

Experimental investigation on surface tension of metal oxide–water nanofluids[☆]



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ABSTRACT

"Nanofluids", smart fluids with advanced thermal properties, have proved their promising potential in enhancing the heat transfer performance of a thermal system as well as mitigating the energy crisis of the universe. Besides all other's thermo-physical properties, surface tension governs the transport of the liquid and plays a crucial role in the heat transfer. However, the studies on the effect of surface tension on the performance of nanofluids are quite a few and demonstrated debatable results. Therefore, the present experimental study attempts to determine the surface tension of the nanofluids by dispersing Al_2O_3 , TiO_2 , and SiO_2 nanoparticles in Distilled Water (DW). The experiment was conducted by using the most common Du-Nöuy ring method in DCAT 11EC automatic surface tensiometer. In this study, the authors analyzed all the possible effects on surface tension of nanofluids with the change in concentrations (from 0.05 to 0.25 vol.%) and temperatures (from 30 °C to 50 °C), as well as the impact of various nanoparticles along with their sizes. The results indicate that the surface tension of the nanofluids increases with concentration, whereas decreases with the increase in temperature. Besides, the smaller nanoparticles exhibit lower surface tension than the larger ones. All in all, the surface tension of the nanofluids augments from 3.1% to 7.8% in compared with the base fluid for concentrations of 0.05 vol.% to 0.25 vol.% and temperatures of 30 °C to 50 °C, in all cases.

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1. Introduction

"Nanofluids" referring to a small amount of ultrafine nanoparticles (less than 100 nm) dispersed in base fluids and initially introduced by Choi et al. [1] have shown dramatic improvements of the thermo-physical properties. The collision between the molecules of liquid and nanoparticles boosts the thermo physical properties and enhances the heat transfer performance of the nanofluids [2,3]. Interfacial properties such as surface tension measure the cohesive energy in an interface, which influences the heat transfer performance of thermal system [4]. In addition, the surface tension has a crucial impact on the boiling heat transfer [5], the heat transfer performance of heat pipes and thermosyphons [6,7], enhancing the critical heat flux (CHF) [8,9], and also inducing the bubble or droplet formation [10,11]. Moreover, the surface tension determines the amount of surface free energy per unit area of the liquid droplet [12].

The surface tension is the governing factor to find the shape of a liquid droplet, which strongly influences the heat and mass transfer of a thermal system. Adding nanoparticles generates the surface roughness and affects

the transportation behavior of the liquid through the modification of surface tension as well as the surface wettability [13,14]. Additionally, the surface-tension plays an enormous role in developing anti-icing coating on the fabrics [15], enhanced oil recovery [16], cleaning the oil spills [17], and influences the soldering operation as well [18,19]. Besides, the surface tension causes the capillary actions of the working fluids in heat pipes where liquid transfers through the porous wick [20]. Further, the maximum heat transport of the heat pipe is determined by the merit number (figure of merit), which is the ratio of the product of the surface tension, the density, and the latent heat of vaporization to the viscosity of the working fluids [21]. Furthermore, nanofluids can reduce the thermal resistance as well as increases the thermal performance of the heat pipes [22,23]. However, one can confront difficulties to optimize the usage of the nanofluids in the heat transfer problems due to the insufficient studies about the surface tension of the nanofluids.

In the literature, there exists a wide range of studies about the thermo-physical properties of the nanofluids, which mostly focus on thermal conductivity, viscosity, density, and specific heat [24–27]. Nevertheless, an inadequate number of studies have been performed to measure the surface tension of the nanofluids even though, contradictory results have been reported [28]. In fact, a negligible variations were observed while measuring the surface tension of Al_2O_3 -H₂O nanofluids [5,29]. Despite these findings, Zhu et al. [30] reported that the surface tensions of the nanofluids decrease with increasing volume concentrations and

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Nomenclature

nm	nanometer
h	hour
DW	distilled water
DCAT	dynamic contact angle tensiometer

Greek symbols

σ_E	surface tension enhancement (%)
σ_{nf}	surface tension of nanofluids (mN m^{-1})
σ_{bf}	surface tension of base fluids (mN m^{-1})

Subscripts

E	enhancement
bf	base fluids
nf	nanofluids

temperatures. Using an automatic tensiometer, they stated that the surface tension of the $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$ nanofluid enhances with the increase of nanoparticle sizes. However, Murshed et al. [31] pointed out that the surface tension of $\text{TiO}_2\text{-DIW}$ (Deionized water) nanofluids reduced almost axially with the increase in temperature. Correspondingly, Radiom et al. [32] experimentally investigated $\text{TiO}_2\text{-DIW}$ nanofluids and observed that the surface tension of nanofluids mostly depends on the particle concentration showing a decreasing trend at higher concentrations.

