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Conduction heat transfer characteristics and dispersion behaviour of carbon nanofluids as a function of different parameters

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Thermal conductivity enhancements in aqueous media in the presence of carbon nanotubes (SWNTs) are investigated. The SWNTs nanofluids are prepared using a two-step method. The concentration of SWNTs suspensions is below 1 wt%. The thermal conductivities of the SWNTs suspensions are measured by a modified transient hot wire method (KD2 thermal property meter). Zeta potential, turbidity measurements and sedimentation photographs have been used to characterise quantitatively colloidal stability of the dispersions. Different parameters such as mass fraction, temperature, effect of various surfactants and pH, and effect of various physical treatment techniques are discussed. The results show that SWNTs suspensions have noticeably higher thermal conductivities than the base fluid without SWNTs. For SWNTs–water suspensions at 1wt%, thermal conductivity is enhanced by 30% at 25°C. The application of a suitable surfactant (such as GA and SDS), leads to better dispersion behaviour in nanofluids and increases the settling time from 24h to several months. At pH 9.5, a good dispersion was obtained which is attributed to charge build-up on the surface of SWNTs due to adding the dispersants (for GA and SDS). This also indicates that, among various physical treatment techniques employed in this study, the ultrasonic disruptor was the most effective method to break down the agglomerated nanoparticles suspended in base fluids.

Keywords: carbon nanofluids; SWNTs; thermal conductivity; stability

1. Introduction

Since their discovery in 1991 [1], carbon nanotubes (SWNTs) have attracted considerable interest for their potential applications [2], such as polymer composites, field emission displays, hydrogen storage media and nanoscale semiconductor probes. It has long been recognised that suspensions of solid particles in liquids provide useful advantages in industrial fluid systems, including heat transfer fluid, magnetic fluid and lubricant fluid [1–5]. Since the working fluids have the limitation of heat transfer performance, solid particles were dispersed in the working fluids to improve their thermal properties or heat

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transfer characteristics [6–9]. However, those previous practical applications were mostly confined to the suspensions with millimetre or micrometre-sized particles, which tend to quickly settle down and subsequently resulted in severe clogging in micro-channels. There are two major methods for producing nanofluids: (i) the one-step direct method represents the direct formation of the nanoparticles inside the base fluids; (ii) the two-step method represents the formation of nanoparticles and subsequent dispersion of the nanoparticles in the base fluids. In either case, the preparation of a uniformly dispersed nanofluid is essential for obtaining stable reproduction of physical properties or superior characteristics of the nanofluids [10–17]. Although many experimental studies on nanofluid systems have been performed, the preparation methods for stable nanofluids have not been not systematically studied yet. In this work, the two-step method was selected to prepare the nanofluids. Preparation of nanofluids is the first key step in applying nanophase particles to changing the heat transfer performance of conventional fluids. The nanofluid does not simply refer to a liquid–solid mixture. Some special requirements are necessary, such as even suspension, stable suspension, durable suspension, low agglomeration of particles and no chemical change of the fluid. In general, these are effective methods used for preparation of suspensions [18]: (1) to change the pH value of suspensions; (2) to use surface activators and/or dispersants; (3) to use ultrasonic vibration. All these techniques aim at changing the surface properties of suspended particles and suppressing the formation of particles cluster in order to obtain stable suspensions. It depends upon the application case how these techniques are used. In this work, according to literatures and our experiments, the effect of some factors such as mass fraction, temperature, various surfactants, pH and various physical treatment techniques were selected and the effects of this parameter on the suspended nanoparticle size, thermal conductivity and dispersity in the water-based fluids are discussed.

2. Experimental

2.1. *Material and preparation of nanofluids*

Distilled water and single-walled carbon nanotubes were used to produce nanofluids. The carbon nanotubes were provided by the Research Institute of Petroleum Industry, Iran. They were synthesised by catalytic decomposition of 20% methane in hydrogen over Co–Mo/MgO catalysts at 1000°C [19]. Figure 1(a) and (b) show, respectively, the TEM image and Raman spectroscopy (Philips, 200 kV) of the sample. It can be seen that the nanotubes are entangled and some are in the format of agglomerates. It indicates that IG/ID of sample is almost 8. The ID and OD of SWNTs are 0.8–1.1 nm and 1–4 nm, respectively.

It is known that SWNTs have a hydrophobic surface, which is prone to aggregation and precipitation in water in the absence of a dispersant/surfactant [20]. Lots of efforts were therefore made in the initial stage of the work, searching for an appropriate dispersant. Sodium dodecyl sulfonate (SDS), Triton X-100 (TX-100), cetyl trimethyl ammonium bromide (CTAB) and gum Arabic (GA) were found to be able to stabilise carbon nanotubes for more than a month without visual observable sedimentation.

A typical process for nanofluids preparation involves in series: (a) sonicating a SWNTs sample with a known weight in an ultrasonic bath (KQ2200DE Ultrasonic Cleanser, 100 W, Equipment Company, Italy) for over 2 h, or disruptor (Vibronic ultrasonic processor P1-250 W) for 30 min and (b) dispersing the sonicated SWNTs into a preset

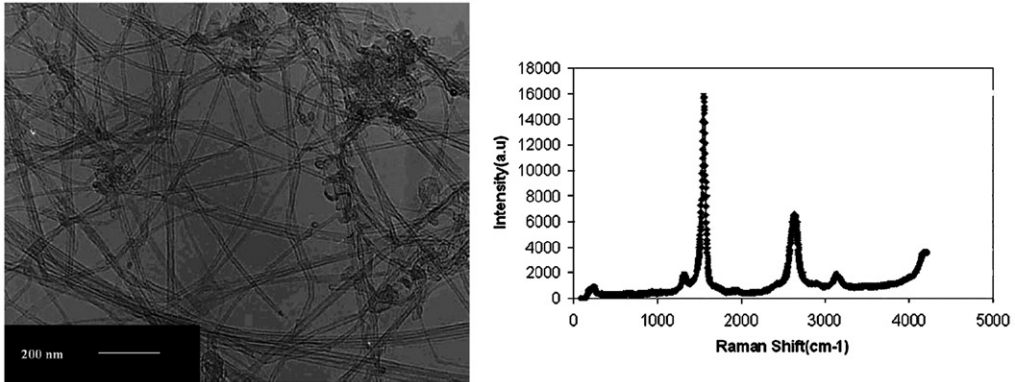


Figure 1. (a) The TEM of ripi SWNTs; (b) Raman spectroscopy of ripi SWNTs.

amount of distilled water contain Gum Arabic dispersant and adjusting the suspension to a preset pH level. The pH value of system was adjusted with HCl and NaOH solutions by precise pH Meter (WTW-25, Spain).

