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Effects of surfactant on stability and thermo-physical properties of metal oxide nanofluids

M.A. Khairul¹, Kalpit Shah¹, Elham Doroodchi², Reza Azizian³, Behdad Moghtaderi^{1,}*

¹Priority Research Centre for Frontier Energy Technologies and Utilisation, Chemical Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia.

²Center for Advanced Particle Processing, Chemical Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia.

³Nuclear Science and Engineering Department, Massachusetts Institute of Technology (MIT), 77 Massachusetts Ave., Cambridge 02139, MA, USA.

ABSTRACT

Optimal thermo-physical properties of nanofluids provide an opportunity to overcome energy associated difficulties, in addition to providing new alternatives to catch, store and exchange of energy. A significant reduction in energy consumption is possible by improving the performance of a heat exchanger circuit, and may in part alleviate current energy related challenging issues such as global warming, climate change, and the fuel crisis. The objective of this work is to gain an insight into the overall stability of nanofluids with respect to pH, zeta potential, particle size distribution, and its effect on viscosity and thermal conductivity. For the purpose of this study two nanofluids were selected (water based alumina and copper oxide). Various nanoparticles concentrations as well as anionic surfactants (sodium dodecylbenzene sulfonate) were investigated for their stability, viscosity as well as thermal conductivity. The results clearly showed that nanofluid stability has a strong relation with viscosity and thermal conductivity. The stability of the nanofluid was found to be improved with a decrease in viscosity and an increase in thermal conductivity.

*Corresponding author: Tel: +61 2 4033-9062, Fax: +61 2 4033-9095
Email: Behdad.Moghtaderi@newcastle.edu.au (Attn: Professor Behdad Moghtaderi)

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1. Introduction

Cooling is one of the most important scientific challenges in production related industries, such as, transportation, manufacturing and microelectronics. Technological advancements have led to increase in thermal load and thus, improvements to cooling systems have become a necessity. Maximising the surface area of heated surface and increasing the coolant flow rate are the conventional approaches for enhancing heat dissipation. However, these methods lead to an undesirable increase in the size and cost of thermal management systems. Thus, there is an urgency for an alternative coolants with an enhanced thermal performance. One such coolant is the innovative concept of ‘nanofluids’, which is a mixture of metallic/nonmetallic nanoparticles in a base fluid. The term nanofluid was originally introduced by Choi at Argonne National Laboratory [1]. A substantial difference in thermo-physical properties of the nanofluids in comparison to a basefluid, is the unique feature of the nanofluids. Apart from thermophysical properties, the relatively large overall surface area of the nanoparticles not only improves heat transfer capabilities, but also increases the stability of the suspension by alleviating particle settlement phenomenon. There are also several advantages in employing nanofluids, specifically: better long-standing stability compared to millimetre or even micrometre sized particle suspensions and lower erosion and pressure drop, especially in micro-channels.

Stability of the nanoparticles is a vital concern in nanofluid research, as achieving the long term well suspended nanofluid remains as a big challenge. Nanofluid generally is treated as a two component mixture (base fluid + nanoparticles) with no chemical reaction between these two components. In this case, the stability of the nanoparticles in a base fluid depends on various

parameters for instance [2]: (a) nanofluids are multiphase dispersion systems with high surface energy of the nanoparticles results in an overall thermodynamically unstable colloid, (b) nanoparticles dispersed in the base fluid have a strong Brownian motions. The nanoparticles' movement can offset their sedimentation due to gravity, (c) the dispersed nanoparticles in the base fluid may settle out with time because of nanoparticle aggregation, which is initiated by van der Waals forces. Therefore it is clear that the aggregation and sedimentation are the two critical phenomena in relation to the stability of a nanofluid which can directly affect its thermo-physical properties [3]. It is well established from the literature that the thermal developing length of some of the nanofluids is higher when compared to the pure base fluid [4]. Therefore, the increment in heat transfer, when using nanofluids, can be related to the reduced thermal boundary layer thickness because of the non-uniform distribution of viscosity and thermal conductivity resulting from Brownian motion of the nanoparticles [5]. Nanoparticle clustering is considered as a notable reason for disagreement in experimental results [6]. Though there are no universally recognised and accepted quantitative values, it is well-known that the level of clustering has an effect on the viscosity and thermal conductivity of nanofluids [7, 8]. The clustering level relies on several variables such as the addition of surfactants and tuning the value of the nanofluids' pH to allow for better dispersion, and prevent the extent of clustering [9].

