Thermal conductivity of nanofluids – Experimental and Theoretical

M. J. Assael[1], I. N. Metaxa, K. Kakosimos, D. Konstadinou

Chemical Engineering Department, Aristotle University, 54124 Thessaloniki, Greece

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[1] To whom correspondence should be addressed. E-mail: assael@auth.gr

ABSTRACT

The thermal conductivity of nanofluids has been studied experimentally using the transient hot-wire method and it is shown that significant increase can be obtained. Existing methods for prediction and correlation of the thermal conductivity are discussed. In an attempt to understand the heat transfer mechanism in aqueous nanofluids containing carbon multi-walled nanotubes (C-MWNTs), initial simulations employing the Finite Element (FEM) were performed. The results are very encouraging, but it is believed that more work still needs to be done in this field.

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 nanoparticles and alternatively carbon nanotubes provided the most promising results so far, with observed thermal conductivity enhancement of 40 % and 160 % respectively in relation to the base fluid [2-5]. It should be pointed out that more studies should be concluded before actually using this new type of fluids in real heat transfer devices. There is a great 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 complete 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 better than 2 % [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 formations. Spherical copper 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 it was aforementioned, the suspensions of spherical nanoparticles studied in our previous work [8] involved mainly the dispersion of copper nanoparticles. Other types of nanospheres have been also employed, showing interesting results [8-12].

2.1.1 Suspensions of Copper nanoparticles

The copper nanospheres were dispersed in ethylene glycol, both provided by MER Corporation U.S.A., with the aid of ultrasonic homogenisation for 60 minutes (Bandelin Electronics Model HD 2200) [8]. The results obtained for the thermal conductivity enhancement of suspensions with various nanoparticle concentrations are shown in Figure 1, as a ratio of the thermal conductivity of the dispersion λ over the thermal conductivity of the base fluid λ_0. It is noted that attempts were made to prepare stable suspensions of Cu nanoparticles in vacuum oil TKO-19Ultra, provided by MER Corporation U.S.A. The outcome was a sample with very low Cu content (0.0002 vol %) and it 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 copper nanospheres compared to our samples. It is noted that larger increase is observed when using nanoparticles with 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 copper nanofluids with thioglycolic acid (TGA) [8] were attributed to the partial destruction of the protective Ta_2O_5 layer used for the electric 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 increase for larger volume fractions of nanoparticles, compared to the ones of 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 rhythms of heat transfer.

Moreover, attempts 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 barely 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 ^{o}C and 4.5 % for 0.001 vol % Ag at 60 ^{o}C).

Preparing 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.* gave interesting results [17]. 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

Carbon nanotubes (C-NTs) are fascinating materials. They combine the micro-scale (length) with the nano-scale (diameter) dimensions. They also exhibit a number of interesting properties, among which are their particularly high thermal conductivity (6,600 W/m/K for carbon single-walled nanotubes, C-SWNT) [18] and their low density.

It is noted that carbon nanotubes 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.

2.2.1. Carbon nanotube suspensions without dispersants

It was initially attempted to disperse 0.25 vol % carbon multi-walled nanotubes (C-MWNTs), with a mean diameter of 120 nm, in ethylene glycol (both provided by MER Corporation) 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 vol % and 0.03125 vol %. The results of the measurements are shown in Figure 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 ^{o}C). Then, they were used to prepare the suspensions discussed in the first part of the following section (Figure 3).

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 Figure 2, the SDS content ranged from 0.35 mass % to 1.2 mass %. The resulting suspensions were uniform and stable throughout the duration of the experiments. The 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 %, 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 homogenisation. 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 was 39 % for a 0.6 vol % C-MWNTs suspension with 0.1 mass % SDS after 30 min of treatment with ultrasounds. Again, as shown in Figure 2, minor changes (0.1 mass % to 0.5 mass %) in the SDS content do not have a great impact in the thermal conductivity increase (differences shown in Table I refer to different sonication times). Nevertheless, for higher SDS concentrations (0.1 mass % to 2 mass %), the samples were more uniform, but the enhancement of the transport property is significantly smaller. Moreover, the subjection of the suspensions to higher homogenisation times led to the depletion of the thermal conductivity. At this point it should be noted that samples prepared after condensation or regeneration processes presented smaller increases [8]. It should be mentioned that after the regeneration procedure was completed traces of SDS could still be found in the specimen. Thus, it was concluded that the aforementioned procedures affect the interaction of the carbon material with the surfactant and that they lead to the shortening of the nanotubes. In this way, the thermal conductivity enhancement is not favored.