The stirrers (RTY-67, UK) used in preparing SWNTs nanofluids were 1500 rpm and 40°C, respectively. Two types of sonicators were also employed in this study. One was the ultrasonic bath (40 kHz) and the other was the ultrasonic disruptor (20 kHz, 250 W). The ultrasonic wave was transferred to the test sample through water for the ultrasonic bath while it was propagated directly to the test sample from a vibrating horn for the ultrasonic disruptor. The suspensions were sonicated for 30 min for both the ultrasonic bath and disruptor. SWNTs nanofluids made in this way were found to be very stable for months without visual observable sedimentation.

2.2. Characterisation method

The thermal conductivity was measured by using a KD2 thermal property meter (Labcell Ltd, UK), which is based on the transient hot wire method. The KD2 meter has a probe 60 mm in length and 0.9 mm in diameter, which integrates in its interior a heating element and a thermoresistor, and is connected to a microprocessor for controlling and conducting the measurements. The KD2 meter was calibrated by using distilled water before any set of measurements. In order to study the effect of temperature on the effective thermal conductivity of nanofluids, a thermostat bath (GD120-S12, Grant, UK) was used, which was able to maintain temperature uniformity within $\pm 0.1^\circ\text{C}$.

Zeta potential, turbidity measurements and sedimentation photographs have been used to characterise quantitatively *colloidal stability* of the dispersions (the dispersion behaviour). Ten millilitres of each suspension were poured into test tubes, and then the samples were allowed to deposit for several days. The above solution for certain height of the suspensions was taken and then absorbency of the suspensions was measured on the turbidity (Hitachi Instrument Inc, Japan) after depositing for several time. After the suspensions were stirred thoroughly and ultrasonicated for at least 20 min, 2–4 mL of suspensions were transferred into a measuring cell. Then zeta potential and particle size distribution were measured by a Malvern ZS Nano S analyser (Malvern Instrument Inc,

London, UK). The measurement was run at $V=10\text{ V}$, $T=25^\circ\text{C}$ with switch time at $t=50\text{ s}$. Each experiment was repeated at least 10 times to calculate the mean value of the experimental data.

3. Results and discussion

3.1. Influence of the various temperature and nanoparticles concentration

Several nanofluids (fluids containing specified mass fractions of nanoparticles) were prepared by dispersing preweighed quantities of SWNTs particles in water at ambient conditions. Figure 2 shows that SWNTs suspensions have noticeably higher thermal conductivities than the suspensions by low SWNTs concentration. For SWNTs–water suspensions at 0.1 wt%, thermal conductivity is enhanced by 11% (temperature = 25°C). On the other hand, for SWNTs–water suspension, thermal conductivity is enhanced by 30% at 1 wt%. Because of higher thermal conductivity of SWNTs suspension, all samples are prepared by these nanoparticles instead of MWNTs.

The effective thermal conductivity of nanofluids as a function of SWNTs concentration at different temperatures is also shown in Figure 2. It can be seen that the effective thermal conductivity increases with increasing temperature and SWNTs concentration. At 20 and 25°C , the dependence of the thermal conductivity levels off at SWNTs concentrations greater than 0.5 wt%, while this does not occur at 30°C . The enhancement of the thermal conductivity shown in Figure 2 is higher than that reported by Ding et al. [20], Xie and Li [21] and Wen and Ding [22]. The exact reason for this difference is unclear, but it is believed to be associated with the thermal properties of SWNTs used, liquid–SWNTs interfacial resistance and the aspect ratio of SWNTs used [10]. Because the dependence of the thermal conductivity on temperature was much more significant, particle size characteristics for one sample in two temperatures were done.

Figure 3 illustrates the particle size distributions of SWNTs– H_2O nano-suspensions at (a) 25°C and (b) 30°C and shows that there are obvious variations in the particle size characteristics between two temperatures. The result shows that the average particle sizes obtained at low temperature increases at higher temperature.

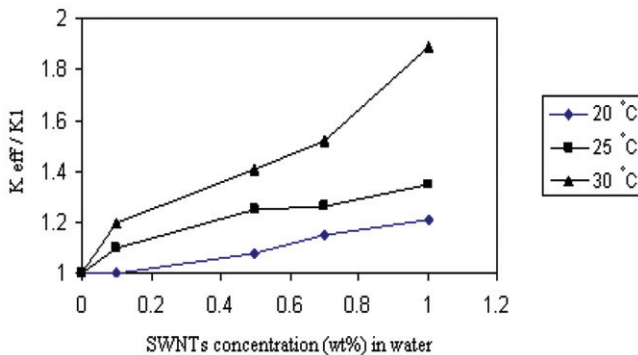


Figure 2. Thermal conductivity of SWNTs nanofluids under different conditions (SDS concentration is 1 wt% with respect to water).

Therefore, thermal conductivity and stabilisation of SWNTs–H₂O suspension at high temperature are better.

3.2. Influence of the various physical treatment techniques

The effect of various physical treatment techniques on stability and thermal conductivities of nanofluids was investigated by three methods: (1) the kind of physical treatment including the stirrer, ultrasonic bath and ultrasonic disruptor, (2) power of ultrasonication (Watt) and (3) time of ultrasonication. Physical treatment techniques based on two-step method, including stirrer, ultrasonic bath and ultrasonic disruptor were systematically tested to verify their versatility for preparing stable nanofluids. The ultrasonic wave was transferred to the test sample through water for the ultrasonic bath while it was propagated directly to the test sample from a vibrating horn for the ultrasonic disruptor. The suspensions were sonicated for 10 min for both ultrasonic bath and disruptor. There was no appreciable change in suspended particle morphology for more than 20 min sonication. To see the effect of physical treatment on the suspended particle morphology, we performed SEM analysis for two-step method-assisted SWNTs nanoparticles in DI-water nanofluids as seen in Figure 4. After using the stirrer, there was no appreciable change in particle morphology (Figure 4(a)). However, after using the ultrasonic bath and ultrasonic disruptor, the size of agglomerated particles and the number of primary particles in the particle cluster was significantly decreased (Figure 4(b) and (c)). As one can see in Figure 4(c), the disruptor was found to be the most effective method to deagglomerate the SWNTs nanoparticles in the suspensions.

