of Nanofluids

Base Fluid	Dispersed Phase	Dispersant	Maximum Enhancement (%)
Ethylene glycol	Cu (up to 0.48 vol%)	–	3
Ethylene glycol	C-MWNT (up to 0.25 vol%)	–	9
Ethylene glycol	C-MWNT 0.6 vol%	SDS 0.35 mass%	21
Ethylene glycol	C-MWNT 0.6 vol%	SDS 0.6 mass%	20
Ethylene glycol	C-MWNT 0.6 vol%	SDS 1.2 mass%	14
H_2O	C-MWNT 0.6 vol% new	SDS 0.1 mass%	39
H_2O	C-MWNT 0.6 vol% new	SDS 0.5 mass%	23
H_2O	C-MWNT 0.6 vol% new	SDS 2 mass%	30
H_2O	C-MWNT 0.6 vol% new	SDS 3 mass%	28
H_2O	C-MWNT 0.6 vol% condensed	SDS 1.1 mass%	12
H_2O	C-MWNT 0.6 vol% condensed	SDS 1.5 mass%	8
H_2O	C-MWNT 0.6 vol% condensed	SDS 2 mass%	7
H_2O	C-MWNT 0.6 vol% regenerated	SDS traces	12
H_2O	C-MWNT 0.6 vol% regenerated	SDS 0.5 mass%	11
TKO-19 Ultra	C-MWNT 0.6 vol%	SDS 0.1 mass%	9
H_2O	C-MWNT 0.6 vol%	CTAB 0.1 mass%	19
H_2O	C-MWNT 0.6 vol%	CTAB 1 mass%	34
H_2O	C-MWNT 0.6 vol%	CTAB 3 mass%	34
H_2O	C-MWNT 0.6 vol%	CTAB 6 mass%	28
H_2O	C-DWNT 0.75 vol%	CTAB 1 mass%	3
H_2O	C-DWNT 0.75 vol%	CTAB 3 mass%	2
H_2O	C-DWNT 1 vol%	CTAB 5.5 mass%	8
H_2O	C-MWNT 0.6 vol%	Triton X-100 0.17 mass%	11
H_2O	C-MWNT 0.6 vol%	Triton X-100 0.35 mass%	12
H_2O	C-MWNT 0.6 vol%	Triton X-100 0.5 mass%	13
H_2O	C-MWNT 0.6 vol%	Triton X-100 1 mass%	11
H_2O	C-MWNT 0.6 vol%	Nanosperse 0.7 mass%	28

U.S.A. The outcome was a sample with very low Cu content (0.0002 vol%) and this result did not encourage further tests.

It is important to mention that our results are in agreement with those of other research groups. Eastman et al. [13] and Xuan and Li [14] used different techniques to disperse larger volume fractions of significantly smaller Cu nanospheres compared to our samples. It is noted that a

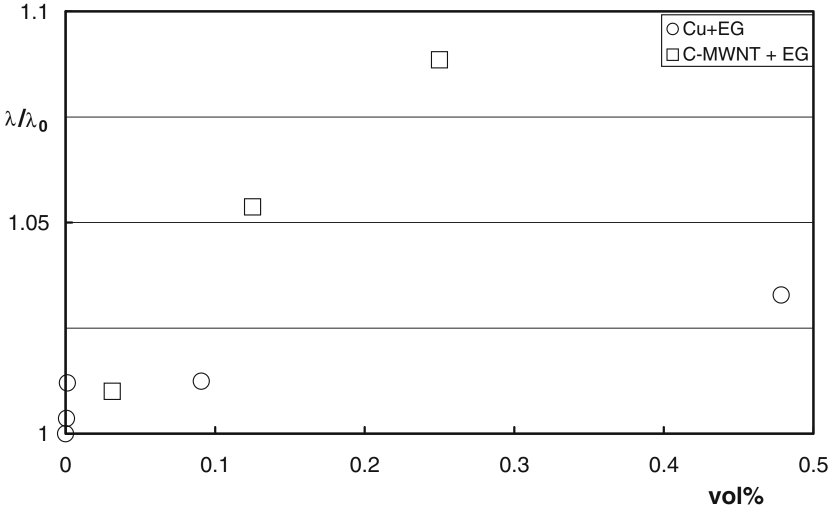

Fig. 1. Thermal conductivity enhancement of Cu and C-MWNT suspensions in ethylene glycol without dispersants.

larger increase is observed when using nanoparticles with a smaller diameter [15]. Taking into account these differences, we conclude that the measured thermal conductivity enhancements are comparable.

