

Thermal conductivity and viscosity of deionised water and ethylene glycol-based nanofluids

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ABSTRACT

This paper focused on thermal conductivity and viscosity of deionised water and ethylene glycol-based nanofluids at three different temperatures (6°C, 25°C and 40°C). For the preparation of nanofluids, a two-step method, comprised of homogenisation and sonication, was used on a mixture of MWCNT-OH, PVP and the base fluid. The results revealed that thermal conductivity was enhanced by about 8.86% for 0.8 wt% deionised water-based MWCNT-OH nanofluid, and by 5.37% for 0.2 wt% ethylene glycol-based MWCNT-OH nanofluid. Meanwhile, in viscosity test, the highest temperature of 40°C exhibited lowest viscosity. This phenomenon happened only with ethylene glycol-based nanofluid, whilst the data on the viscosity of deionised water-based nanofluid was inconsistent at certain nanofluid concentrations. In conclusion, addition of MWCNT-OH into base fluid enhanced base fluid performance, giving it the potential to be used in cooling system applications.

Keywords: Nanofluids; thermal conductivity; viscosity.

INTRODUCTION

Developments in science and technology have led to the discovery of nanofluids as part of “Nanotechnology”. This term was used in 1974 by a Japanese scientist, Norio Taniguchi [1]. A nanofluid is generally understood to mean a suspension of nano-sized particles having diameter of about 1 nm to 100 nm in a conventional base fluid [2-4]. The beauty of nanofluid is that it can improve or enhance thermo-physical properties such as thermal conductivity, thermal diffusivity, viscosity and convective heat transfer coefficient [5-10]. Nanofluids are generally classified into two categories, namely metallic nanofluids (aluminium, copper, nickel, etc.) and non-metallic nanofluids (metal oxides, CNT, graphene, etc.) [1, 5, 11]. Meanwhile, the conventional base fluids used are water, organic liquids (ethylene glycol, oil, biological liquids, etc.), and polymer solutions, where it is commonly used in cooling system applications. However, the use of conventional base fluids has its limitations in terms of thermo-physical properties [5].

Thus, the introduction of CNTs mixed with base fluid is believed to enhance thermo-physical properties. To date, researchers have reported that CNTs have extremely energising physicochemical properties. For example, CNTs have high aspect ratio, ultra-light weight, high mechanical strength, high electrical conductivity, high thermal conductivity and high surface area as compared to other types of metallic or oxide nanoparticles [12-14]. Literature on thermal conductivity has highlighted that the addition of nanoparticles, such as Al_2Cu and Ag_2Al , at concentrations of 0.2 vol% to 1.5 vol% to ethylene glycol and deionised water has resulted in an enhancement of about 50% to 150% higher than that of standard base fluid, whereas enhancement of 12.7% at 1.0 vol% of CNT was reported for ethylene glycol-based nanofluids [2, 9, 15-18]. Studies conducted by researchers have found that the inclusion of a surfactant in nanofluids influences effective thermal conductivity, where enhancement was about 22.2% at 0.5 wt% of CNT and 0.01 wt% of PVP [19]. In addition, thermal conductivity value of CNT was between 1800 W/m.K to 2000 W/m.K [20]. Thermal conductivity of nanofluids increases if sonication time is longer, but the reverse occurs with viscosity. Viscosity of nanofluids increases when sonication time is shorter [21]. A novel study in a previous research stated that viscosity of nanofluids is also affected by temperature, particle size, and concentration of nanoparticles [5]. In previous research, increase in viscosity was about 60% at 5% volume concentration of Al_2O_3 -water nanofluid and enhancement in viscosity was 90% in a 5% volume fraction of nanofluid as compared to common heat transfer fluids [22].