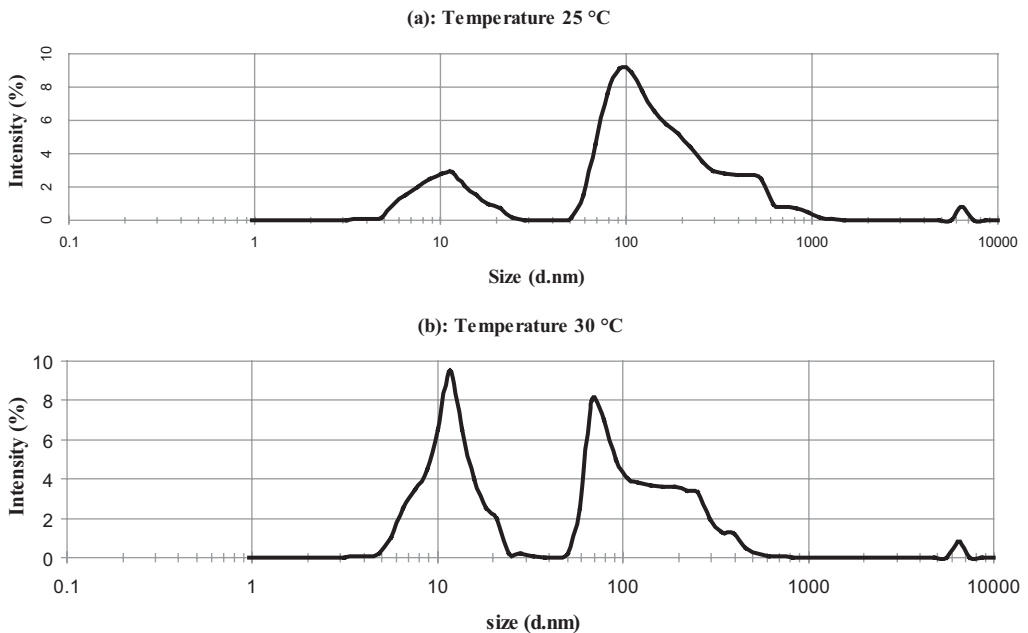


Figure 3. The particle size distributions of SWNTs–H₂O at (a) 25°C, and (b) 30°C.

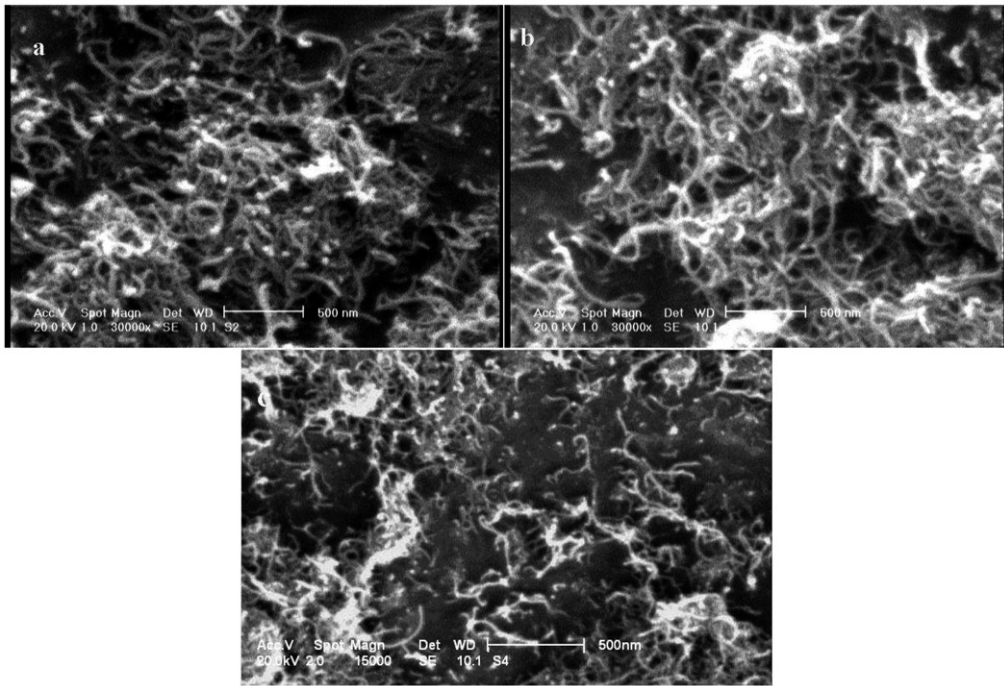


Figure 4. The SEM images of SWNTs nanoparticles in water-based nanofluids prepared by two-step methods: (a) stirrer, (b) ultrasonic bath and (c) ultrasonic disruptor (the inserted scale bar is 500 nm).

After using various physical treatment techniques including the stirrer, the ultrasonic bath and the ultrasonic disruptor the average diameter of SWNTs nanoparticles was reduced. These results indicate that the mechanical energy generated by the stirrer and bath ultrasonication was not sufficient to break down the clusters of primary particles. However, the ultrasonic disruptor was able to provide sufficient energy to deagglomerate the particle clusters with strong impaction on the nanoparticle clusters. After using various physical treatment techniques, the thermal conductivity of these samples was measured and, as indicated, the thermal conductivity of the suspensions prepared by the disruptor have better results for the above reasons (Figure 5).

The effect of various ultrasonic powers was done by two points of disruptor Watt (50 and 100 W).

To corroborate the effect of each disruptor Watt on the level of particle deagglomeration, particle size distributions for each SWNTs–H₂O nanofluid prepared by two-step methods as shown in Figure 6 were measured.