At this point, it is worth pointing out the puzzling results reported earlier for Cu nanofluids with thioglycolic acid (TGA) [8] were attributed to the partial destruction of the protective Ta_2O_5 layer used for the electrical insulation of the Ta wire employed in the transient hot-wire instrument. This caused current leakage and thus the confusing results.

2.1.2. Suspensions of Nanoparticles Other than Copper

Several scientific groups have studied the enhancement of the thermal conductivity of various fluids in the presence of oxide nanoparticles, such as CuO and Al_2O_3 [9–12]. It should be mentioned that the experiments showed considerable increases for larger volume fractions of nanoparticles, compared to those for Cu nanofluids. This fact makes oxides less probable to be used in industrial applications, due to the clogging effect that could be caused because of the large volume fraction of particles in the dispersion needed to achieve greater rates of heat transfer.

Moreover, attempts were made to use nanodiamonds as the dispersed phase, but they were not fruitful, as the resulting samples were stable only for a few minutes and the thermal conductivity was only minimally increased, due to the large amount of surfactant needed to achieve the dispersion [8]. Additionally, Au and Ag nanofluids were prepared and studied by Patel et al. [16]. The enhancement was considerable for aqueous dispersions of small volume fractions (8.3% for 0.00026 vol% Au at 60°C and 4.5% for 0.001 vol% Ag at 60°C). The preparation of considerable quantities of nanofluids at viable costs for large-scale applications is one of the challenges to be confronted in this case. On the other hand, the dispersion of 0.55 vol% of Fe nanoparticles with an average diameter of 10 nm in ethylene glycol by Hong et al. [17] gave interesting results. The observed 18% increase of the thermal conductivity is higher than the one obtained for Cu nanofluids of the same volume fraction (less than 12%) with 18 nm mean size by Eastman et al. [5]. It s obvious that the thermal conductivity of the dispersed phase is not the only factor to be considered. In that case, it would have been anticipated to observe a greater enhancement for the dispersions of Cu nanoparticles, which are more conductive in the bulk phase. Consequently, the observed increase of the thermal conductivity is believed to be affected by a number of factors, such as the average size of the nanoparticles, the method employed for the preparation of the nanofluids, the temperature of the measurements, and the concentration of the dispersed solid phase.

2.2. Carbon Nanotube Suspensions

C-NTs are fascinating materials. They combine microscale (length) with nanoscale (diameter) dimensions. They also exhibit a number of interesting properties, among which are their particularly high thermal conductivity (6,600 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ for carbon single-walled nanotubes, C-SWNT) [18] and their low density.

It is noted that C-NTs are not miscible with water and that it is difficult to disperse them in ethylene glycol. Hence, it was decided that it was necessary to add a dispersant that would enable the suspension of the nanotubes in the aforementioned heat-transfer fluids. Several surfactants were used, and ultrasonic homogenization was also employed to assist in the formation of the nanofluids. The pristine nanotubes and the resulting suspensions were characterized with microscopic methods (HR-TEM, C-TEM, SEM) and spectroscopic methods (Raman) as described elsewhere [3, 4, 8].

2.2.1. Carbon Nanotube Suspensions Without Dispersants

It was initially attempted to disperse 0.25 vol% C-MWNTs, with a mean diameter of 120 nm, in ethylene glycol (both provided by MER Corp.) without the use of dispersants. The prepared sample was subjected to ultrasonic vibration for 60 min, and the increase of the thermal conductivity in relation to the base fluid was measured with the transient hot-wire technique. The suspension was then diluted to 0.125 and 0.03125 vol%. The results of the measurements are shown in Fig. 1. It seems that for small loads of C-MWNTs the enhancement increases almost linearly with the concentration of nanotubes. It is pointed out that the suspensions were stable and homogeneous during the measurements, but they precipitated quickly after that. Therefore, the addition of surfactants was suggested in order to achieve more stable dispersions. The samples were concentrated to 0.6-vol% C-MWNTs by evaporation of the excess ethylene glycol after mildly heating the nanofluids (at about 40°C). Then, they were used to prepare the suspensions discussed in the first part of the following section (Fig. 2).

2.2.2. Carbon Nanotube Suspensions with Anionic Dispersant

The commonly used sodium dodecyl sulfate (SDS, Fluka Biochemica) was chosen as the representative anionic dispersant. The aliphatic chain interacts with the carbon material, and the hydrophilic part helps suspend them in the polar environment of ethylene glycol or water. It should be mentioned that the suspensions were more uniform and stable compared to the ones prepared without the addition of a dispersant.