Stability is always crucial in CNT nanofluids synthesis. This is due to the hydrophobic nature of CNTs, which have higher tendency to agglomerate in conventional fluids [23-28]. Stability is the main factor that contributes to thermo-physical performance [29]. An efficient way to solve this problem is to add a surfactant for better dispersion and prevent agglomeration [1, 15, 30]. However, agglomeration of nanoparticles is also temperature-dependant. More particles agglomerate at low temperatures than at higher temperatures due to surface energy of particles [31]. Therefore, in this work, thermal conductivity and viscosity of ethylene glycol and deionised water-based nanofluids, with the inclusion of hydroxyl functionalized multiwalled carbon nanotubes (MWCNT-OH), were investigated at three different temperatures (6°C, 25°C and 40°C). The concentration of the MWCNT-OH ranged from 0.1 wt% to 1.0 wt%.

METHODS AND MATERIALS

Selection of Material

The hydroxyl functionalised multiwalled carbon nanotube (MWCNT-OH) nanoparticles were purchased from Nanostructured & Amorphous Materials, Inc., and properties of MWCNT-OH are shown in Table 1. Meanwhile, polyvinylpyrrolidone (PVP) with a density of 1.6 g/cm³ and an average mol. wt of about 10000, which was chosen as the surfactant for nanofluids preparation, was sourced from Sigma Aldrich, Co. The base fluids used in this work were ethylene glycol and deionised water.

Preparation of MWCNT-OH Nanofluids

A two-step preparation process was used for the synthesis of the ethylene glycol and deionised water-based MWCNT-OH nanofluids. The preparation began with stability test, where weight percentage of MWCNT-OH used was 1.0 wt% and weight percentages for the PVP were 0.1 wt% and 0.2 wt%. The purpose of this procedure was to choose a

suitable weight percentage of PVP that can provide stability to nanofluids. The most stable nanofluids that do not have any sedimentation or agglomeration can provide the best results in a thermo-physical test. According to previous research, PVP acts as dispersant agent, and the use of PVP in nanofluids formulation can increase stability thus overcome agglomeration of solid particles nanofluids [1, 19]. Meanwhile, a vital process that can maintain particles dispersion and stability of nanofluids for a long period of more than 100 hours is ultrasonication process. The amount of sediment particles in nanofluids decreases when they go through an ultrasonication process [32].

Table 1. Properties of MWCNT-OH.

CNT properties	Specification
Outer diameter	10-30 nm
Inner diameter	5-10 nm
Length	10-30 μm
Purity	> 90%
Density	2.1 g/cm^3
Surface area	40-300 cm^2/g
Melting point	3652-3697 $^{\circ}\text{C}$



Figure 1. Steps used in the preparation of nanofluids (a) homogenisation process; (b) sonication process; (c) stability process.

In this study, mixtures of MWCNT-OH, PVP and base fluids were homogenised at three different times (0 minute., 5 minutes. and 15 minutes.) by using Wise Tis HG-15D homogeniser at 10000 rpm as shown in Figure 1 (a) and sonicated at 50 kHz to 60 kHz using Elma Schmidbauer GmbH ultrasonicator, as shown in Figure 1 (b). The reason for varying time for the dispersion process was to determine the best time for dispersion in order to provide better stability to nanofluids. The mixtures were controlled at $\text{pH} \pm 9$ at room temperature. Next, mixtures were monitored for more than 100 hours to ensure dispersion and stability of nanofluids. A stability test rig (STR) was used to test stability of mixtures or samples, as shown in Figure 1 (c) [33], and the micrograph of nanoparticles dispersion in base fluid was captured at 10K magnification using ZEISS inverted microscope. Hence, the stable sample in stability test was used as reference in the next preparation of nanofluids. Weight percentages of MWCNT-OH-based nanofluids for the next samples ranged from 0.1 wt% to 1.0 wt% of MWCNT-OH. These samples were subjected to thermal conductivity and viscosity tests.