These results indicate that the low mechanical energy (50 W) generated by the ultrasonic disruptor was not sufficient to break down all the clusters of primary particles and this parameter must be optimised.

Figure 7 shows that the SWNTs suspensions prepared in 100 W have noticeably higher thermal conductivities. The reason for this increase is the aggregation of nanoparticles. When the nanoparticle clusters are exposed to ultrasonic vibrations they become more

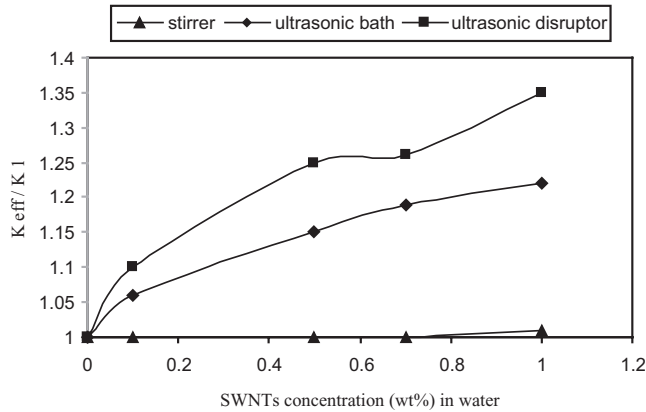


Figure 5. Effects of various ultrasonication treatment on thermal conductivity of carbon nanofluids in 25°C with SDS.

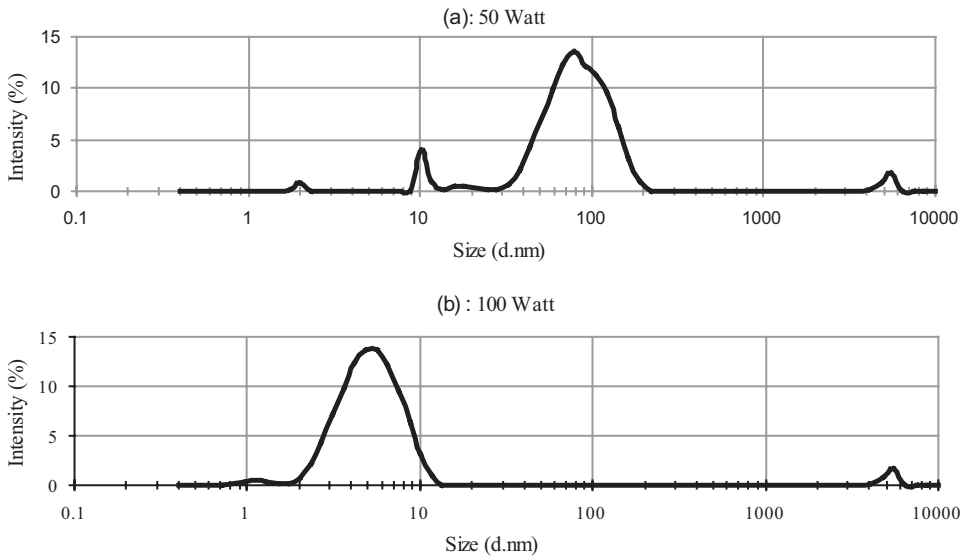


Figure 6. The particle size distributions in nanofluids as a function of the disruptor Watt: (a) 50 W and (b) 100 W.

loosely packed and/or individual nanoparticles and for the stronger disruptor Watt, the individual particles are more than the nanoparticle cluster and at higher volume fraction the thermal conductivity of the individual particles suspension increases. The effect of various disruptor times is almost similar to the disruptor Watt that was done by Amrollahi et al. in 2008 [23]. After using various physical treatment techniques, Watt and time, we put the nanofluids in the transparent glass for six months and observed if there was any precipitation at the edge and/or bottom of the test tube (Figure 8).

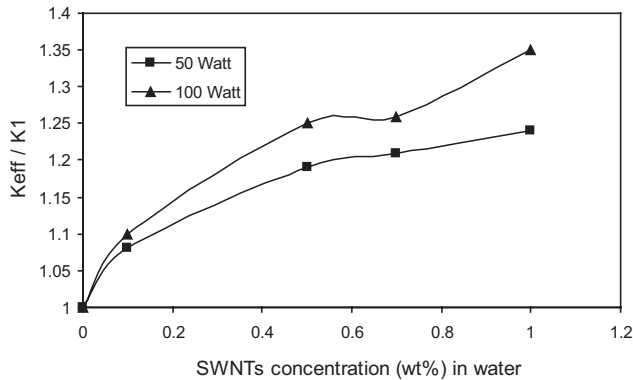


Figure 7. Effects of various disruptor Watt on thermal conductivity of carbon nanofluids.

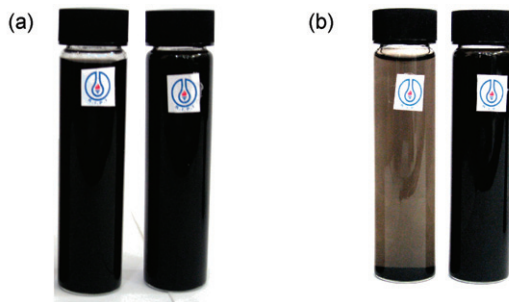


Figure 8. Sediment photographs: (a) 1 h after prepared, (b) 6 months later. Sample 1: disruptor Watt = 50 W, sample 2: disruptor Watt = 100 W. Concentration of SWNTs and GA are 0.5% (mass fraction).

After six months the thermal conductivity of these samples was measured (Figure 9) and the result shows that the thermal conductivity decreases strongly with elapsed time due to clustering of nanoparticles with time, as confirmed microscopically.

3.3. Influence of the dispersant on thermal conductivity and stability of SWNTs suspensions

It is known that SWNTs have a hydrophobic surface, which is prone to aggregation and precipitation in water in the absence of a dispersant/surfactant [24]. Lots of efforts were therefore made in the initial stage of the work to search for an appropriate dispersant. After many trial and error tests, SDS, GA, CTAB and Triton X-100 were found to be able to stabilise carbon nanotubes for more than a month without visually observable sedimentation. Triton X-100 (TX-100) can be used as nonionic surfactant, SDS as anionic dispersant and CTAB as cationic surfactant. The chemical structures of all the dispersants are shown in Figure 10.