For the dispersions in ethylene glycol, as shown in Fig. 2, the SDS content ranged from 0.35 to 1.2 mass%. The resulting suspensions were uniform and stable throughout the duration of the experiments. The

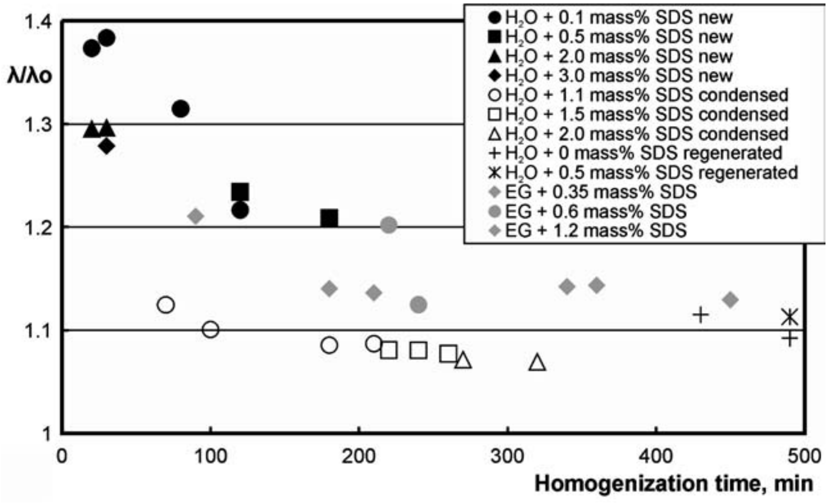

Fig. 2. Thermal conductivity enhancement of 0.6 vol% C-MWNT suspensions with SDS.

maximum observed enhancement of the thermal conductivity in relation to that of the base fluid was 21% for a 0.6-vol% suspension of C-MWNTs with 0.35 mass% SDS after 90 min of ultrasonic homogenization. It is pointed out that the thermal conductivity enhancement was only marginally affected by the different SDS content and that it decreased with the duration of ultrasonic homogenization. The latter observation is in agreement with similar studies [3, 19].

In the case where water (Reidel de Haën, CHROMASOLV) was the base fluid, the resulting samples were stable and homogeneous. The maximum increase of the thermal conductivity observed was 39% for a 0.6-vol% C-MWNTs suspension with 0.1 mass% SDS after 30 min of treatment with ultrasound. The Scanning electron microscopy (SEM) analysis of such samples gave images as shown in Fig. 3, where it was possible to see well-defined nanotubes with lengths exceeding 70 μm (length-to-diameter ratio of about 500). Furthermore, as shown in Fig. 2, minor changes (0.1–0.5 mass%) in the SDS content did not have a great impact in the thermal conductivity increase (differences shown in Table I refer to different sonication times). For higher SDS concentrations (0.1–2 mass%), the samples were more uniform, but the thermal conductivity increase was significantly smaller. Subjecting the suspensions to higher homogenization times led to a decrease in the thermal conductivity. Samples prepared after condensation or regeneration processes resulted also in smaller increases [8]. It was thus concluded that both the homogenization and regeneration procedures affect the interaction of the carbon material with the surfactant and lead to the shortening of the nanotubes. This shortening can be seen in SEM images of the samples, Fig. 4 (length-to-diameter ratio of about 30), subjected to the regeneration procedure.

The same surfactant, SDS, was also employed for the dispersion of C-MWNTs in the commercially available mineral oil TKO-19 Ultra. The samples were stable during the measurements, but they precipitated after several hours. The thermal conductivity increase was measured at 9% for a suspension of 0.6-vol% C-MWNTs in TKO-19 Ultra with 0.1 mass% SDS.

At this point, it is of interest to make a comment on the influence of the base fluid on the thermal conductivity enhancement. It has been clearly shown that the observed increase for the suspensions in mineral oil is substantially smaller than for the ones in polar fluids, such as ethylene glycol or water. The above results are in agreement with other findings by Xie et al. [20, 21]. Moreover, it was concluded that anionic dispersants such as SDS are possible candidates for the dispersion of C-NTs in polar fluids.