The same surfactant, SDS, was also employed for the dispersion of C-MWNTs in the commercially available mineral oil TKO-19 Ultra. It should be noted that the samples were stable during the measurements, but they precipitated after several hours. The 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 [20, 21] by Xie *et al.* (2002, 2003). Moreover, it was concluded that anionic dispersants such as SDS are possible candidates for the dispersion of carbon nanotubes in polar fluids.

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. It should be pointed out that 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 mass % and 3 mass % CTAB, after sonication for 11 min and 12 min respectively (Figure 3). It is obvious that the different concentration of the dispersant has a minor effect on the enhancement of the transport property. On the other hand, the homogenisation 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 carbon nanotubes with fewer graphite sheets in water, with the aid of CTAB. The pristine nanotube material (carbon double-walled nanotubes, 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 large configurations, thus producing dispersion that could not be referred to as a nanofluid. The greater enhancement measured was 7.6 % for 1 vol % of nanotubes in water with 5.5 mass % CTAB after 120 min of sonication, as it is shown in Figure 3. The difference in the dispersant concentration did not have an important effect on the thermal conductivity increase. It should be mentioned that the ultrasonic vibration had an inverse result, compared to other samples studied. The homogenisation enabled the disentanglement of the nanotubes, along with their shortening. Therefore, it was possible to keep in suspension smaller nanotube formations, where separate nanotubes could be found. Nevertheless, 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 has a quite different molecule compared to the other surfactants discussed so far. The greater 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 homogenisation (Figure 4). 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 scanning electron microscopy (SEM) showed a homogeneous phase, where the nanotubes could not be separately defined. Moreover, the enhancement was smaller 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 enough. Therefore, it is suggested to favor the use of ionic surfactants rather than the non-ionic, for the dispersion of carbon nanotubes in polar fluids.

2.2.5. Carbon nanotube suspensions with Nanosperse

It was considered of interest to test a commercially available dispersant, suitable for the suspension of carbon nanotubes in water. It was decided to use Nanosperse AQ (NanoLab Inc.), whose synthesis was not available to us. The form of the suspensions, as it 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 it can be seen in Figure 4, the 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 homogenisation. It is believed that the nature of the dispersant also affects the increase of the 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 carbon nanotubes. 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 to a length/diameter (L/D) ratio of approximately 2,000. The base fluid was a synthetic poly (α-olefin) oil and the observed increase was 160 % for 1 vol % loading of C-MWNTs. It is also noted that the thermal conductivity was measured with a different approach of the transient hot-wire method, compared to the one used by our group. Additionally, the method for the preparation of the nanofluids was probably different, although more information has not been made available. It should be mentioned that the enhancement observed for 0.6 vol % of nanotubes was about 60 %, which is not far of from the 40 % increase reported by our group. One should consider several factors, such as the different L/D ratios, pristine materials, base fluid, and dispersion method. The importance of the L/D is stressed here, because larger ratios are believed to be responsible for enhanced heat transfer. Taking the aforementioned parameters into consideration, the results are comparable.

Moreover, Xie *et al.* studied this phenomenon and they reported results on the thermal conductivity increase for dispersions of chemically treated C-MWNTs in distilled water, ethylene glycol and decene [21]. The maximum observed enhancements for 1 vol. % loadings 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]. Moreover, in this case, the pristine nanotubes had mean diameters and lengths of 15 nm and 30 μm respectively. Nevertheless, 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 resulted shorter L/D ratio, along with the different preparation method and pristine material explain the measurement of smaller increases compared to the other studies discussed here. It is also mentioned that, the enhancements for suspensions of volume loadings comparable to the ones used by our group, are similar with our results for the samples with smaller L/D ratios, due to intensive sonication.

Moreover, 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 L/D ratio of the nanotubes in suspension.

3. THEORETICAL STUDIES

It should be kept in mind that nanofluids are candidates for advanced technology and industrial applications. Therefore, it is of interest to understand the mechanisms that enable the enhancement of the thermal conductivity, which has been observed in the experiments. 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 the discussion is rising on the mechanisms of heat flow in nanofluids and on the ability of the scientists to correlate and predict their properties, among which is also the thermal conductivity.

3.1. Possible heat transfer mechanisms

The 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 L/D 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 contribute to the enhancement of the thermal conductivity are:

1. The ordered structure of the liquid at the solid-liquid interfaces [23-27].

2. The interfacial resistance [15, 28, 29].
3. Brownian motion of the nanoparticles enabling the formation of loosely packed clusters [15, 24, 30] and convection-like effects at the nanoscale [15, 29].

These and more factors may contribute more or less significantly to the observed increase of the thermal conductivity.

3.2 Prediction of the thermal conductivity

Naturally, another aspect of the research on heat transfer in nanofluids is attempting to predict their properties. 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 III.