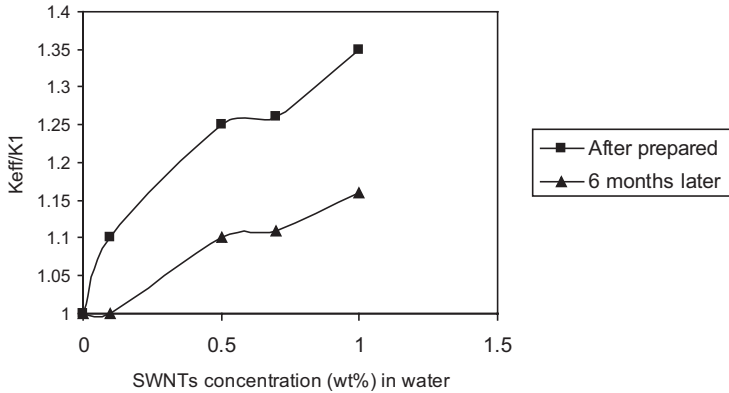


Figure 9. Thermal conductivity of SWNTs suspension after six months. Concentration of SWNTs and GA are 0.1% (mass fraction), disruptor Watt = 100 W.

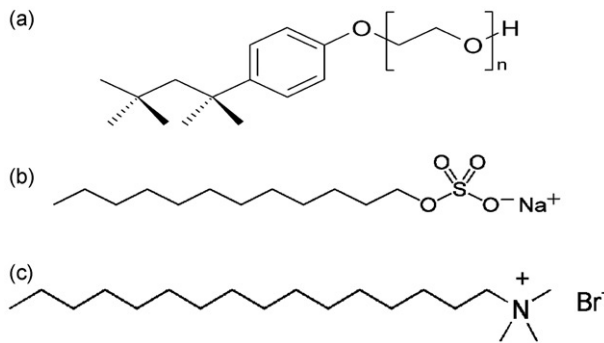


Figure 10. Chemical structure of (a) TX-100, (b) SDS, and (c) CTAB.

The results demonstrated that the application of a suitable surfactant leads to better dispersion behaviour in nanofluids, increased thermal conductivity and a change in the settling time from 24 hours to several months. It is important that we know that the thermal conductivity of functionalised SWNTs suspensions have noticeably higher thermal conductivities than the SWNTs nanofluid with these surfactants.

A well-dispersed suspension can be obtained with high-surface charge density to generate strong repulsive forces. Therefore, the study of the electrophoretic behaviour through measurement of the zeta potential becomes important for understanding the dispersion behaviour of SWNTs particles in a liquid medium. Also the results show that the zeta potential has good corresponding relation with turbidity, and that the higher the absolute value of zeta potential and the absorbency are, the better the dispersion and stability in the system is. Turbidity measurements have been used to characterise quantitatively colloidal stability of the dispersions. They can be applied to all base fluids, while zeta potential analysis is limited to the viscosity of base fluid. Recently, a new method which can be used to estimate the suspension concentration with increasing sediment time was introduced. The zeta potential values of SWNTs–H₂O suspensions and

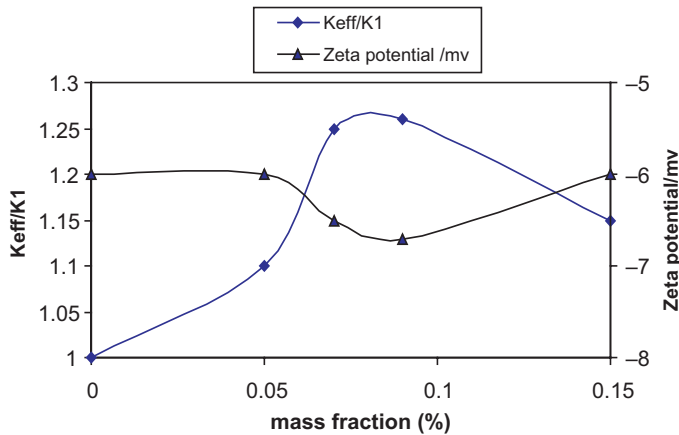


Figure 11. Effect of GA concentration on the zeta potential and thermal conductivity of SWNTs suspension (pH 9.5). The concentrations of SWNT and GA for the measurement of zeta potential are 0.05% (mass fraction).

turbidity with different dispersants at the optimised pH values for each surfactant are presented in Figures 11–19. According to the zeta potential values of suspensions or turbidity (Table 1), pH 9.5 for GA, pH 8.5–9.0 for SDS, pH 9.5 for TX-100 and pH 10 for CTAB can be selected as an operating pH, because, at these pH, the absolute values of zeta potential are higher: $\xi_{\text{SWNT(GA)}} = -10.3 \text{ mV}$, $\xi_{\text{SWNT(SDS)}} = -45.5 \text{ mV}$, and $\xi_{\text{SWNT(TX-100)}} = -8.6 \text{ mV}$, $\xi_{\text{SWNT(CATB)}} = 25.1 \text{ mV}$, respectively.

Figure 11 shows the zeta potentials and thermal conductivity of the SWNTs suspensions as a function of surfactant concentration with GA at pH=9.5. These suspensions were prepared with the ultrasonic disruptor at 100 W. The measured zeta potential of the SWNTs suspended in water without surfactant prepared by the ultrasonic disruptor was found to be -7 mV at pH 9.5. However, with the simple addition of the GA (0.5 wt%), the zeta potential of the SWNTs fluid was reduced to -10 mV at the same pH level of 9.5 and also at this point the thermal conductivity is higher. This indicates that the addition of GA in SWNTs nanofluids presumably results in strong electrostatic repulsion between the SWNTs nanoparticles, and that it promotes the stabilisation of the SWNTs nanofluids. As explained in Section 3.4, the zeta potential of SWNTs suspension was decreased with increasing pH value and this increase is higher in SDS suspension. However, with the controlled-amount addition of GA or SDS, the zeta potential of the SWNTs suspension remained at a relatively low negative charge range regardless of pH value, indicating that the hydrophilic segment of the GA or SDS added was presumably negatively ionised in the broad pH ranges. In the other words these two parameters (pH and concentration of surfactant) interact in the thermal conductivity and stability of nanofluids.