Chen et al. [10] suggested that the aggregation of nanoparticles is one of the main reasons for the observed enhancement in viscosity of nanofluids when compared to the theory (i.e. the classical Einstein equation). To take into account the effect of aggregation, Chen et al. [10] proposed their model by adding an aggregation effect to the original Krieger and Dougherty [11] model. Good agreement was found between their experimental data and the proposed model. Wang et al. [9] studied the effect of aggregation and stability on heat transfer performance of

water based nanofluids through changing the pH value as well as sodium dodecylbenzene sulfonate (SDBS) surfactant concentrations. They concluded that the nanofluids stability have a direct relation to the improvement in thermal conductivity, in other words the improved surfactant behaviour was the cause for the observed enhancement in thermal conductivity.

True evaluation of nanofluid feasibility should be performed while the thermal conductivity and viscosity of nanofluid taken into account at the same time. Prasher et al. [12] have shown that if the increase in viscosity ratio (the ratio of viscosity of nanofluid to viscosity of base fluid) becomes more than four times that of a comparable increase in thermal conductivity ratio (ratio of the nanofluid thermal conductivity to the base fluid thermal conductivity), then the use of nanofluid is not economically viable due to increased pumping power. They found that this ratio is equal to two for alumina/propylene glycol (PG) nanofluids, as a result alumina-PG nanofluids may be more efficient than the base fluid for heat transfer applications. However, the cost associated with alumina/PD nanofluids and their losses need to be taken into consideration for practical applications. Venerus et al. [13] also ran a benchmark study on the viscosity behaviour of ten different nanofluids and concluded that all of the nanofluids used in their study clearly failed the qualifications of practical nanofluids proposed by Prasher et al. [12].

For implementing nanofluid in practical applications, true evaluation of thermo-physical properties of the nanofluid of interest such as pH and zeta potential, effective thermal conductivity, dynamic viscosity and particle size distribution should be analysed. A number of methods have been employed to determine the dispersion stability of nanofluids, such as a Malvern ZS Nano S analyzer (Dynamic Light Scattering) [14], UV-vis. Spectrophotometer [15], Small Angle X-ray Scattering (SAXS) [16] etc. These methods are able to determine the degree of dispersion between the initial state of the nanofluid preparation and afterwards.

A number of studies have investigated the outstanding thermo-physical properties (such as thermal conductivity, density, specific heat and viscosity etc.) of nanofluids [7, 17, 18]. However, the number of studies on the effect of zeta potential and particle size distribution on nanofluid viscosity as well as thermal conductivity is very limited in the current literature. Moreover, small attention has been given to understand the influence of anionic surfactants on pH, viscosity, thermal conductivity and stability mechanism (in terms of zeta potential and particles size distribution in base fluid) of nanofluids. As mentioned earlier, the overall effectiveness of nanofluids in heat transfer applications can be best evaluated if the enhancements in both thermal conductivity and viscosity are considered at the same time. When the real application of nanofluids is taken into consideration, two key issues emerge: settlement and erosion. Possible difficulties related to these issues need to be explored and solved prior to the commercialisation of nanofluids. It should also be noted that nanofluids may enhance the viscosity under certain conditions and this is a significant disadvantage due to the associated rise in pumping power. Keeping this in mind, the current work focuses on the investigation of nanofluids' stability and attempted to demonstrate correlations among stability features, thermal conductivity and the viscosity of nano-suspensions. In particular, surface potential is controlled by changing the weight concentrations of SDBS and nanoparticles. Afterward, the effects of SDBS and nanoparticle weight concentrations on the stability of nanofluids in terms of viscosity, thermal conductivity ratio, zeta potential and particle size distribution in base fluid is analysed. The alumina and copper oxide nanoparticles have been selected for the purpose of this study, broadly used material in a water based nanofluid applications [2]. The current work focuses on investigating the stability characteristics of Al_2O_3 and CuO nanofluids with different weight concentrations of SDBS and nanoparticle in a DI-water as a base fluid. The ultimate aim of this

work is to evaluate the optimum weight fraction of SDBS as well as nanoparticles in base fluid to achieve the most stable and most efficient nanofluid which may lead to a decrease in the value of viscosity and enhancement in thermal conductivity, thus enhance the overall heat transfer performance.