3.2.1 Theoretical models

Several analytical models have been proposed for deriving the thermal conductivity of nanofluids. Some of them are an attempt to derive an equation based on theory. Since the idea of dispersing particles in fluids to enhance heat transfer is not new, the first studies were for suspensions of micro-sized particles by Hamilton and Crosser, Jeffrey, Davis, Lu and Lin, Hasselman and Johnson and Yamada and Ota [31-36]. The aforementioned schemes were applied for the prediction of the thermal conductivity enhancement for some typical suspensions chosen arbitrarily (Table II). For the first five cases, 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 are also made to account for the interactions between the particles. The resulting increase is very small compared to the experiments for these schemes, because these equations were not intended to be used for dispersions of nanostructures.

In the particular case of Yamada *et al.* [Yamada] the obtained increase is greater than anticipated. Perhaps it would be valuable to include terms for the parameters hindering the heat transfer such the interfacial resistance and the close-packed clustering effect. It would be also interesting to revise the constants employed for the case of nanofluids.

Recently, a theoretical approach was considered taking into account the particle size, movement of the particle, concentration and temperature by Kumar *et al.* [37]. The authors use a constant for including the effect of particle size. It would be interesting to get a more detailed expression for this parameter. Although it is on the whole a promising idea, important factors are not considered, such as the interface resistance or the presence of dispersants. Moreover, it was proposed to think of the nanofluid as a form of a network, taking into account fractal dimensions by Wang *et al.* and Xuan *et al.* [38, 39] and incorporating the Brownian motion in the equation [39]. The results for the representative nanofluids (Table II) were not very encouraging, because significant increase was not obtained. The shape of the particles and a stronger influence of the clustering effect 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.* and Yu *et al.* [29, 40]. In this case the convection-like effect of the Brownian motion is considered for the increase of the thermal conductivity. It is an interesting idea, but it would be valuable to incorporate more terms to account for other parameters influencing the heat transfer.

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.* for suspensions of carbon nanotubes [41] and it was applied for the representative nanofluids of Table II. The enhancement calculated was greater than the experimentally observed for the nanotube suspensions, because of the great thermal conductivity of the carbon material. It is noted that 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.

Therefore, it is believed that much more work is needed to reach 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 transport property. These studies are valuable, because 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, 23, 25, 26, 29, 38, 42], the correlation depends on a parameter whose value is determined by the experimentally observed thermal conductivity enhancement. Such a parameter could be 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 needs still 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 the nanofluid was attempted using a Brownian simulation method by Bhattacharya *et al.* [43]. 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 in order to investigate the nanoparticle distribution in a stationary nanofluid [44]. The information deduced from this model could be employed in a scheme for the prediction of the thermal conductivity. Xue *et al.* used non-equilibrium molecular dynamics simulations to investigate the effect of the layered liquid on the enhancement of the thermal conductivity [44]. 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.*, where the authors employed classical molecular dynamics to study the interfacial resistance for heat flow between a carbon nanotube and octane liquid [28]. 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 L/D ratio is increased, which is corresponding 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.

In the present work the 2 Dimensional Ritz-Galerkin Finite Elements Method (2D-FEM) was employed. It is a numerical method that employs the discredization of the full geometry of the system and the design of a geometric mesh in full detail. It is also possible to create a mesh that is denser at areas close to interfaces and points of interests, in order to represent more realistically the actual problem. The mesh was formed by elements of different sizes that may be rectangles (source code developed in our laboratory) or triangles (commercial computer package). The results were comparable for the two cases.

The nanofluid considered was composed by water and C-MWNTs. With the FEM we tried to simulate the actual experimental setup, i.e. the heat transfer from the transient hot-wire sensor to the nanofluid. Hence, a symmetric mesh composed of connected nanotubes in water was constructed, next to the transient hot-wire. The experimentally observed heat input was assumed, as well as the physical parameters of water and C-MWNTs. By iterating the thermal conductivity of the nanofluid, the experimentally observed temperature rise was obtained. Preliminary results indicate:

1. Different volume fractions of nanotubes were spread as a network throughout the specimen. It was found that the thermal conductivity increases with increasing volume ratio. This result is in agreement with our experimental work discussed in previous sections.
2. Several Length/Diameter (L/D) ratios were tested for the same volume fraction of nanotubes forming a network. It was concluded that when the aspect ratio is increased, the thermal conductivity is enhanced. This is also in agreement with the experimental results.
3. The same volume fraction of nanotubes was spread in water as a network and as isolated nanotubes. It was deduced that the enhancement of the thermal conductivity is larger in the case that nanotubes are in contact. It is noted that the nanotubes in a

network do not constitute agglomerates, since they are isolated nanotubes arranged in contact at several points (Figure 5). The formed network is believed to offer an easier path to heat and works as a thermal bridge.