Figure 14 shows the zeta potentials of the SWNTs suspensions and thermal conductivity as a function of surfactant concentration with SDS at pH=8.5. The measured zeta potential of the SWNTs suspended in water without surfactant prepared by the ultrasonic disruptor was found to be -2.1 mV at pH 8.5. However, with the simple addition of the SDS (0.07 wt%), the zeta potential of the SWNTs fluid was significantly

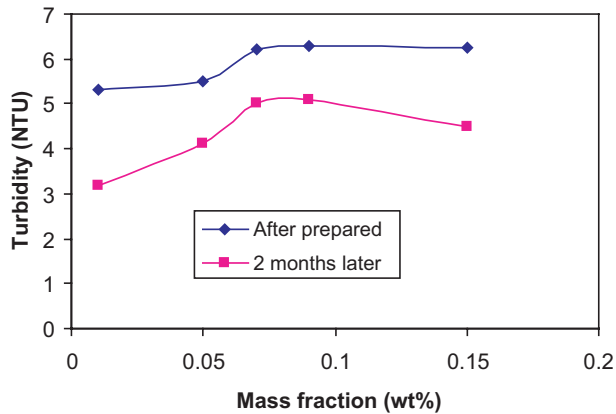


Figure 12. Effect of time on turbidity of SWNT-H₂O suspensions.

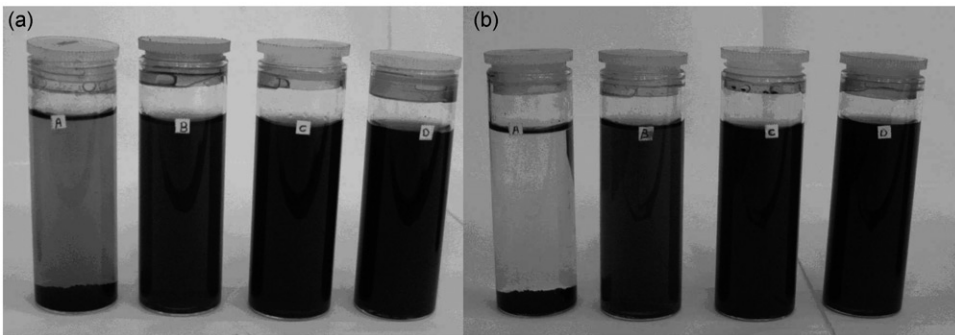


Figure 13. Sediment photographs vs. GA concentration (0.03, 0.05, 0.1, 0.20, 0.43%, respectively) depositing for: (a) 1 h after prepared and (b) after 2 months. Concentration of SWNTs is 0.05% (mass fraction).

reduced to -45.5mV at the same pH level of 8.5. This indicates that the addition of SDS in SWNTs nanofluids presumably results in strong electrostatic repulsion between the SWNTs nanoparticles, and that it promotes the stabilisation of the SWNTs nanofluids. As explained in Section 3.4, the zeta potential of the SWNTs suspension was significantly decreased with the increasing pH value. However, with the controlled-amount addition of SDS, the zeta potential of the SWNTs suspension remained at a relatively low negative charge range regardless of pH value, indicating that the hydrophilic segment of the SDS added was presumably negatively ionised in the broad pH ranges. In other words, these two parameters (pH and concentration of surfactant) interact in the thermal conductivity and stability of nanofluids. Figure 15 shows sediment photographs that indicate that thermal conductivity and stability reduce with the time elapsed.

By the same method, for the 0.5% SWNTs suspensions, the optimising concentrations for GA, SDS, TX-100 and CTAB are 0.09, 0.07, 0.3, 0.06%, respectively, which have the best dispersion and thermal conductivity results (Figures 16–19).

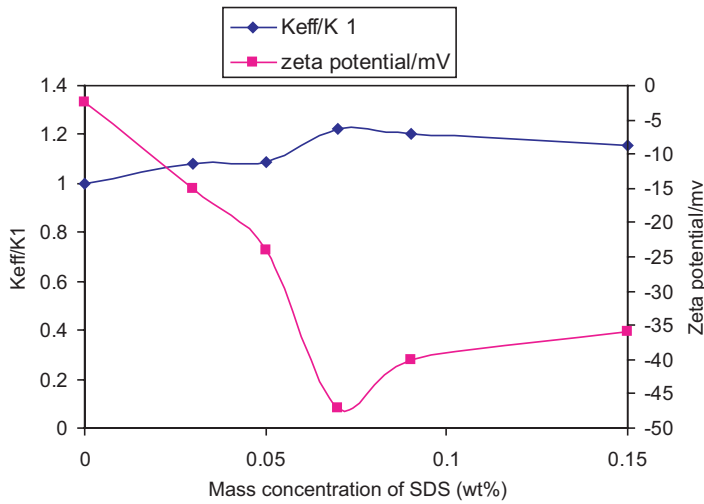


Figure 14. Effect of SDS concentration on the zeta potential and thermal conductivity of SWNTs suspension (pH 9.0). Concentration of SWNTs is 0.05% (mass fraction).

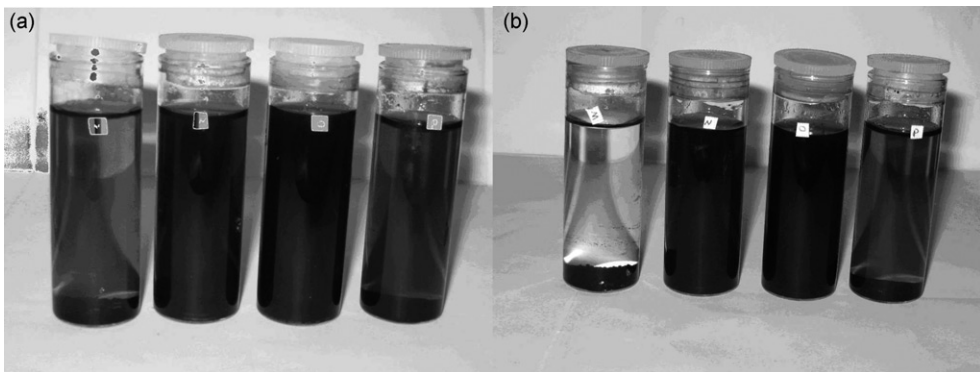


Figure 15. Sediment photographs vs. SDS concentration (0.025, 0.05, 0.07, 0.09%, respectively) depositing for: (a) 1 h after prepared and (b) after 2 months. Concentration of SWNTs is 0.05% (mass fraction).