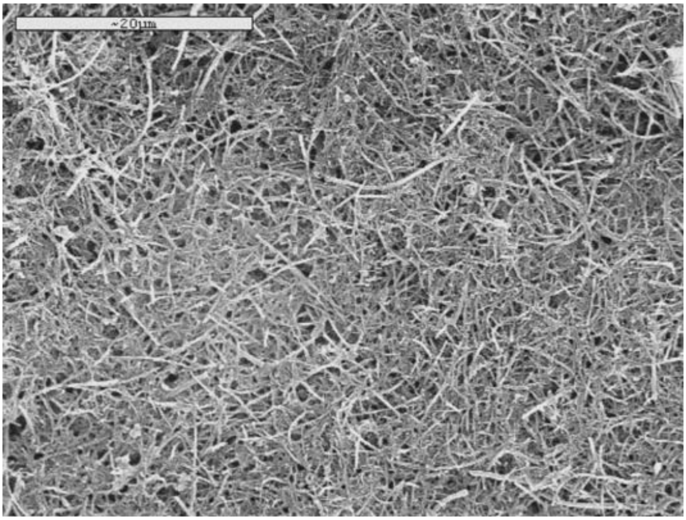

Fig. 3. SEM image of a 0.6 vol% suspension of C-MWNTs suspended in water with 0.1 mass% SDS, after 30 min of ultrasonic homogenization.

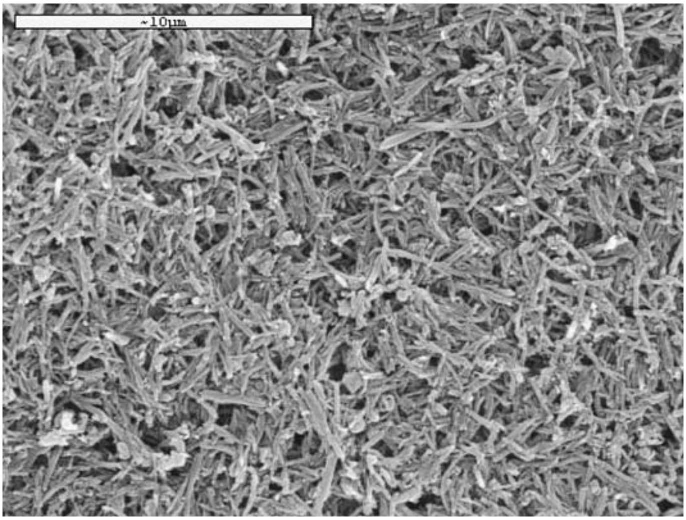

Fig. 4. SEM image of a 0.6 vol% suspension of C-MWNTs suspended in water with 0.5 mass% SDS, after regeneration and 490 min of ultrasonic homogenization.

2.2.3. Carbon Nanotube Suspensions with Cationic Dispersant

In order to examine the suitability of cationic dispersants, the widely employed hexadecyltrimethyl ammonium bromide (CTAB) was selected. CTAB and SDS have comparable number of carbon atoms in their molecules, although they are arranged differently.

In this case, the highest measured increase of the thermal conductivity was about 34% for 0.6 vol% suspensions of C-MWNTs in water, with the addition of 1 and 3 mass% CTAB, after sonication for 11 and 12 min, respectively (Fig. 5). It is obvious that the different concentration of the dispersant has a minor effect on the enhancement of the thermal conductivity. On the other hand, the homogenization time favors the increase when it is small (less than 30 min) and has the opposite effect as it augments. Additionally, it is pointed out that the enhancement for the aqueous nanotube suspensions with SDS and CTAB are comparable. Therefore, it is concluded that both anionic and cationic surfactants are suitable for the dispersion of C-MWNTs in polar fluids.

Moreover, it was attempted to disperse C-NTs with fewer graphite sheets in water, with the aid of CTAB. The pristine nanotube material (C-DWNTs as produced by Iljin Nanotech Co. Ltd.) had a different form, because the tubes were closely packed and entangled [8]. Nanotubes with more than two graphite sheets were present, and the tubes formed very large configurations. The measured enhancement was 7.6% for 1 vol% of