2. Experimental procedure

2.1. Preparation of nanofluids

Nanoparticles used in this study were CuO and Al₂O₃ with sizes of 30-50 nm and 10 nm respectively, supplied by Nanostructured & Amorphous Materials, Inc., USA. The experiments were carried out with different nanoparticles weight fractions in the range of 0.05% to 0.15%. Deionised water was utilised as the base fluid. Different weight fractions, from 0.05% to 0.2%, of the dispersant sodium dodecylbenzene sulfonate (SDBS, Sigma-Aldrich Pty. Ltd.) were used to stabilise the nanoparticles. All the samples were prepared at ambient temperature by the two-step method [2]. The prepared nanofluids did not show any visual signs of nanoparticle sedimentation and were found to be very stable, with the visual stability lasting over a week in all cases. Tables 1 presents the properties of Al₂O₃ and CuO nanoparticles utilised in this study.

Table 1: Properties of Al₂O₃ and CuO nanoparticles

2.2.Measurement of rheological behaviour

The dynamic viscosity of Al₂O₃/DI-water and CuO/DI-water nanofluids was measured using an AR-G2 rotational rheometer (TA Instruments) at atmospheric pressure and a constant temperature of 298 K. A plate-cone, of the geometry 1° cone and 60 mm diameter, was mounted [19]. Before taking measurements, the non-zero moment of inertia of the rheometer spindle as

well as the measurement geometry and the friction of the instrument were calibrated. The viscosity measurements were carried out with different shear rates (from 5 to 1050 s⁻¹) at constant temperature and each measurement point is the average of three successive measurements at a constant temperature.

2.3.Measurement of nanoparticles size distribution and zeta potential

The particle size distribution and zeta potential of Al₂O₃/DI-water and CuO/DI-water nanofluids were examined using a Zetasizer Nano ZS (Malvern Instruments Ltd, Malvern, UK) with a minimum of 10 runs being carried out in a disposable folded capillary cell (DTS 1070) at 298 K. Each data point shown in this study is the average of three consequent sample measurements. The particle size distribution in water based suspensions was identified by the Dynamic Light Scattering (DLS) method. Fig. 1 shows a schematic diagram of the DLS setup. The working principle of DLS is established on the theory of Brownian motion [20].

Fig. 1. Schematic Diagram of dynamic light scattering setup [21].

A typical DLS system comprises of three major components as shown in Fig. 1; a laser source, a goniometer and a detector. All measured electrophoretic mobilities were converted into zeta potential applying Smoluchowski's formula [22, 23].

A pH meter (F-51, HORIBA, Ltd.) was employed to measure the pH of nanofluid dispersions at different concentrations of nanoparticles and SDBS at a constant room temperature of 298 K. Each data reported is the average of at least five consecutive pH measurements.

2.4.Measurement of thermal conductivity

A KD2-Pro (Decagon, USA) portable thermal conductivity measurement device was used to measure the thermal conductivity of samples tested in this study. The KD2-Pro works based on

the transient hot wire (THW) principle. Before each thermal conductivity measurement, the setup was calibrated with fluids such as DI-water and Glycerin of well-known thermal conductivity. Samples prepared at different particle volume fractions were placed in a water bath to maintain a constant temperature of 298 K.

3. Results and discussion

3.1. Effect of SDBS concentrations on pH, zeta potential and particle size distribution of nanofluids

Effect of various nanoparticles as well as SDBS concentrations on the pH value of the Al_2O_3 /water and CuO/water nanofluids are presented in Fig. 2 and 3 respectively. It is clear that the increase in volume fraction of Al_2O_3 and CuO nanoparticles result in an increase in pH value toward more basic values. Moreover, a similar trend was noticed by raising the weight concentration of anionic surfactant.

Fig. 2. Effect of SDBS weight fraction on pH value of alumina nanofluid at various weight fractions of Al_2O_3 nanoparticles (T = 298 K).

Fig. 3. Effect of SDBS weight fraction on pH value of copper oxide nanofluid at various weight fractions of CuO nanoparticles (T = 298 K).