3.4. Influence of pH on stability of SWNTs suspensions

The stability of SWNTs suspension in aqueous solution is closely related to its electrokinetic properties. Therefore, the study of the electrophoretic behaviour through measurement of the zeta potential becomes important for understanding the dispersion behaviour of SWNTs particles in a liquid medium [25]. Figure 20 shows the change of zeta potential for SWNTs–H₂O suspensions with GA dispersant as a function of pH. According to the zeta potential values of SWNTs suspension, pH 8.0–9.0 can be selected as an operating pH for the suspensions with GA dispersants because, in the pH, the absolute values of zeta potential for suspensions with GA dispersants is higher

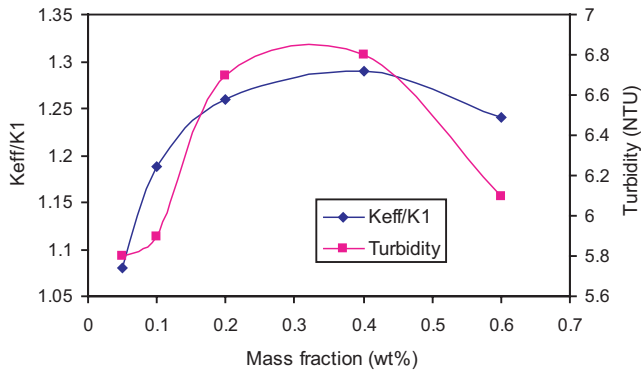


Figure 16. Effect of TX-100 concentration on the zeta potential and turbidity (pH 9.5). Concentration of SWNTs and TX-100 for the measurement of zeta potential is 0.05% (mass fraction).

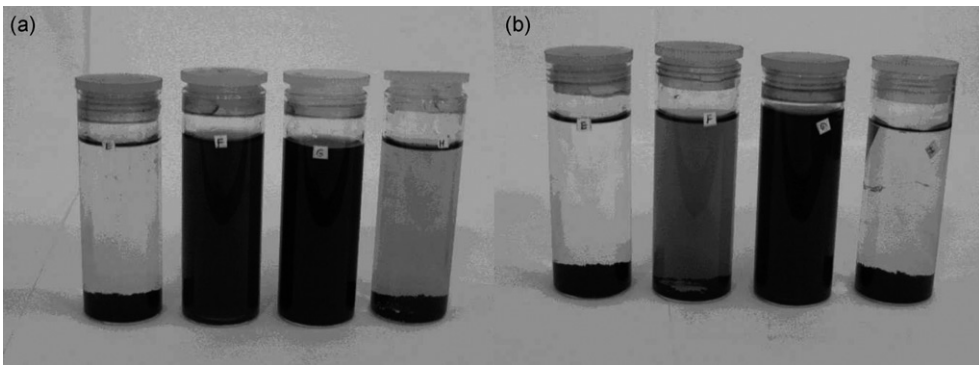


Figure 17. Sediment photographs vs. TX-100 concentration (0.05, 0.1, 0.20, 0.4%, respectively) depositing for: (a) 1 h after prepared and (b) after 2 months. Concentration of SWNTs is 0.05% (mass fraction).

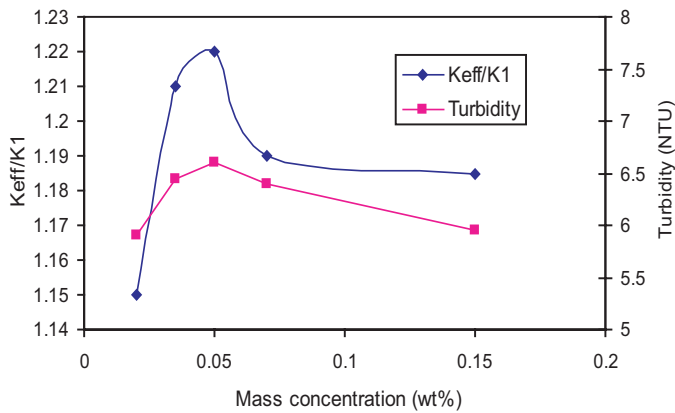


Figure 18. Effect of CTAB concentration on the zeta potential and turbidity (pH 9.0). Concentration of SWNTs is 0.05% (mass fraction).

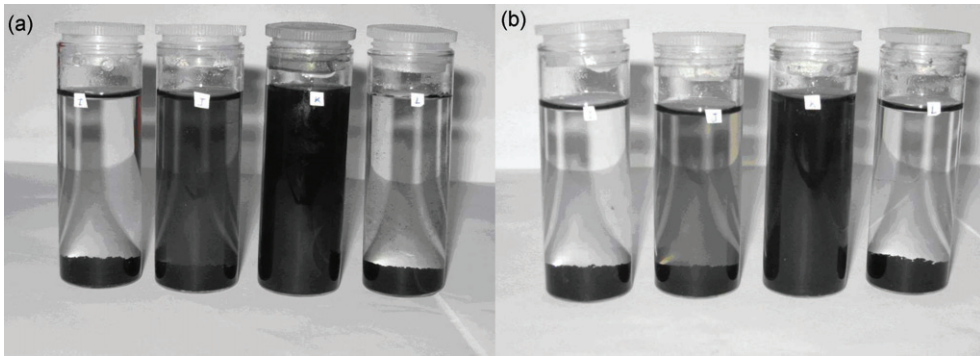


Figure 19. Sediment photographs vs. CTAB concentration (0.02, 0.035, 0.05, 0.07%, respectively) depositing for: (a) 1 h after prepared and (b) after 2 months. Concentration of SWNTs is 0.05% (mass fraction).

Table 1. Zeta potential and operation pH for different surfactants.