It can be inferred that the surface tension of the nanofluids reduces with increasing temperature and concentration. However, a little bit of augmentations were mentioned by Kim et al. [14] when they studied Al_2O_3 , ZrO_2 , and SiO_2 nanoparticles dispersed in water at low concentrations. Moosavi et al. [33] also demonstrated that the surface tension ratio of ZnO/EG (Ethylene Glycol) nanofluid increases by increasing the volume fraction. Similarly, Tanvir et al. [34] found out that surface tension rises linearly by increasing both the particle concentration and size. Nonetheless, they outlined that the surface tension decreases when a surfactant is added to base fluids. Interestingly, Vafaei et al. [35] discovered that the surface tension of nanofluids exhibits ambiguous results with the increase of concentration. They found that the surface tension reaches a minimum and then again tends to rise with Bi_2Te_3 nanoparticles dispersed in aqueous solution. In a nutshell, the previous studies could not present a consistent result regarding the effect of nanoparticles on the surface tension of nanofluids since many factors affect this parameter such as: measuring methods, instruments, particle sizes, base fluids, concentrations, and temperatures. Therefore, it is imperative to measure the surface tension of the nanofluids at least in terms of concentration and temperature. The present study experimentally investigates all the possible effects on the surface tension of $\text{Al}_2\text{O}_3\text{-DW}$, $\text{TiO}_2\text{-DW}$, and $\text{SiO}_2\text{-DW}$ for 0.05 vol.% to 0.25 vol.% concentrations at a temperature range of 30 °C to 50 °C along with the variation of nanoparticles' sizes. The outcomes also were compared with the base fluid.

2. Experimental procedure

2.1. Materials and sample preparation

Preparation of the nanofluids is an important factor when measuring the surface tension of the nanofluids. The degree of nanoparticles agglomeration, sedimentation, and also a superior dispersion depends on the preparation methods. In the present study, the two step method

was applied to prepare the nanofluids with different volume fractions (0.05 vol.% to 0.25 vol.%). First, Al_2O_3 (13 nm and 50 nm), TiO_2 (21 nm) and SiO_2 (5–15 nm and 10–20 nm) nanoparticles were purchased and then dispersed in DW. Afterwards, the samples were sonicated to obtain the oxide based nanofluids. All the nanoparticles used in this study were procured from Sigma Aldrich, Malaysia and DW was produced from water distiller (W4L, Favorit, Malaysia).

To find the required volume fraction, the mass of the nanoparticles was first calculated by a digital weight gauge and then the particles were dispersed in the required amount of DW. Next, the mixture was vigorously vibrated by a mechanical shaker (an orbital incubator type) for 1 h at 150 rpm to homogenize the nanoparticles in the DW. Subsequently, an ultrasonic homogenizer was used to produce high amplitudes to break down the particle clusters. As a result, the nanoparticles were uniformly and evenly distributed in the solution. The sonication process was maintained in a series of 2-second long pulses in 2 s apart for 2 h at the frequency of 20 kHz with 50% amplitude. Moreover, the process was performed in a refrigerated circulator bath (C-DRC 8, CPT Inc., South Korea) to maintain a constant temperature (20 °C) within the mixture. The microstructure of the nanofluids was analyzed after 24 h of preparation using the Transmission Electron Microscopy (TEM) with 120 kV by using TEM LEO-Libra 120, made by Zeiss, Germany. Fig. 1 shows that the nanoparticles are well dispersed. However, some clusters are exhibited among the nanoparticles.

2.2. Surface tension measurement

The surface tension of the nanofluids can be measured by different methods such as Pendant drop, Du-Nouy ring, Wilhelmy plate, Capillary tube, and Bubble pressure drop methods using a manual or an automatic tensiometer [28]. In the present study, the traditional Du-Nouy ring method (DIN 53915 and ASTM-971) was used to determine the surface tension of the nanofluids by an automatic surface tensionometer (DCAT 11EC, Data Physics Instruments GmbH, Germany). All the measurements were performed at atmospheric pressure. Three readings were taken for a particular solution and for the final calculations, the average value was taken. The schematic of experimental set-up of surface tension measurement is shown in Fig. 2.

The automatic tensiometer contains a high performance electrodynamic compensation balance (0.1 mg to 210 g \pm 0.01 mg) with an auto calibration function. The instruments can measure 1 to 1000 $\text{mN m}^{-1} \pm$ 0.001 mN m^{-1} . Moreover, the device uses an integrated digital thermometer with a temperature control unit for measuring the surface tension value at constant temperatures. A Du-Nouy ring RG11, (Platinum-Iridium, and Part no. 2000321) as well as 70 mm diameter sample vessel was used to measure the surface tension of the nanofluids. The instrument first identifies the surface by moving the sample vessel up to the upper surface of the liquid until the balance detects a weight difference. Then, the stage moves downward until the balance senses a maximum weight and afterwards up again to the defined immersion depth. The up-down, moving cycle continues until reaching the maximum number of cycles to measure the surface tension. SCAT 31 software is used to collect the values of surface tension.