4. Nanotubes were places at different distances from each other and from the tantalum wire, which is the heat source in our experimental setup. It was found that when the distance is increased, the thermal conductivity decreases.

Taking into account the aforementioned observations that resulted from the 2D-FEM simulations, it is possible to distinguish the desired characteristics for the optimum design of a nanofluid. Hence, it is concluded that it is preferred to use nanotubes of large aspect ratio (L/D) values. Moreover, the use of dispersants is favoured because they help nanotubes interact with the base fluid and with each other, thus resulting to greater enhancement of the thermal conductivity. It is pointed out that more results can be anticipated from FEM simulations, for example after incorporating the surfactant in the nanofluid matrix.

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FIGURE CAPTIONS

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

Fig. 2. Thermal Conductivity enhancement of 0.6 vol % C-MWNTs suspensions with SDS.

Fig. 3. Thermal Conductivity enhancement of suspensions of carbon nanotubes in water with CTAB.

Fig. 4. Thermal Conductivity enhancement of suspensions of carbon nanotubes in water with Triton X-100 and Nanosperse AQ.

Fig. 5. 2 Dimensional Finite Element Simulation

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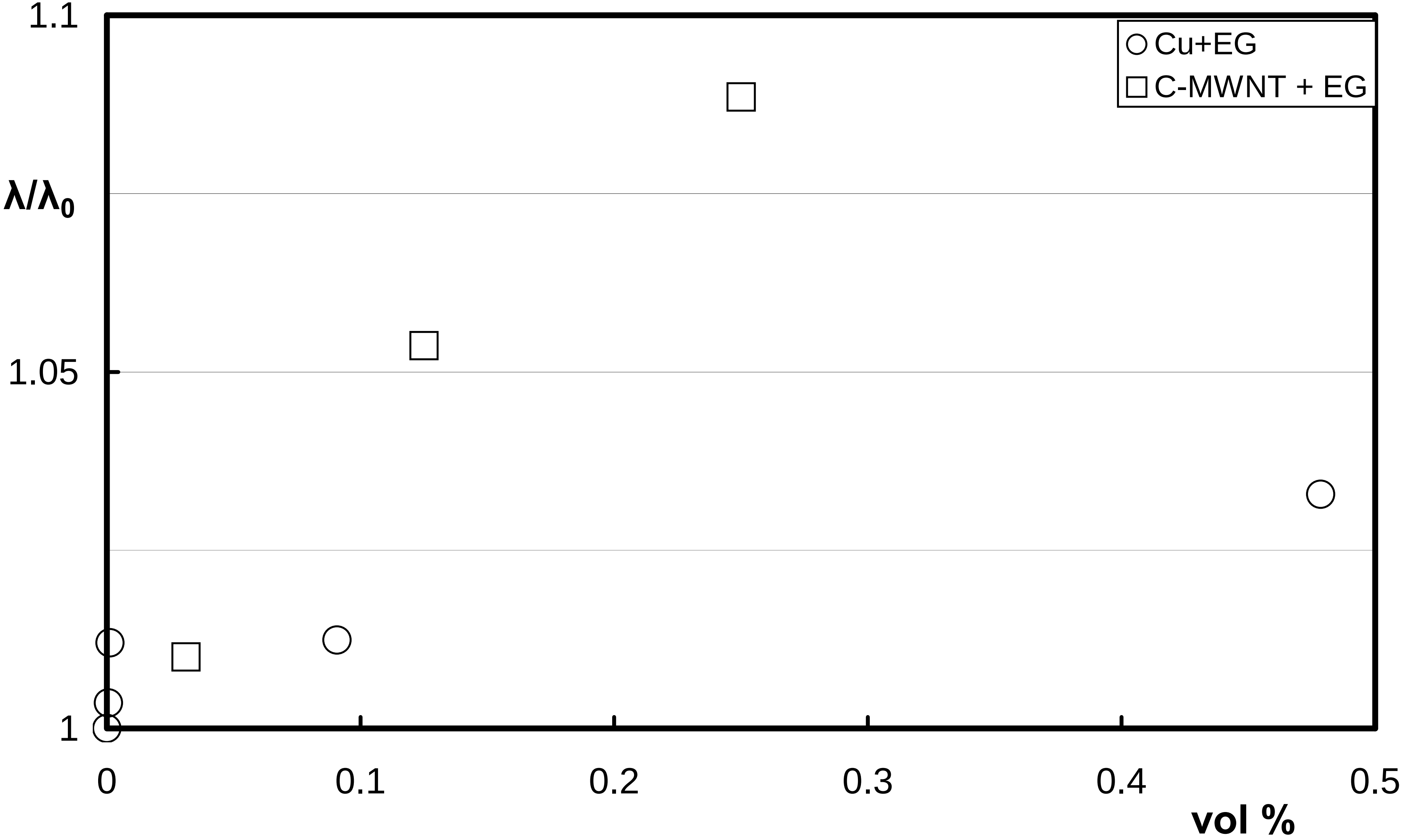
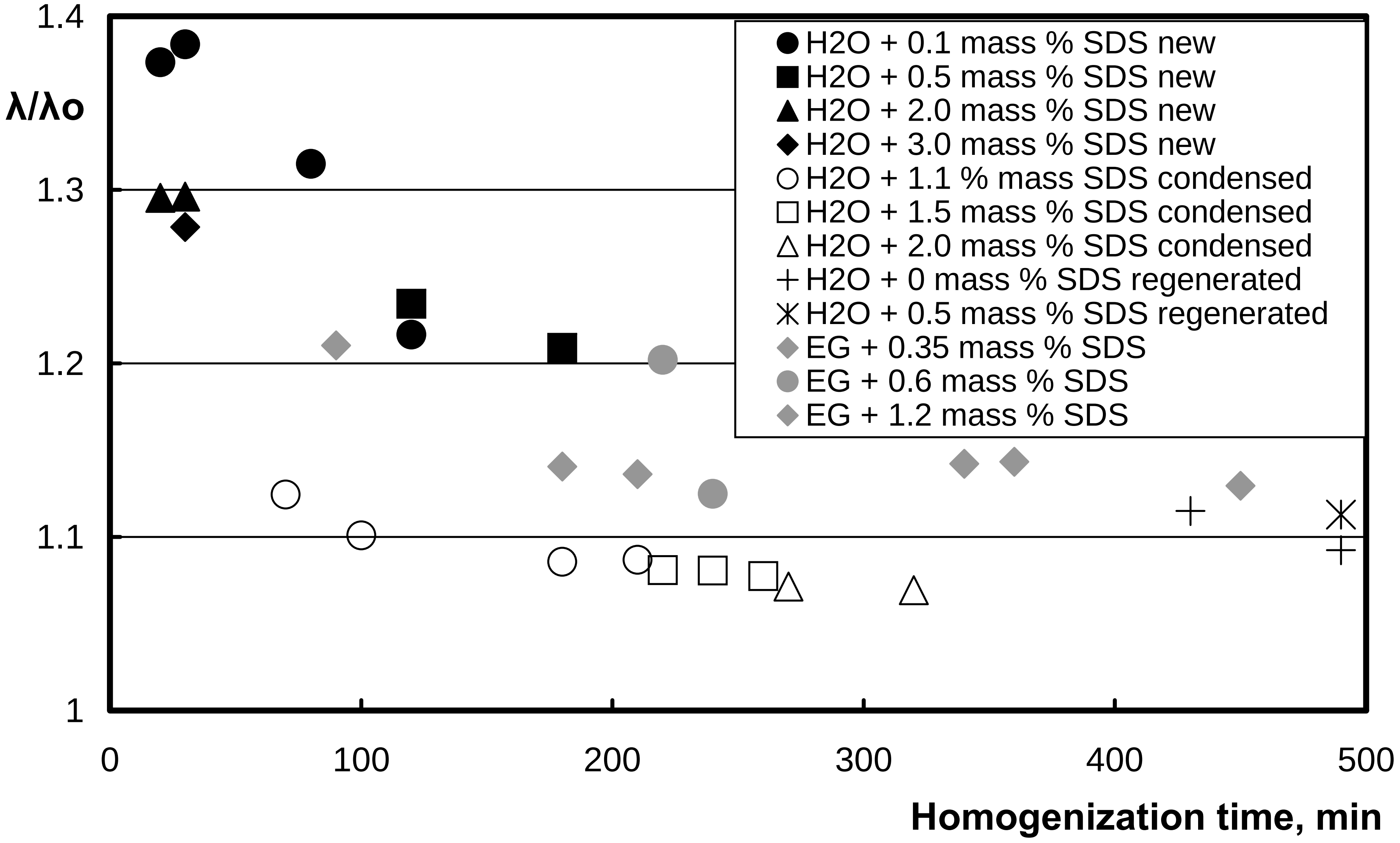
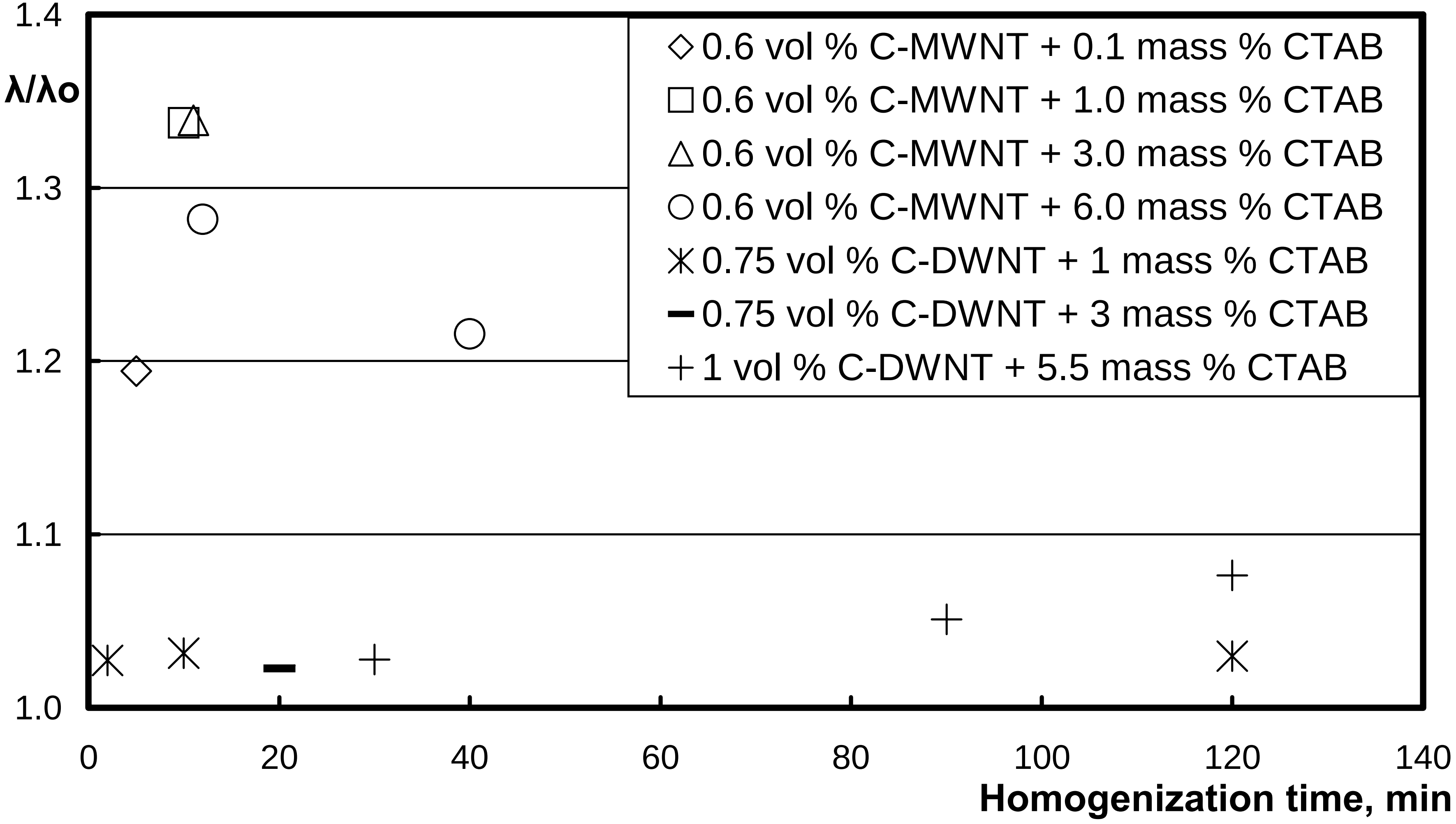
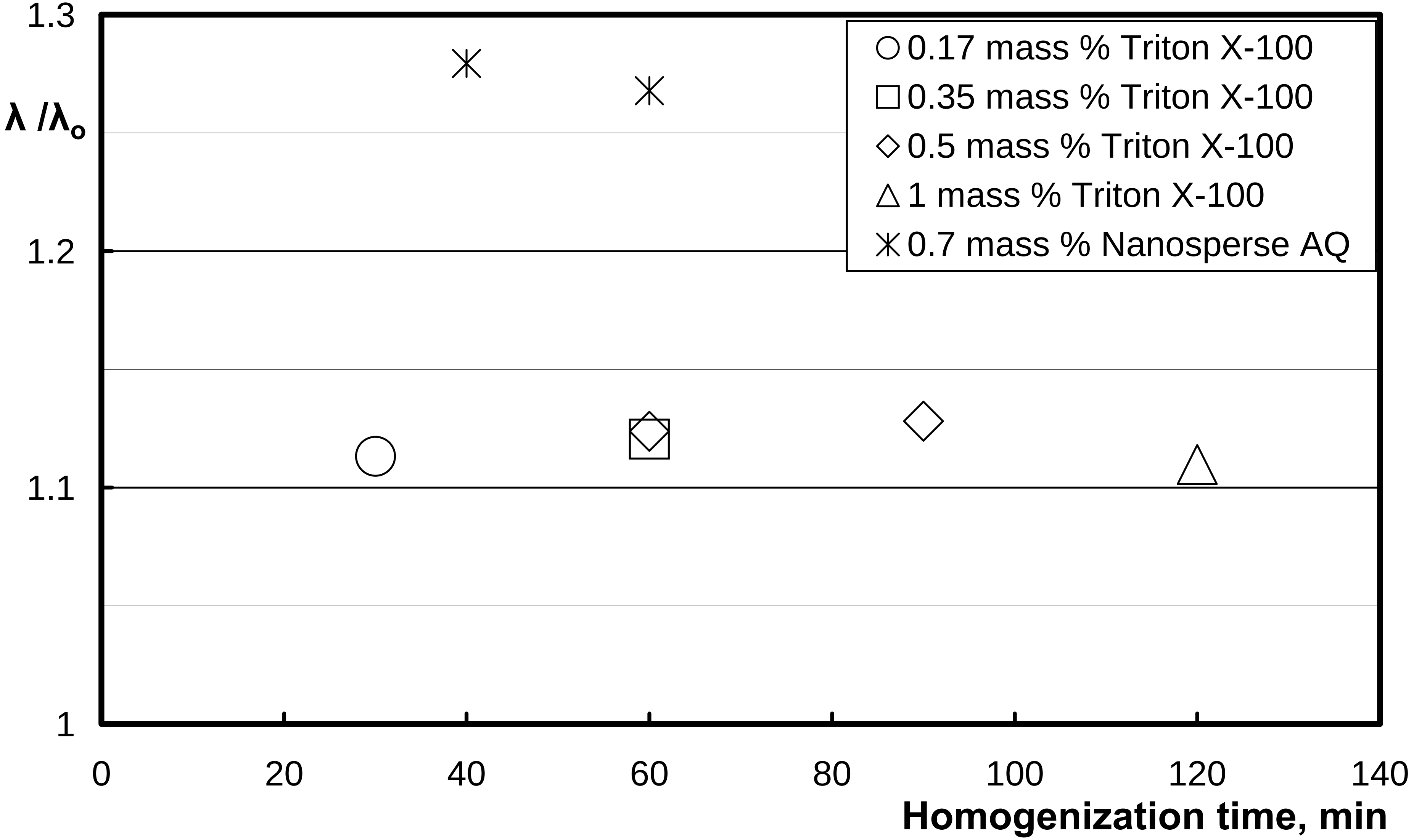