Thermo-physical Test

Thermal Conductivity Test

TC-KD2 Pro thermal properties analyser manufactured by Decagon Devices, Inc. comes aligned from the manufacturing plant and includes performance verification standards, where TC-KD2 Pro complies with ASTM D5334-14 and IEEE 442-03 standards. The device consists of a controller and a sensor. In this work, a KS-1 sensor, which is a single-needle sensor with a diameter of about 1.3 mm and a length of 6 cm, was used to measure thermal conductivity. The accuracy of this sensor is about ± 0.01 W/m.K. Nanofluids samples were placed in a refrigerated water bath at 6°C, 25°C and 40°C. Then, sensor was inserted in the nanofluid samples so as to take reading for thermal conductivity values. Reading was taken at three different temperatures (6°C, 25°C and 40°C), three times for each sample of MWCNT-OH-based nanofluid (0.1 wt% to 1.0 wt%), pure ethylene glycol and pure deionised water. Moreover, to avoid errors during measurement, gap between next thermal conductivity readings was about 15 minutes for each sample.

Viscosity Test

In this experiment, a DV-11+Pro viscometer with an SC4-18 spindle manufactured by Brookfield Engineering was used to measure viscosity of MWCNT-OH-based nanofluids (0.1 wt% to 1.0 wt%), pure ethylene glycol and pure deionised water at three different temperatures (6°C, 25°C and 40°C). Pipe from a refrigerated water bath was connected to the DV-11+Pro viscometer so as to control temperature, while the amount of nanofluid that was required to be inserted into the container of the viscometer until the fluid touched the spindle was about 6.7 ml. nanofluid viscosity was determined by the rotational speed of spindle and measurement was in centipoise (cP). In addition, reading for viscosity was taken three times for each sample of nanofluid at all different temperatures.

RESULT AND DISCUSSION

Stability Test

The prepared nanofluids consisted of MWCNT-OH, PVP and base fluid. Table 2 shows the composition of materials in 40 ml nanofluids. Samples were homogenised and sonicated at (0 minute, 5 minutes and 15 minutes) and stabilised for 100 hours. The dispersion of nanoparticles in base fluid was investigated in order to observe the particles agglomeration in fluid when two different weight percentages of PVP were used for dispersion process. Table 3 and Table 4 show micrograph of nanoparticles dispersion in base fluids where the homogenisation and sonication processes were run at 0 minute, 5 minutes and 15 minutes.

Table 2. Composition of the materials in 40 ml nanofluids

Sample	MWCNT-OH (wt%)	PVP (wt%)	Base fluid
NF01	0.1	0.1	Deionised water
NF02		0.2	
NF03	0.1	0.1	Ethylene glycol
NF04		0.2	

Table 3. Micrograph of nanoparticles dispersion in deionised water based nanofluids.

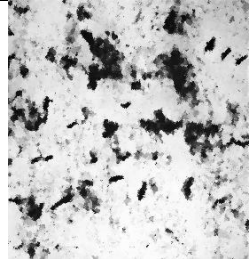
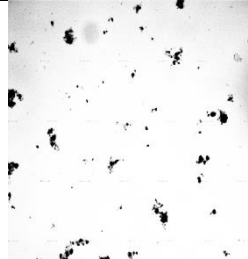
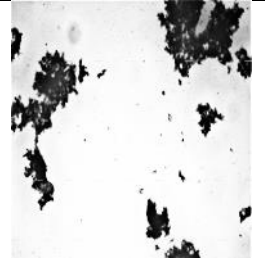
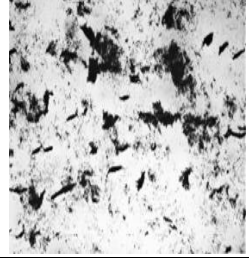
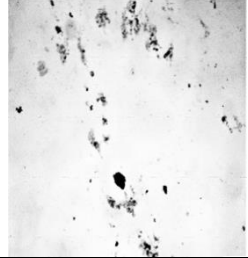