The liquid layer surrounding the particles contains two different regions; an inner region (stern layer) and an outer (diffuse) region. At the inner region ions are firmly bounded and at outer region they are less strongly associated. There is a notional boundary inside the outer layer where the particles and ions form a stable entity. The potential at this boundary is known as zeta potential. Zeta potential of a colloidal suspension is highly dependent on the pH value of the solution. This is because changing the pH value will alter the electrical charge density on the particles surface and guides to either larger or smaller repulsive force between the particles. This

influence of surface electrical forces can be best stated in terms of isoelectric point (IEP) at which a given surface carries no net electrical charge (i.e. the positive and negative charges are equal). At or near IEP, the electrostatic repulsive between particles is no longer sufficient to keep the particles apart from each other. As a result, particles aggregate and reach its maximum size. On the other hand, the particle aggregation and clustering is fairly weak at pH values away from IEP and the tendency of aggregate formation far from IEP is nearly zero [3]. Therefore, the zeta potential magnitude provides a valuable piece of information regarding the stability of the suspension system. If all the particles in suspension have a high positive or negative value of zeta potential then the particles tend to repel one another and there is no propensity for the particles to aggregate. Nevertheless, there is no opposing force to stop the particles sticking together at low zeta potential values. The general dividing line between unstable and stable suspensions is usually considered at either +30 or -30 mV, which means that the particles with zeta potentials greater positive than +30 mV or with lower negative value than -30 mV are believed as stable suspension [24]. To confirm this, the measurements of nanoparticle size distribution in base fluid as well as zeta potential measurement were performed by dynamic light scattering method (Fig. 4 and 5).

Fig. 4. Effect of SDBS weight fraction on the zeta potential and particle size of Al_2O_3 /water nanofluids ($T = 298 \text{ K}$).

Fig. 5. Effect of SDBS weight fraction on the zeta potential and particle size of CuO /water nanofluids ($T = 298 \text{ K}$).

The stability of alumina and copper oxide nanoparticles in base fluids is directly linked to their electrokinetic properties. Substantially well-dispersed nanofluids can be found with large surface charge density to create strong repulsive forces. Thus, the electrophoretic behaviour

study by taking the measurement of particle size and zeta potential become crucial for better understanding of the nanoparticles distribution behaviour in a base fluid [25, 26]. The greater magnitude of zeta potential indicates the smaller aggregate size in the base fluid, and in return more stable nanofluid.

Zeta potential measurements were performed in order to determine the surface charge on the nanoparticles. Figs. 4 and 5 show the variation of particle size and zeta potential as the function of SDBS weight concentration for $\text{Al}_2\text{O}_3/\text{water}$ and CuO/water nanofluids, at various particle concentrations, respectively. The $\text{Al}_2\text{O}_3/\text{water}$ and CuO/water nanofluids without any surfactant showed a zeta potential of approximately +30 to +40 mV and +14 to +28 mV respectively. This indicates that both of the nanofluids were comprised of highly positively charged Al_2O_3 and CuO nanoparticles at all weight concentrations analysed. Since all of the nanoparticles carried a high positive charge, the surface charges of the nanoparticles were altered by adding the negatively charged surfactant. This is because the SDBS separates in the suspension to produce phenyl sulfonic groups which adsorbed on the nanoparticles, successively increasing the net negative charge on the nanoparticles surface and the repulsive forces. It was observed that both of the nanofluids showed similar behaviour with respect to the change in pH value. From these observations it is apparent that an optimised value of SDBS exists (i.e. 0.10 wt% of SDBS in $\text{Al}_2\text{O}_3/\text{water}$ nanofluids and 0.15 wt% of SDBS in CuO/water nanofluids) at which the magnitude of zeta potential is a maximum $\xi_{\text{Al}_2\text{O}_3} = -72.2\text{mV}$, $\xi_{\text{CuO}} = -85.1\text{mV}$, and the particle size is minimum $d_{p(\text{Al}_2\text{O}_3)} = 101\text{nm}$, $d_{p(\text{CuO})} = 169\text{nm}$, respectively. Therefore, in the region of 0.10 wt% SDBS concentration, the dispersion behaviour of alumina nanoparticle is superior in comparison to copper oxide nanoparticles at the same weight fraction. However, at 0.15 wt% SDBS concentration, the dispersion behaviour of alumina particle is poorer in

comparison to the copper oxide nanoparticles at equal weight fractions. From the zeta potential graphs, the optimum weight fractions of anionic surfactant were found to be 0.10 wt% and 0.15 wt% for alumina and copper oxide respectively, under the test conditions reported in this study.