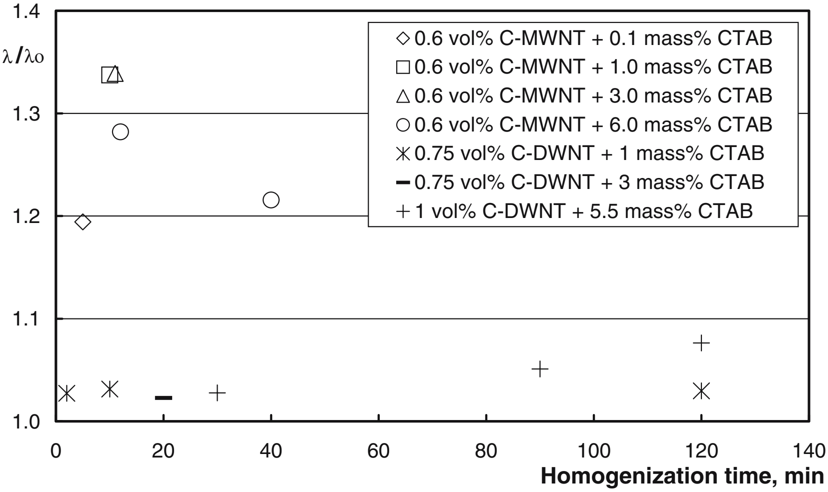

Fig. 5. Thermal conductivity enhancement of suspensions of carbon nanotubes in water with CTAB.

nanotubes in water with 5.5 mass% CTAB after 120 min of sonication, as shown in Fig. 5. The difference in the dispersant concentration did not have an important effect on the thermal conductivity increase. It should also be mentioned that the ultrasonic vibration had an inverse result, compared to other samples studied. The homogenization enabled the disentanglement of the nanotubes, along with their shortening. Therefore, it was possible to keep smaller nanotube formations in suspension, where separate nanotubes could be found. The samples prepared with CTAB were stable throughout the measurements.

The study of nanotube suspensions with the aid of the cationic surfactant led to the conclusion that this type of substance is also suitable for the preparation of stable dispersions.

2.2.4. Carbon Nanotube Suspensions with Non-ionic Dispersant

Along with the measurements discussed in the previous sections, it was decided to prepare samples using a non-ionic dispersant. The representative substance chosen was *t*-octylphenoxypolyethoxyethanol (Triton X-100), which is a quite different molecule compared to the other surfactants discussed so far. The increase obtained was 13% for a 0.6 vol% suspension of C-MWNTs in water with 0.5 mass% Triton X-100, after 90 min of ultrasonic homogenization (Fig. 6). It is of interest to note that the different surfactant contents and sonication times did not affect significantly the thermal conductivity of the prepared samples. Additionally, it should be stressed that the form of the suspensions was different, compared to the other C-MWNT dispersions measured. Analysis with SEM showed a homogeneous phase, where the nanotubes could not be separately defined. Moreover, the enhancement was smaller compared to the one measured for the suspensions with ionic dispersants.

Although the suspensions were homogeneous, their form and the increase of the thermal conductivity were not satisfactory. Therefore, it is suggested to favor the use of ionic surfactants rather than non-ionic, for the dispersion of C-NTs in polar fluids.

2.2.5. Carbon Nanotube Suspensions with Nanosperse

It was of interest to test a commercially available dispersant, suitable for the suspension of C-MWNTs in water. It was decided to use Nanosperse AQ (NanoLab Inc.), whose synthesis was not available to us. The form of the suspensions, as was revealed by SEM analysis, was similar to those formed with the aid of Triton X-100. It was possible to observe a uniform network of nanotubes surrounded with the dispersant. Moreover, it was necessary to subject the samples to larger sonication times, in order to obtain stable suspensions. As can be seen in Fig. 6, the

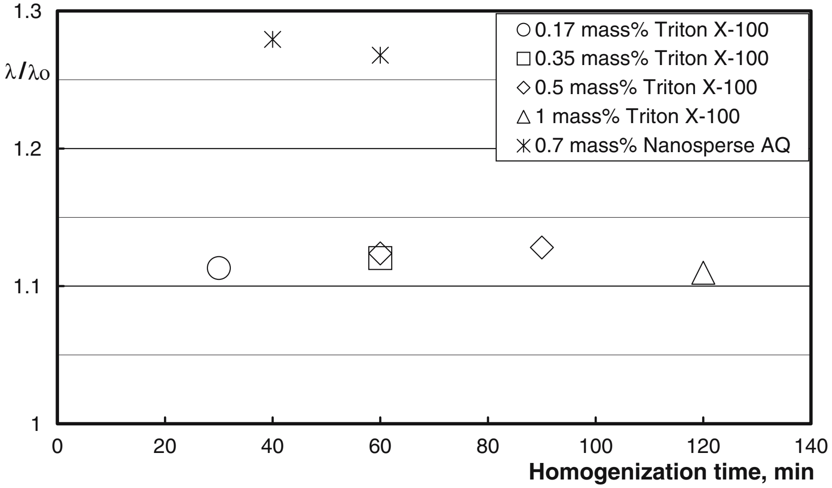

Fig. 6. Thermal conductivity enhancement of suspensions of C-MWNTs in water with Triton X-100 and Nanosperse AQ.

greater enhancement of the thermal conductivity measured was 28% for 0.6-vol% C-MWNT dispersed in water with 0.7 mass% Nanosperse AQ, after 40 min of ultrasonic homogenization. It is believed that the nature of the dispersant also affects the increase of heat transfer in the prepared nanofluids.