1.1
1.05
1
λ/λ$_0$
0
0.1
0.2
0.3
0.4
0.5
vol %
○ Cu+EG
□ C-MWNT + EG


λ/λo
1.4
1.3
1.2
1.1
1
0
100
200
300
400
500
Homogenization time, min
● H2O + 0.1 mass % SDS new
■ H2O + 0.5 mass % SDS new
▲ H2O + 2.0 mass % SDS new
◆ H2O + 3.0 mass % SDS new
○ H2O + 1.1 % mass SDS condensed
□ H2O + 1.5 mass % SDS condensed
△ H2O + 2.0 mass % SDS condensed
+ H2O + 0 mass % SDS regenerated
✳ H2O + 0.5 mass % SDS regenerated
◆ EG + 0.35 mass % SDS
● EG + 0.6 mass % SDS
◆ EG + 1.2 mass % SDS


λ/λo
1.4
1.3
1.2
1.1
1.0
0
20
40
60
80
100
120
140
Homogenization time, min
◇ 0.6 vol % C-MWNT + 0.1 mass % CTAB
□ 0.6 vol % C-MWNT + 1.0 mass % CTAB
△ 0.6 vol % C-MWNT + 3.0 mass % CTAB
○ 0.6 vol % C-MWNT + 6.0 mass % CTAB
✳ 0.75 vol % C-DWNT + 1 mass % CTAB
▬ 0.75 vol % C-DWNT + 3 mass % CTAB
+ 1 vol % C-DWNT + 5.5 mass % CTAB


1.3
1.2
1.1
1
λ /λo
0
20
40
60
80
100
120
140
Homogenization time, min
○ 0.17 mass % Triton X-100
□ 0.35 mass % Triton X-100
◇ 0.5 mass % Triton X-100
△ 1 mass % Triton X-100
✳ 0.7 mass % Nanosperse AQ