3.2. Effect of SDBS concentration on viscosity

The viscosity of the Al_2O_3 /DI-water and CuO /DI-water nanofluids was measured at four different SDBS weight fractions. Figs. 6 and 7 present the viscosity of Al_2O_3 /water and CuO /water nanofluids as a function of shear rate respectively. From the similarity of experimental data found in Fig. 6(a)-6(c) and Fig. 7(a)-7(c), it is clear that the value of nanofluid's viscosity is depend on the weight fraction of SDBS concentration in the suspensions.

It was also observed that the viscosity of the Al_2O_3 /water and CuO /water nanofluids synthesised without using any additive was approximately 4% and 6% higher than the viscosity of the nanofluids synthesised by adding SDBS in concentrations of 0.10 wt% and 0.15 wt%, respectively. SDBS was implemented to ensure uniform dispersion of the Al_2O_3 and CuO nanoparticles in the DI-water. This observation clearly confirms that the stability of nanofluids has a direct relation with the viscosity, in that better dispersion correlated to a lower viscosity of the nano-suspensions. Thus, clearly utilising the optimal weight concentration of SDBS could be resulted in lower viscosity value of the nanofluid, which in turn makes nanofluid more favourable for practical applications.

Fig. 6. Viscosity as a function of shear rate for different concentrations of SDBS at 298K for (a) 0.05 wt%, (b) 0.10 wt%, and (c) 0.15 wt% of Al_2O_3 /DI-water nanofluids.

Fig. 7. Viscosity as a function of shear rate for different concentrations of SDBS at 298K for (a) 0.05 wt%, (b) 0.10 wt%, and (c) 0.15 wt% of CuO /DI-water nanofluids.

Figs. 8 and 9 present the viscosity of the nanofluids as a function of the shear rate at the constant optimum SDBS related to each case. It should be noted that in general, the value of viscosity at low shear rate for all nanofluids is high [27, 28]. This is because rotational rheometers are limited in terms of sensitivity and have some limitations for low viscosity shear thinning fluids and are not compatible for the fluid behaviour at sufficiently low shear-rate [29]. Therefore, for measurements at low shear rates (at shear rate 5-70 1/s), exceptionally high viscosity values for different nanofluids can be attributed to high measurement uncertainty, associated with the small torque in the instrument. The accuracy of the measurements performed in this study were within 1%, well within the 5% accuracy declared by the manufacturer [30]. As shown in Figs. 8 and 9, non-linear rheological behaviour was observed for the nanofluids, which is akin to the properties of a shear thinning liquid. The shear thinning behaviour was obtained from shear rates of 0-360 1/s and 0-400 1/s for alumina and copper oxide nanofluids respectively. In addition, an increase in viscosity was observed for increases in nanoparticle weight concentration. This indicates that the viscosity and stability characteristics of the nanofluids can be hampered by changing the concentration of nanoparticles. Molecular dynamic simulation [31] showed that effective viscosity of nanoparticle suspensions (η_{eff}) is proportional to the volume concentration of dispersed nanoparticles and can be described as,

$$\eta_{eff}(\phi) = \eta_0(1 + A_1\phi + A_2\phi^2) \quad (1)$$

where η_0 is the viscosity of the base fluid and A_1 and A_2 are constants.

Fig. 8. Viscosity as a function of shear rate for different concentration of Al_2O_3 nanoparticles at a constant concentration of SDBS (0.10 wt%) and 298K.

Fig. 9. Viscosity as a function of shear rate for different concentration of CuO nanoparticles at a constant concentration of SDBS (0.15 wt%) and 298K.

Nanofluid viscosity as a function of the SDBS surfactant and nanoparticles weight concentrations at a constant shear rate of 134 S^{-1} and 150 S^{-1} is presented in Figs. 10 and 11 for $\text{Al}_2\text{O}_3/\text{water}$ and CuO/water nanofluids (absence and presence of SDBS) respectively. In Figs. 10 and 11, the value of viscosity began to decrease after a certain weight fraction of dispersant because the amount of dispersant has a direct relation with the stability and the viscosity of the nanofluids. For $\text{Al}_2\text{O}_3/\text{water}$ nanofluids (Fig. 10) the lowest viscosity occurred at 0.1 wt% SDBS, while for CuO/water nanofluids (Fig. 11), the lowest viscosity occurred at 0.15 wt% SDBS. At each of these corresponding points the average particle size was also found to be a minimum. Further, if nanoparticles settle out, this causes variation in the hydrodynamic size, morphology and weight concentration. This then results in a higher viscosity of the colloidal system as was observed.