2.2.6. Comparison of the Thermal Conductivity Measurements for Nanotube Suspensions

At this point it would be valuable to discuss other studies available to us on the enhancement of the thermal conductivity of nanofluids with C-NTs. The greater increase was reported by Choi et al. [2] that dispersed C-MWNTs with mean diameters of about 25 nm and lengths of 50 μm, thus resulting in a length-to-diameter ratio of about 2,000. The base fluid was a synthetic poly (α-olefin) oil and the observed thermal conductivity increase was 160% for 1 vol% loading of C-MWNTs. For these measurements, Choi et al. [2] employed a transient hot-wire instrument with a single, coated platinum wire of 76 μm diameter and performed measurement at times up to 10 s. At such conditions, however, transient hot-wire instruments do not perform reliably and are affected by convection. Furthermore, no information is given for the preparation of these nanofluids.

Choi et al. [2] also reported measurements with 0.6 vol% of nanotubes in synthetic poly (α-olefin) oil. In this case, the enhancement reported was about 60%, which is still higher than the 40% increase reported by our group. One should consider several factors, such as the different length-to-diameter ratios, pristine materials, base fluid, and dispersion method. The importance of the length-to-diameter ratio is stressed here, because larger ratios are believed to be responsible for more enhanced heat transfer.

Xie et al. [21] also studied this phenomenon and reported results on the thermal conductivity increase for dispersions of chemically treated C-MWNTs in distilled water, ethylene glycol, and decene. The maximum observed enhancements for 1 vol% loading of nanotubes were about 20%, 12%, and 6% for the different base fluids, respectively. The method employed for the measurement of the thermal conductivity was similar to the one used by Choi et al. [2]. In this case, the pristine nanotubes had mean diameters and lengths of 15 nm and 30 μm, respectively. However, chemical treatment and intensive sonication are believed to have modified the aforementioned dimensions of the nanotubes in the dispersion according to our studies and to the work by Vaccarini et al. [3, 4, 22]. Hence, the resultant shorter length-to-diameter ratio, along with the different preparation method and pristine material, explain the measurement of smaller increases compared to the other studies discussed here. The effect of the different ratio is also mentioned by Keblinski et al. [23]. It is also pointed out that the enhancements for suspensions of volume loadings comparable to the ones used by our group are similar to our results for the samples with smaller length-to-diameter ratios due to intensive sonication.

The studies conducted by our group revealed that the thermal conductivity enhancement is affected by several factors, among which is the volume fraction of the dispersed phase, the use of dispersants, the type of the dispersants, and the length-to-diameter ratio of the nanotubes in suspension.

3. THEORETICAL STUDIES

As nanofluids are candidates for advanced technology and industrial applications, it is of interest to understand the mechanisms that enable the experimentally observed enhancement of the thermal conductivity. The objective is to be able to predict the properties of the suspensions. Thus, it would be possible to prepare nanofluids with the desired features and to concentrate on overcoming any undesirable properties. During the last five years discussions on the mechanisms of heat flow in nanofluids and on the ability of the scientists to correlate and predict their properties have increased. The thermal conductivity has attracted considerable interest.

3.1. Possible Heat Transfer Mechanisms

Consideration of the available measurements leads to the conclusion that a lot of parameters may be responsible for the unique thermal behavior of nanofluids.

Following the experimental results of our work [3, 4, 8], the most probable factors influencing the thermal conductivity enhancement are:

(a) the particle size and shape,
(b) the length-to-diameter ratio,
(c) the homogenization time, and
(d) the volume fraction of the dispersed phase.

Moreover, the existence of agglomerates and close packing of the dispersed phase, as well as the presence and type of dispersants, can also influence negatively the increase of the thermal conductivity.

Factors suggested by other groups that could also contribute to the enhancement of the thermal conductivity are:

1. the ordered structure of the liquid at the solid–liquid interfaces [24–28],
2. the interfacial resistance [15, 29, 30], and
3. Brownian motion of the nanoparticles enabling the formation of loosely packed clusters [15, 24, 31] and convection-like effects at the nanoscale [15, 30].