	GA	SDS	TX-100	CTAB
Operation pH	9.5	8.5–9	9	10
Zeta potential	−10.3	−45.5	−8.6	25.1

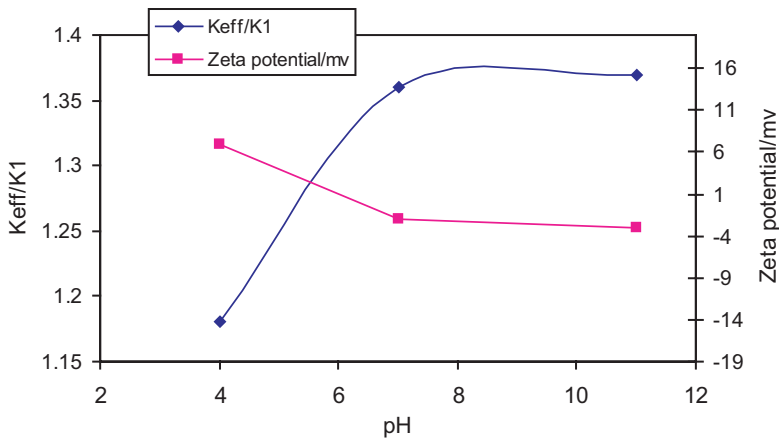


Figure 20. Effect of pH on thermal conductivity and zeta potential of SWNTs–H₂O suspensions. Concentration of SWNTs and dispersants are 0.5% (mass fraction).

(SWNTs–GA/H₂O = −3 mV). Also, the thermal conductivity values of SWNTs–H₂O suspensions with GA dispersants at different pH values are presented in Figure 20.

The results show that the pH of the nanofluid strongly affects the thermal conductivity of the suspension. As the pH of the nanofluid increases, the surface charge increases because of more frequent attacks to the SWNTs surface with surfactant, and the colloidal

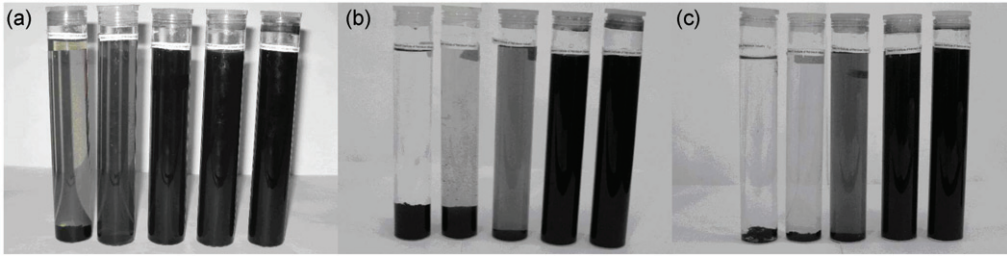


Figure 21. Sediment photographs vs. pH value depositing for (a) 1 h, (b) 2 months, and (c) 6 months. Concentration of SWNTs and GA are 0.5% (mass fraction).

particles get more stable and eventually alter the thermal conductivity of the fluid. Strong acid treatments could give rise to stability of SWNTs, but damage their structure and decrease their thermal stability. This indicates that the increase in pH SWNTs nanofluids is presumably resulted in the strong electrostatic repulsion between the SWNTs nanoparticles and it promotes the stabilisation of the SWNTs nanofluids. In this way, we can infer that there are more surface charges at pH 8.0–9.0, at which the thermal conductivity is higher.

To gain insight into the effects of the pH on the SWNTs suspension stability, their dispersity in solvents is investigated. Water of different pH includes 4, 7, and 11. Figure 21 presents the solubility observations in deionised water after several periods of time. In Figure 21, SWNTs suspension can be seen to precipitate from the deionised water at 30 min after a 30-min sonication and exhibit more precipitate 1 week later, although the precipitate appears to be swollen.

As indicated in Figure 21, thermal conductivity and stability decrease with increased time regardless of pH value.

4. Conclusions

This research presents the dispersion behaviours and thermal conductivity of SWNTs nanofluid under different temperatures, concentrations, various physical treatments, pH values and different dispersant and their concentration. The key conclusions can be summarised as follows:

- Zeta potential and absorbency are important bases for selecting conditions for dispersing particles. There is a good correlation with turbidity.
- SWNTs suspensions by two-step method were prepared. The particle size distribution shows better dispersion behaviour in suspensions with the addition of dispersant.
- Thermal conductivity and stabilisation of SWNTs–H₂O suspensions with high temperature and high concentration (by good stability) are better.
- To get stable nanofluids, one should employ the high energy assisted deagglomeration process of particle clusters dispersed in a base fluid with suitable surfactants. In this work, we have systematically tested the effect of various physical dispersing methods, pH and suitable surfactant on dispersity and

stability of nanoparticles in nanofluids, which may provide useful guidelines for choosing a suitable method to prepare stable nanofluids in various nanofluid-based applications.

- Among the two-step methods, the most stable nanofluid was prepared by the ultrasonic disruptor. It is believed that the highly agglomerated nanoparticles were able to be easily broken by the combination of strong shear force and cavitation generated by the h disruptor.
- The effect of pH on the stability of the SWNTs suspension was critical. At pH 8.0, a good dispersion of SWNTs particles was obtained which is attributed to charge build-up on the surface of SWNTs particles due to addition of SDS dispersants. As the pH of the nanofluid increases, the surface charge increases and the colloidal particles get more stable and eventually alter the thermal conductivity of the fluid. In this way, we can infer that there are more surface charges at pH 8.0–9.0, at which levels the thermal conductivity is higher.
- The GA dispersants can significantly increase the absolute value of zeta potential of particle surfaces by electrostatic repulsions, which lead to the enhancement of the stability for SWNTs suspensions. In the 0.5 wt% nano-suspensions, the optimising concentration for GA is 0.10 wt%, which has the best dispersion results.
- The use of SWNTs as the dispersed phase in water can significantly enhance the thermal conductivity, and the enhancement increases with particle concentration under the conditions of this work. The maximum thermal conductivity enhancements of up to 35% are observed at the 0.5 wt% suspension.
- The thermal conductivity can be improved by adding optimising GA and SDS dispersant.

However, the combined treatment with both pH and chemical dispersant is recommended to improve the thermal conductivity.

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