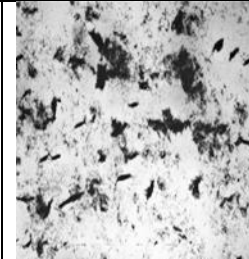

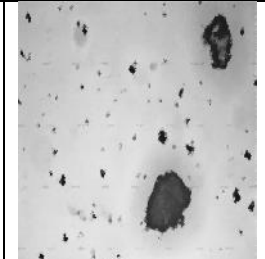
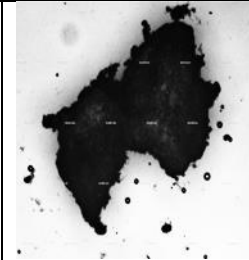
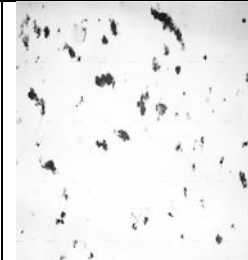
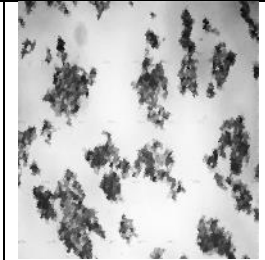
PVP (wt%)	0 minute	5 minutes	15 minutes
0.1			
0.2			

Table 4. Micrograph of nanoparticles dispersion in ethylene glycol based nanofluids.

PVP (wt%)	0 minute	5 minutes	15 minutes
0.1			
0.2			

Based on both Table 3 and Table 4, microstructure of dispersed MWCNT-OH nanoparticles in deionised water and ethylene glycol could be seen clearly at 0.1 wt% and 0.2 wt% of PVP at 0 minute which, without the sonication and homogenisation processes, had the biggest agglomeration of nanoparticles as compared to other samples of nanofluids. It was shown in this figure that at 5 minutes of dispersion, the nanoparticles in deionised water and ethylene glycol-based nanofluids had spread or dispersed well in the base fluid and there was only a slight agglomeration of nanoparticles when 0.1 wt% and 0.2 wt% of PVP were used. As a result, the nanofluids were stable. In addition, 0.1 wt% of PVP had a much better dispersion as compared to 0.2 wt% of PVP at 5 minutes of dispersion, where the size of agglomerated particles was much smaller at 0.1 wt% of PVP than at 0.2 wt% of PVP. However, the size of the agglomerated particles was bigger at 15 minutes of dispersion for both concentrations of PVP, and this caused the nanofluids

to be unstable. Hence, it was proven that sonication and homogenisation can reduce agglomeration of nanoparticles in base fluids and enable the nanofluids to attain stability [32]. However, if ultrasonication process takes too long, it can cause sedimentation in nanofluids [34]. Based on the results, 0.1 wt% PVP was chosen to be used in the next nanofluids preparation. A lower weight percentage of PVP was chosen in this study because a high weight percentage of surfactant in base fluid can decrease thermal conductivity of nanofluid [20]. Moreover, data reported here was supported by a previous research claim that 10% PVP from the weight percentage of MWCNT-OH gives an effective stability to the MWCNT-OH-based nanofluids, where the sample was tested with 0.1 wt % of MWCNT-OH and 0.01 wt % of PVP, and was proven to be stable even after one month [19].

Thermal Conductivity

Figures 2 (a) and (b) show thermal conductivities of deionised water and ethylene glycol-based nanofluids. In Figure 2 (a), the thermal conductivity for standard deionised water was 0.546 W/m.K, 0.579 W/m.K and 0.598 W/m.K at 6°C, 25°C and 40°C, respectively. At 6°C and 25°C, the highest thermal conductivities were for 0.1 wt% MWCNT-OH-based nanofluids, where the values were 0.573 W/m.K and 0.630 W/m.K, whilst at 40°C the highest value of 0.651 W/m.K was obtained for 0.8 wt% MWCNT-OH. Meanwhile, the lowest thermal conductivities for deionised water-based nanofluids were obtained for 0.6 wt% (0.551 W/m.K), 0.9 wt% (0.592 W/m.K) and 1.0 wt% (0.619 W/m.K) of MWCNT-OH for temperatures of 6°C, 25°C and 40°C, respectively. Although these nanofluid samples had the lowest thermal conductivities, these values were still enhanced as compared to the standard base fluid, where there was an enhancement of 0.9157%, 2.245% and 3.512% in thermal conductivity with the inclusion of MWCNT-OH nanoparticles in deionised water. In deionised water-based nanofluids, highest percentage of enhancement of 8.86% in thermal conductivity occurred at 40°C for 0.8 wt% MWCNT-OH. The second highest percentage of enhancement of 8.81% in thermal conductivity occurred at 25°C for 0.1 wt% MWCNT-OH. Third highest percentage of enhancement in thermal conductivity was 8.36% at 40°C for 0.1 wt% MWCNT-OH. Enhancement in thermal conductivity was calculated using Eq. (1).