The surface tension measurement of the base fluid (distilled water) at different temperatures was shown in Fig. 3. The results exhibit a similar trend to that of presented by Murshed et al. [31]. The deviation between the two measurements is about 1.34%. The change in the surface tension was measured for different nanoparticles at various volume fractions and temperatures. The enhancement in surface tension is calculated in Eq. (1).

$$\sigma_E = \frac{\sigma_{nf} - \sigma_{bf}}{\sigma_{bf}} \times 100\%. \quad (1)$$

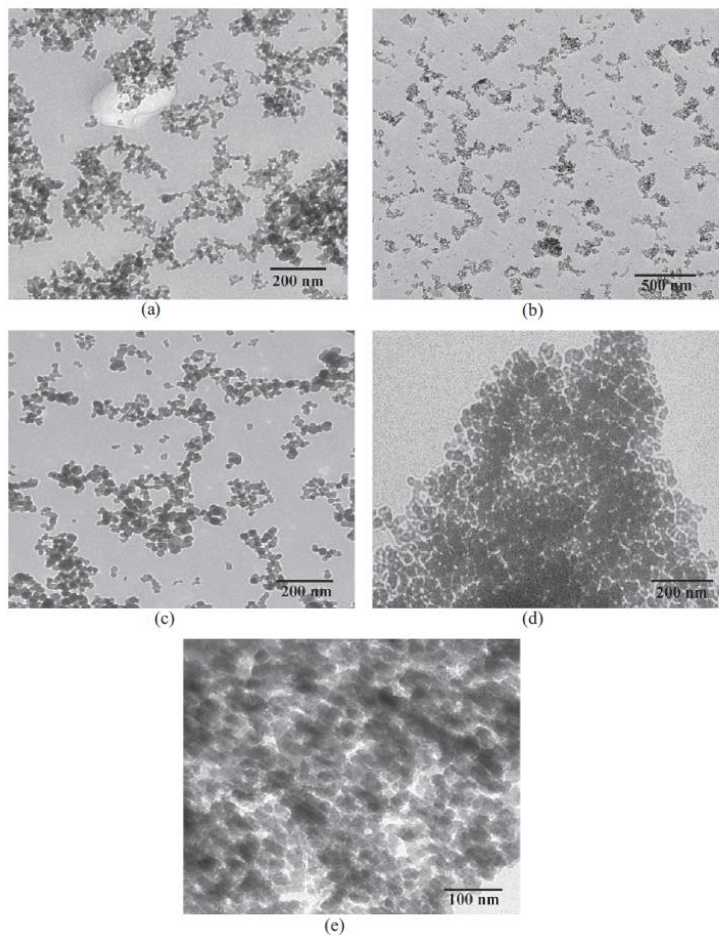


Fig. 1. TEM image of a) Al₂O₃ (13 nm) b) Al₂O₃ (50 nm) c) TiO₂ (21 nm) d) SiO₂ (5–15 nm) and e) SiO₂ (10–20 nm) nanoparticles dispersed in DW.

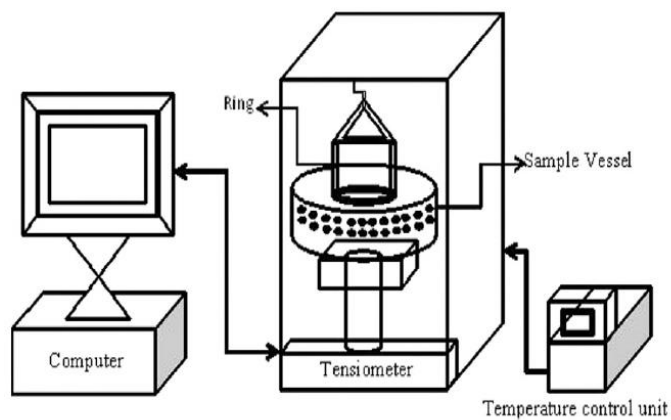


Fig. 2. Schematic of surface tension measurement.

3. Results and discussion

3.1. Effect of concentration on the surface tension of the nanofluids

The effect of change in volume concentrations (from 0.05 to 0.25 vol.%) on the surface tension of the nanofluids have been shown in Figs. 4–8. The results clearly indicate that the value of the surface tension of the nanofluids increases with the increase in nanoparticle volume fractions. For example, in Fig. 4, surface tension of Al_2O_3 (13 nm)–DW nanofluids varies from 71.39 mN m^{-1} to 71.94 mN m^{-1} for the concentrations of 0.05 to 0.25 vol.% at 30°C . The similar trends are also observed for other temperatures. In a similar way, Figs. 5–8 exhibit that the surface tension of Al_2O_3 (50 nm)–DW, TiO_2 (21 nm)–DW, and SiO_2 (5–15 nm and 10–20 nm)–DW nanofluids rise with the increase in concentrations. The results correspond to those from the experimental studies of Godson et al. [36] and Tanvir et al. [34]. However, a small amount of the surface tension variation observed at lower concentrations (up to 0.1 vol.%) of the nanofluids. This outcome is also consistent with the conclusion made by Kim et al. [14] and Golubovic et al. [29].