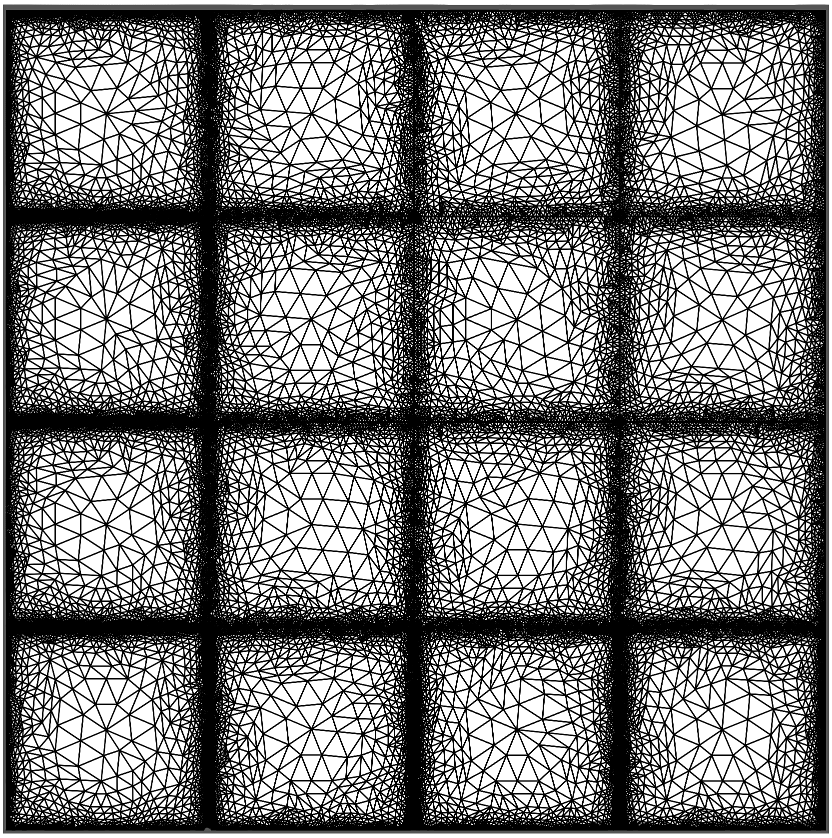


Table I. Thermal Conductivity Measurements

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

Table II. Typical nanofluids

Base Fluid	Dispersed Phase	Dispersant	Enhancement %
synthetic (α-olefin) oil	C-MWNT 1 vol %	-	160
H_2O	C-MWNT 0.6 vol % new	SDS 0.1 mass %	38
H_2O	C-MWNT 0.6 vol % regenerated	SDS traces	9
Ethylene Glycol	Cu 0.5 vol %	-	3
Ethylene Glycol	Cu 0.3 vol %	TGA < 1 vol %	40
H_2O	Nanodiamonds 1 mass %	SDS 45 mass %	2

Table III. Models for the evaluation of thermal conductivity

Model type	**Year**	**Author(s)**	**Notes**
Analytical	1962	Hamilton-Crosser [31]	Micro-dimensions, various particle shapes
Analytical	1973	Jeffrey [32]	Micro-dimensions, spheres
Analytical	1986	Davis [34]	Micro-dimensions, spheres
Analytical	1996	Lu-Lin [35]	Micro-dimensions, spheres
Analytical	1987	Hasselman-Johnson [33]	Micro-dimensions, spheres
Analytical	1980	Yamada-Ota [36]	Micro-dimensions, parallelepiped
Analytical	2004	Kumar *et al.* [37]	Nanospheres
Analytical	2003	Wang-Zhou-Peng [38]	Nano-dimensions, network of non-metallic spheres
Analytical	2003	Xuan-Li-Hu [39]	Nano-dimensions, network of spheres
Analytical	2005	Prasher *et al.* [29]	Nanospheres
Analytical	2003	Yu-Hull-Choi [40]	Nanospheres
Analytical	2003	Nan-Shi-Lin [41]	Nano-dimensions, carbon nanotubes suspensions
Correlation	2004	Jang-Choi [15]	Nanospheres
Correlation	2004	Yu-Choi [23]	Nanospheres
Correlation	2005	Xue-Xu [25]	Nanospheres with interfacial shells
Correlation	2003	Xue [26]	Nanospheres and nanotubes with interfacial shells
Correlation	2005	Prasher *et al.* [29]	Nanospheres
Correlation	2003	Wang-Zhou-Peng [38]	Network of nanospheres with interfacial shells
Correlation	2004	Koo-Kleinstreuer [42]	Nanospheres
Simulation	2004	Bhattacharya et al. [43]	Brownian dynamics
Simulation	2005	Xuan-Yao [44]	Lattice Boltzmann
Simulation	2004	Xue *et al.* [27]	Non-equilibrium molecular dynamics
Simulation	2004	Shenogin *et al* [28].	Classical molecular dynamics
Simulation	2005	Present work	Finite Elements