3.2. Prediction of the Thermal Conductivity

Studies have been initiated for the development of a model for the prediction of the thermal conductivity of nanofluids. Additionally, simulations are conducted using numerical methods and molecular dynamics. The models discussed in the following paragraphs are summarized in Table II.

3.2.1. Theoretical Models

Several analytical models have been proposed for deriving the thermal conductivity of nanofluids. Since the idea of dispersing particles in fluids to enhance heat transfer is not new, the first studies referred to suspensions of micro-sized particles (Hamilton and Crosser [32], Jeffrey [33], Davis [36], Lu and Lin [34], Hasselman and Johnson [35], and Yamada and Ota [37]). These schemes were applied for the prediction of the

Table II. Models for the Evaluation of the Thermal Conductivity of Nanofluids

Model type	Year	Author(s)	Notes
Analytical	1962	Hamilton-Crosser [32]	Micro-dimensions, various particle shapes
Analytical	1973	Jeffrey [33]	Micro-dimensions, spheres
Analytical	1986	Davis [35]	Micro-dimensions, spheres
Analytical	1996	Lu-Lin [36]	Micro-dimensions, spheres
Analytical	1987	Hasselman-Johnson [34]	Micro-dimensions, spheres
Analytical	1980	Yamada-Ota [37]	Micro-dimensions, parallelepiped
Analytical	2004	Kumar et al. [38]	Nanospheres
Analytical	2003	Wang-Zhou-Peng [39]	Nano-dimensions, network of non-metallic spheres
Analytical	2003	Xuan-Li-Hu [40]	Nano-dimensions, network of spheres
Analytical	2005	Prasher et al. [30]	Nanospheres
Analytical	2003	Yu-Hull-Choi [41]	Nanospheres
Analytical	2003	Nan-Shi-Lin [42]	Nano-dimensions, C-NTs suspensions
Correlation	2004	Jang-Choi [15]	Nanospheres
Correlation	2004	Yu-Choi [24]	Nanospheres
Correlation	2005	Xue-Xu [26]	Nanospheres with interfacial shells
Correlation	2003	Xue [27]	Nanospheres and nanotubes with interfacial shells
Correlation	2005	Prasher et al. [30]	Nanospheres
Correlation	2003	Wang-Zhou-Peng [39]	Network of nanospheres with interfacial shells
Correlation	2004	Koo-Kleinstreuer [44]	Nanospheres
Simulation	2004	Bhattacharya et al. [45]	Brownian dynamics
Simulation	2005	Xuan-Yao [46]	Lattice Boltzmann
Simulation	2004	Xue et al. [28]	Non-equilibrium molecular dynamics
Simulation	2004	Shenogin et al [29]	Classical molecular dynamics
Simulation	2005	Present work	Finite elements

thermal conductivity enhancement for some typical suspensions chosen arbitrarily (Table III).

For the first five cases presented in Table II, the main factors considered in the equations are the thermal conductivity of the dispersed phase and the base fluid along with the volume fraction of the solid in suspension. Some attempts have also been made to account for the interactions between the particles. The resulting increase is very small (2–3%)

Table III. Typical Nanofluids

Base Fluid	Dispersed Phase	Dispersant	Dimensions[a]	Enhancement (%)
Synthetic (α-olefin) oil	C-MWNT 1 vol%	–	$L/D = 2,000$	160
H_2O	C-MWNT 0.6 vol% new	SDS 0.1 mass%	$L/D = 500$	38
H_2O	C-MWNT 0.6 vol% regenerated	SDS traces	$L/D = 30$	9
Ethylene glycol	Cu 0.5 vol%	–	$D = 25$ nm	3
Ethylene glycol	Cu 0.3 vol%	TGA < 1 vol%	$D = 10$ nm	40
H_2O	Nanodiamonds 1 mass%	SDS 45 mass%	$D = 5$ nm	2

[a] D is the mean diameter of the spherical nanoparticles, and L/D is the mean length-to-outer-diameter ratio of the C-MWNTs.

compared to the experimental values, as these equations were not intended to be used for nanostructure dispersions.

In the particular case of Yamada and Ota [37], the obtained increase for the nanofluids presented in Table II is overestimated by more than 200%. Perhaps it would be valuable to include terms for the parameters hindering the heat transfer such as the interfacial resistance and the close-packed clustering effect. It would also be interesting to revise the constants employed for the case of nanofluids.