Figure 2(b) shows that thermal conductivity of standard ethylene glycol increased with temperature rise. Thermal conductivity for standard ethylene glycol was 0.2180 W/m.K, 0.2310 W/m.K and 0.2450 W/m.K at 6°C, 25°C and 40°C, respectively. What stands out in the figure is that the highest thermal conductivity for each temperature was obtained for 1.0 wt% MWCNT-OH at 6°C and 0.2 wt% MWCNT-OH at both temperatures of 25°C and 40°C. The thermal conductivities were 0.2235 W/m.K, 0.2434 W/m.K and 0.2527 W/m.K. However, the lowest thermal conductivity of the nanofluids was obtained for 0.5 wt% MWCNT-OH at each of the three different temperatures. Surprisingly, for the percentage of enhancement of thermal conductivity, the highest percentage of enhancement in this study occurred for 0.2 wt% MWCNT-OH, which was about 5.37%, followed by 0.3 wt% MWCNT-OH (4.85%) at 25°C. At 40°C, the enhancement in the thermal conductivity was about 3.14% for 0.2 wt% MWCNT-OH, which ranked third in terms of thermal conductivity. In summary, findings from this experiment were different from those of previous research, where the highest thermal conductivity occurred for random concentrations of nanofluids. As can be seen in Figures 2 (a) and (b), the pattern of graphs fluctuated and was not the same as in previous research, where thermal conductivity increased with increase in concentration and temperature [35]. Certain factors might have influenced the results of this thermal conductivity test.

A study by Amrollahi et al. showed that thermal conductivity of nanofluids at 2% volume fraction of CNT fluctuates or is inconsistent with temperature rise [32].