According to the findings in the present study, at higher concentrations, the amount of nanoparticles increases in the solution. Hence, more nanoparticles accumulate into the liquid surface, and trying to be close with each other. Therefore, a strong, cohesive force is exerted between the liquid molecules that increases the surface free energy and resulting a higher surface tension [34]. Moreover, when the concentration of the nanoparticles increases, the surface to volume ratio increases. Thus, an attractive Van der Waals force is employed over the electrostatic repulsion forces, which consequently increases the surface energy, and therefore, the surface tension of the nanofluids increases accordingly [35]. However, a slight change of surface tension is observed at lower concentrations due to the distance between nanoparticles and the liquid molecules are longer compared to the case of higher concentrations. Further, a dilute suspension has less influence on the surface free energy resulting in an insignificant change in surface tension. On the other hand, the particle concentration increases, more particles agglomerate in the liquid surface and the attractive forces increase between the particles and molecules, which intensify the surface tension of the nanofluids.

3.2. Effect of temperature on the surface tension of the nanofluids

In addition to the concentration variations, the temperature of the nanofluids also influences the surface tension of the nanofluids. The relationship between the surface tension of the nanofluids and the change

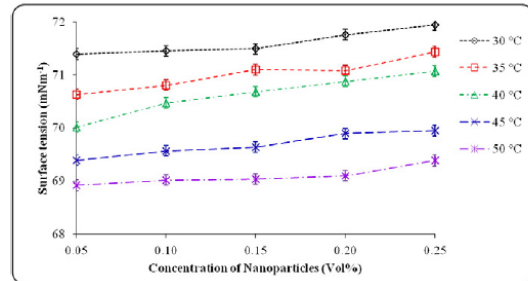


Fig. 4. Surface tension of Al_2O_3 (13 nm)–DW nanofluids as a function of volume concentration.

in temperature has been plotted in Figs. 9–13. The results show a remarkable change of surface tension with the variation of temperatures (from 30°C to 50°C) at a constant concentration. Besides, the results, distinctly reflect that the surface tension of nanofluids reduces almost linearly with the increase in temperature. The outcomes are also in concordance with the experimental studies of Godson et al. [36] and Murshed et al. [31]. For instance, in Fig. 9, the surface tension of Al_2O_3 (13 nm)–DW nanofluid dropped from 71.39 mN m^{-1} to 68.92 mN m^{-1} at 0.05 vol.% concentration for a 20°C temperature difference. Correspondingly, the decreasing trends have been also shown for other nanofluids in Figs. 10–13. Therefore, the change in temperature has an extensive effect on the surface tension of nanofluids.

The reason behind this phenomenon is that when the temperature of the nanofluids increases, the liquid molecules own a higher kinetic energy. As a result, the molecules are expanded vastly, weakening the intermolecular forces, and hence reducing the surface tension of the colloid. Moreover, the densities of the liquid molecules decrease with the increase in the temperature, which leads to the reduction of the shearing forces in liquid layers causing the surface tension to decrease. Furthermore, at higher temperatures, the Brownian motion is built-up in the liquid molecules, which lowers the cohesive energy and accordingly drops the surface tension of the nanofluids [31].

3.3. Effect of different types of nanoparticles and their sizes on the surface tension

Aside from the effect of concentration and temperature variations, type of nanoparticles and their sizes also affect the surface tension.

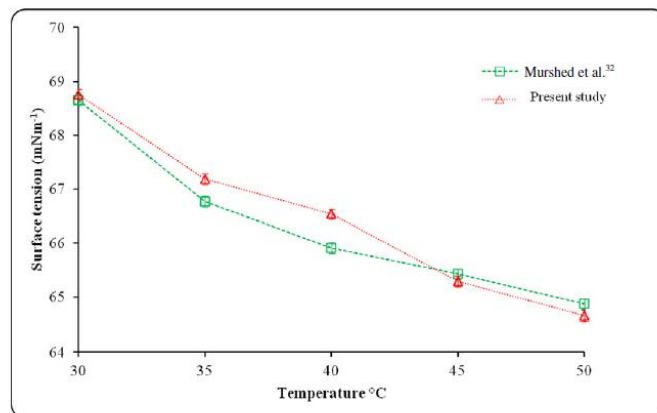


Fig. 3. Surface tension of water as a function of temperature.

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