Recently, a theoretical approach by Kumar et al. [38] was considered taking into account the particle size, movement of the particle, concentration, and temperature. The authors use a constant for including the effect of particle size. Although it is, on the whole, a promising idea, important factors such as the interface resistance or the presence of dispersants are not considered. Moreover, it was proposed to consider the nanofluid as a network, taking into account fractal dimensions by Wang et al. [39] and Xuan et al. [40] and incorporating the Brownian motion in their equation [39]. The results for the representative nanofluids (Table III) were not very encouraging, as a significant increase was not obtained. Nevertheless, some interesting ideas were developed and it would be valuable to examine again the parameters suggested by the authors. The shape of the particles could be taken into consideration along with other factors like the interactions with surfactants and the interfacial resistance.

Another approach worth mentioning is that by Prasher et al. [30] and Yu et al. [41]. In this case the convection-like effect of the Brownian motion is considered for the increase of the thermal conductivity. Although they could not predict the experimental results, it is an interesting idea.

It is noted that most of the aforementioned schemes were developed for spherical or elongated (ellipsoid or parallelepiped) particles. There is an obvious need for corresponding models for nanofluids containing nanotubes.

Hence, a simple model was proposed by Nan et al. [42] for suspensions of C-NTs and it was applied for the representative nanofluids of Table III. The calculated enhancement (more than 250%) was much greater than that experimentally observed. Moreover, the calculations for the nanoparticle suspensions with relatively small volume fractions of the solid phase showed only a minor effect on the thermal conductivity. Again, it is believed that more factors should be considered, in order to get a better approach on the phenomenon.

Vadasz et al. [46] presented some interesting points in relation to the application of the transient hot-wire technique to the measurement of the thermal conductivity of nanofluids.

In conclusion, it is believed that much more work is needed to develop a theoretically based equation for the prediction of the thermal conductivity of nanofluids.

3.2.2. Correlation Models

Some other models based on correlation parameters have been employed for the calculation of the enhancement of the thermal conductivity. These studies are also valuable, as they enable a better understanding of the mechanisms involved in heat transfer in nanofluids and they could possibly lead to a theoretical model for the prediction of the properties of interest.

In most models considered here [15, 25–27, 30, 39, 43], the correlation depends on a parameter whose value is determined by the experimentally observed thermal conductivity enhancement. Such a parameter is usually the thickness of the adsorbed or ordered liquid layer, the thermal conductivity of this layer, a function describing the fluid properties and the particle interactions, as well as constant values. Usually, such schemes work very well for the measurements for which they were developed and seem inadequate when conditions are changed. Thus, it is obvious to us that even in such correlative models, much more work still needs to be done.

3.2.3. Simulation Models

Another theoretical approach on the thermal conductivity enhancement in nanofluids is by using mathematical simulations. It is of interest to consider how such mathematical tools can assist basic science in understanding phenomena.

For instance, the modeling of a nanofluid was attempted using a Brownian simulation method by Bhattacharya et al. [44]. In this particular case parameters needed for the simulation were fitted, employing experimental data. The lattice Boltzmann numerical method was developed by Xuan and Yao [45] in order to investigate the nanoparticle distribution in a stationary nanofluid. The information deduced from this model could be employed in a scheme for the prediction of the thermal conductivity. Xue et al. [28] used non-equilibrium molecular dynamics simulations to investigate the effect of the layered liquid on the enhancement of the thermal conductivity. It was found that, for a monatomic base fluid, there is almost no effect on the thermal transport property of the suspension. This conclusion could be evaluated in future attempts for simulations and development of analytical equations for the prediction of the thermal conductivity.

Another interesting simulation attempt was published by Shenogin et al. [29], where the authors employed classical molecular dynamics to study the interfacial resistance for heat flow between a carbon nanotube and octane liquid. It was found that the interfacial resistance has a large value, due to the weak coupling of the nanotube and the liquid, which is reduced as the length of the nanotube increases. It is of interest to note that the aforementioned findings are in agreement with our experimental results [3, 4, 8]. The thermal conductivity was found to be favored as the length-to-diameter ratio is increased, which corresponds to the elongation of the nanotube in the simulation. Moreover, the addition of surfactants is possible to help overcome the weak interactions between the components of the nanofluid, thus enabling better heat transport.

4. CONCLUSIONS

A review of the thermal conductivity measurements of nanofluids performed in our laboratory is presented. It was shown that the addition of nanoparticles can result in an increase of the thermal conductivity. Existing methods for the prediction and correlation of the thermal conductivity increase were discussed. It was shown that a lot of work still needs to be done in this area.

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