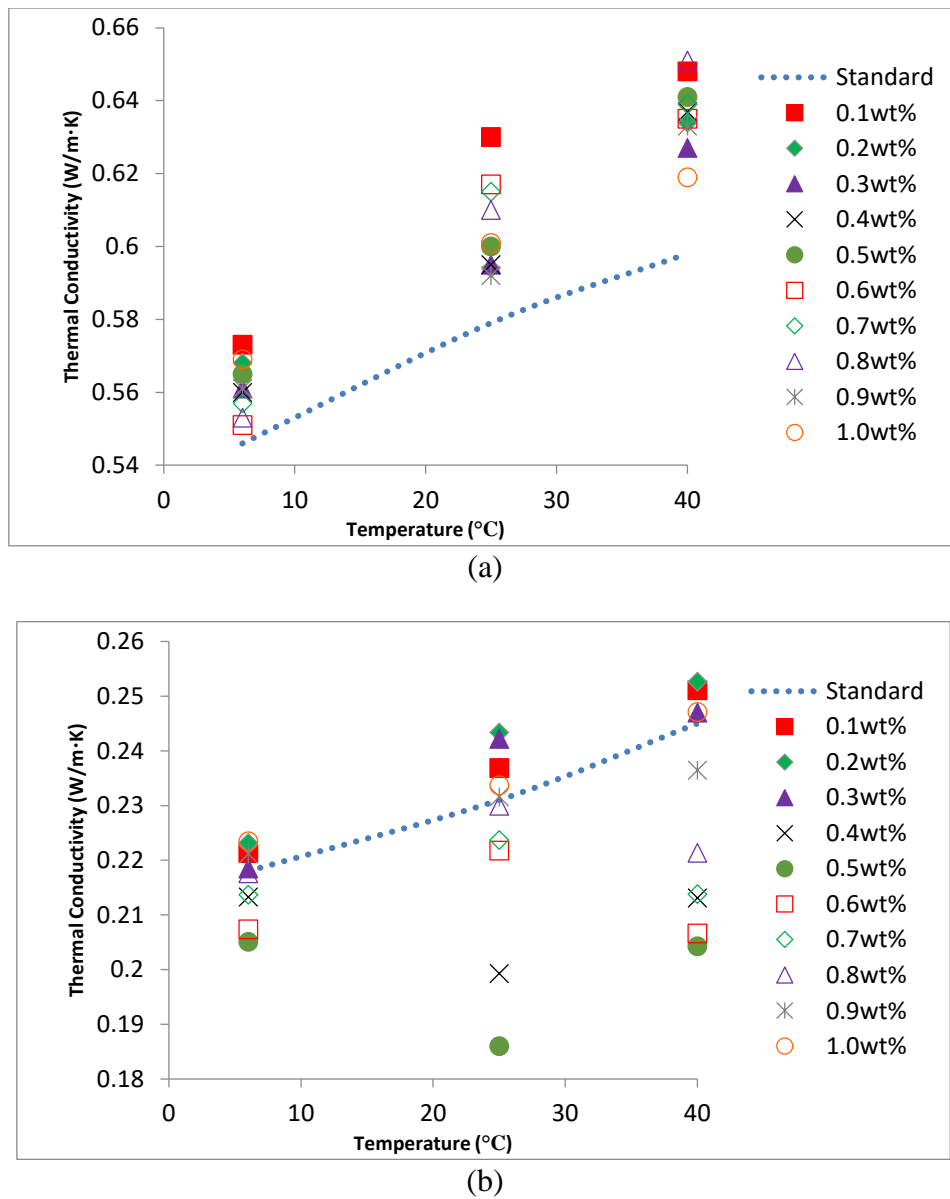


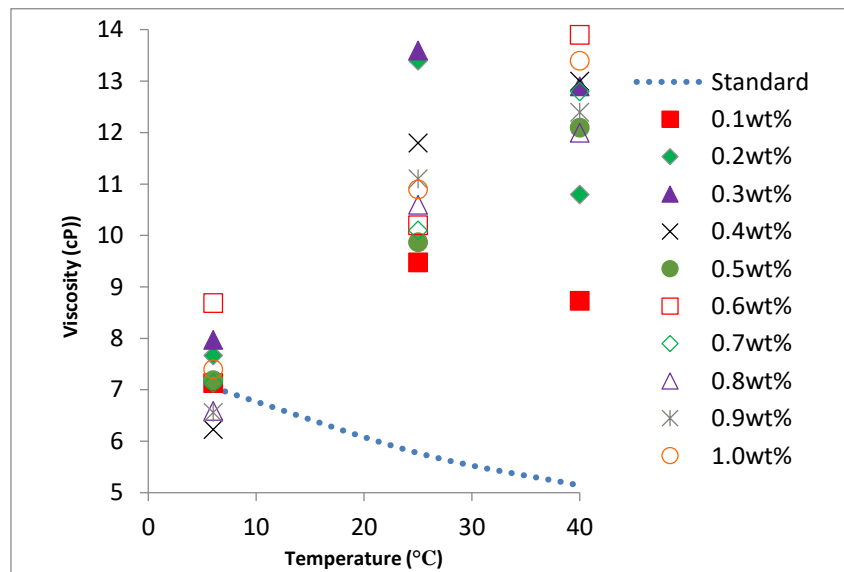
Figure 2. Thermal conductivity plots against temperature for (a) deionised water-based nanofluids; (b) ethylene glycol-based nanofluids

Thermal conductivity of an object happens through particles collision, whereby energy is transferred from one particle to another. At a higher temperature, the collisions rate is higher as the particles move at a higher average velocity. The increased rate of random collisions is known as Brownian motion. Brownian motion results in particles aggregation, which in turn causes the occurrence of thermal conduction. In addition, the Brownian motion of particles affects clustering of nanoparticles, nature of heat transport in nanoparticles themselves, and molecular level layering at the liquid-solid particle interface, which directly influences thermal conductivity. Thermal conductivity test is also influenced by human error or faulty apparatus.

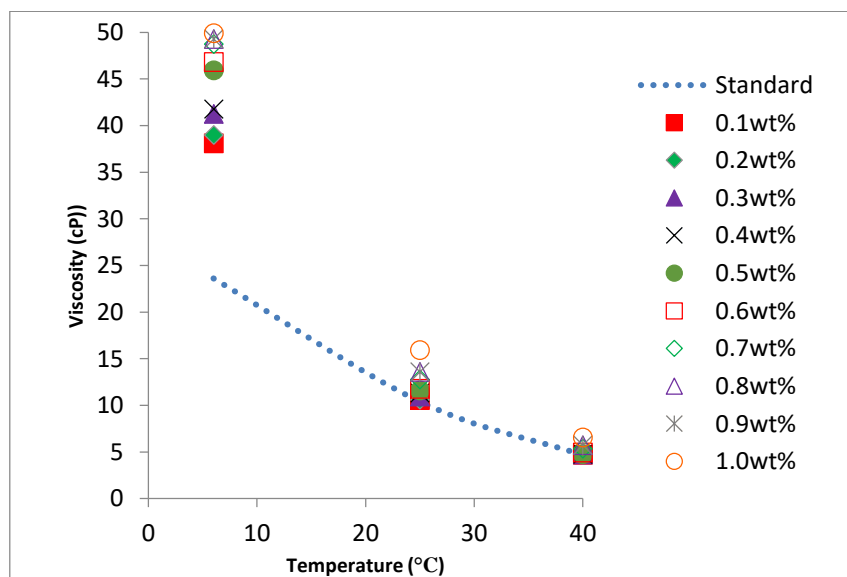
$$\% \text{ of Thermal Conductivity} = \frac{TC \text{ of Nanofluids} - TC \text{ of Base fluid}}{TC \text{ of Base fluid}} \times 100\% \quad (1)$$

Viscosity

In a nanofluid, it is preferable to keep viscosity as low as possible as a high viscosity means that the nanofluid will have a high tendency to clog and stick to the container wall, the pipes and all the parts that the nanofluid comes into contact with. Figures 3 (a) and (b) present viscosity results for deionised water-based nanofluids and ethylene glycol-based nanofluids at three different temperatures for various concentrations of MWCNT-OH ranging from 0.1 wt% to 1.0 wt%.



(a)



(b)

Figure 3. Viscosity plots against temperature for (a) deionised water-based nanofluids; (b) ethylene glycol-based nanofluids

Figure 3(a) shows that the viscosity of pure deionised water decreased with a rise in temperature, where viscosity values were 7.04 cP, 5.77 cP and 5.14 cP for 6°C, 25°C and 40°C, respectively. This natural phenomenon occurred as ions or atoms in deionised water were more active at a higher temperature and were able to break the atom or ion bonds, thereby resulting in a lower viscosity. However, the most surprising data in the viscosity test for deionised water-based nanofluids was the fluctuation in viscosity. At 6°C for 0.4 wt%, 0.8 wt% and 0.9 wt% of MWCNT-OH-based nanofluids, the viscosities of the nanofluids were lower than that of standard fluid. At 25°C, highest viscosity was obtained by 0.3 wt% MWCNT-OH (13.6 cP) and lowest viscosity was obtained by 0.1 wt% MWCNT-OH (9.48 cP). Then, at 40°C, highest viscosity was obtained by 0.6 wt% MWCNT-OH (13.9 cP) and lowest value was obtained by 0.1 wt% MWCNT-OH (8.73 cP).

A previous study found that the issue with researches into viscosity of nanofluids is that they lack systematic data and the experimental data are always antithetical [36]. A possible explanation as to why the nanofluids samples had a lower viscosity than standard deionised water, as occurred in Figure 3 (a), is that apparatus used for viscosity test was a Brookfield DV-II+ Pro Viscometer with an SC4-18 spindle. The sensitivity of the spindle is only useful for range 1.5 to 30000 cP, while viscosity of water starts only at 8 cP. Hence, it is possible that readings were close to the limits and therefore, not absolutely accurate. In 2010, Timofeeva et al. published a paper that stated the increase in nanoparticles size has tendency to reduce the viscosity of nanofluids [37]. The nanoparticle size is related to concentration of nanofluids, where highest concentration of nanofluid has the biggest nanoparticle size. Besides, for nanofluid samples, viscosity increased with temperature rise due to large excess of counter ions over the cationic surfactant solution. This in turn showed a fairly substantial increase in viscosity with a rise in temperature [38]. Thus, with reference to Figure 3 (a), the use of PVP as a surfactant in this study might have promoted the growth of wormlike micelles, which were able to increase viscosity when temperature rose. Meanwhile, Figure 3(b) shows that viscosity of pure ethylene glycol decreased with temperature rise, same as the viscosity of pure deionised water. The viscosity for pure or standard ethylene glycol was 23.6 cP, 10.4 cP and 4.68 cP for 6°C, 25°C and 40°C, respectively. Besides, viscosity for MWCNT-OH-based nanofluids showed that the highest viscosities were obtained by 1.0 wt% MWCNT-OH for various temperatures, namely 49.93 cP (6°C), 15.93 cP (25°C) and 6.56 cP (40°C). It was observed in Figure 3 (b) that viscosity of MWCNT-OH-based nanofluids also decreased with an increase in temperature, same as with the standard base fluid.

This result was supported by previous researches in which temperature played an important role in affecting viscosity of nanofluids, where viscosity decreased at a higher temperature [39, 40]. At higher temperatures, the particles in nanofluids become active and can cause van der Waals forces and hydrogen bonds to break, thereby decreasing viscosity. The concentration of MWCNT-OH also influenced viscosity, where viscosity increased when concentration of CNT was increased [41]. Another reason is that the different functional groups, like the hydroxyl group, that were attached to the surface of MWCNT nanoparticles were chemically linked to ethylene glycol. Thus, when nanofluids temperature was increased, chemical links between MWCNT-OH and fluids were ruined or broken, thereby prompting MWCNT-OH to settle in the fluid [5].

CONCLUSIONS

In conclusion, the stability of MWCNT-OH nanofluids with either deionised water or ethylene glycol as the base fluid is the main factor that contributes to the thermo-physical performance of nanofluids. A stable sample of deionised water-based nanofluid had the highest enhancement of thermal conductivity of 8.86% (0.8 wt% MWCNT-OH). Meanwhile, highest enhancement in thermal conductivity of 5.37% for ethylene glycol-based nanofluid occurred at 25°C for 0.2 wt% MWCNT-OH. The sonication time, temperature, nanoparticles size, Brownian motion and human error affect thermal conductivity of nanofluids. In the viscosity test, it was revealed that the higher temperature of nanofluids led to a reduction in viscosity of the nanofluids. This phenomenon occurred in ethylene glycol-based nanofluid, where nanofluid had the highest viscosity at 6°C and the lowest viscosity at 40°C. Several factors that influenced the result were temperature, concentration and chemical links of MWCNT-OH nanoparticles with base fluid. Nevertheless, in the deionised water based-nanofluid, inconsistent results were obtained due to sensitivity of the SC4-18 spindle, nanoparticles size, and the use of a surfactant. The inclusion of MWCNT-OH in base fluid changed thermo-physical properties of base fluid, thereby enhancing thermal performance of the fluid. Hence, nanofluids can be used in cooling system applications such as car radiators, air conditioning, electrical systems, etc., as a new generation of coolants. The heat transfer of nanofluids must be investigated in future studies so as to support the statement that nanofluids can emerge as powerful platforms for cooling system applications.

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