Fig. 10. Effect of SDBS and Al_2O_3 nanoparticles concentration on viscosity of the nano-suspensions at shear rate of 134 S^{-1} and temperature 298 K.

Fig. 11. Effect of SDBS and CuO nanoparticles concentration on viscosity of the nano-suspensions at shear rate of 150 S^{-1} and temperature 298 K.

Surface charge increases as nanofluid's pH rises beyond the isoelectric point by using anionic surfactant. Derjaguin-Landau-Verwey- Overbeek (DLVO) theory [32] predicts that as charge separation in double electric layer increases, shrinkage of double layer occurs (Debye length $\rightarrow 0$) and at small separations between nanoparticles the van der Waals attraction wins over the double layer repulsion and particle agglomeration occurs (observed as a viscosity increase). This scenario was achieved in the case of maximum pH value by using maximum amount of surfactant in nano-suspensions. Due to the statistics of random clustering, nanoparticle agglomerates are usually elongated [33] and behave similar to high aspect ratio particles,

restricting both rotational and translational motions. This could be the possible reason behind the shear thinning behaviour and higher viscosities of suspensions with respects to agglomerates.

3.3. Effect of pH and SDBS concentration on nanofluids thermal conductivity

Thermal conductivity ratio (i.e. thermal conductivity of the nanofluid to that of base fluid) of the two nanofluids of interest with optimum amount of SDBS dispersant as a function of pH are presented in Figs. 12 and 13. It can be seen from the experimental results of $\text{Al}_2\text{O}_3/\text{water}$ (Fig. 12) and CuO/water (Fig. 13) nanofluids, that the thermal conductivity ratio was clearly dependent on pH value. Alumina nanoparticles have a higher thermal conductivity in comparison to copper oxide nanoparticles, and as a result the thermal conductivity of alumina-water nanofluids was higher than that of copper oxide-water nanofluids. The maximum values of thermal conductivity ratios observed for $\text{Al}_2\text{O}_3/\text{water}$ and CuO/water nanofluids respectively were $(k/k_f)_{\text{Al}_2\text{O}_3} = 1.13$, $(k/k_f)_{\text{CuO}} = 1.11$ at the constant concentration of surfactant (i.e. 0.10 wt% and 0.15 wt% respectively).

Fig. 12. Effect of pH on thermal conductivity ratio of the $\text{Al}_2\text{O}_3/\text{water}$ nanofluids at different particle concentrations and optimum SDBD dispersant ($T = 298 \text{ K}$).

Fig. 13. Effect of pH on thermal conductivity ratio of the CuO/water nanofluids at different particle concentrations and optimum SDBD dispersant ($T = 298 \text{ K}$).

It was observed that the thermal conductivity of the base-fluid was almost constant at various dosages of electrolyte salt and base or acid [9]. Therefore, the increment appears to be associated only with the presence of nanoparticles. When the particles are dispersed into the base fluid, the overall particle-base fluid interaction behaviour depends on the characteristics of the particles surface. In the case of adding SDBS, the higher or lower values of pH result in weaker repulsion

and lower surface charge between the particles by Brownian motion, which may lead to stronger agglomeration. This was apparent from the measurement of the zeta potential, when the pH reached closer to the optimised value [34], the surface charge increased due to the more regular attacking of potential-determining ions (H^+ , OH^- and phenyl sulfonic group) against the surface of phenyl sulfonic groups and hydroxyl groups. This may lead to an enhancement in the electrostatic repulsion force between nanoparticles, with the nanofluids showing notably decreased agglomeration and improved mobility, eventually boosting the heat transport method. Lee et al. [34] reached the same conclusion. They noticed that as the value of pH shifted from the isoelectric point (IEP), the particles attained a higher charge and particle to particle repulsion was enhanced, consequently the nanofluids were more stable leading to the higher thermal conductivities observed. Hence, it appears logical to conclude that having the optimum charge on the surface of the nanoparticles may lead to stabilised nanofluids with ideal thermo-physical properties.

Figs. 14 and 15 present the thermal conductivity ratio of the nanofluids as the function of SDBS concentrations as well as nanoparticles weight fractions. From Figs. 14 and 15, it can be seen that for both nano-suspensions, thermal conductivity ratio increased slowly as the SDBS fraction increased up to 0.1 wt% and 0.15 wt% for alumina and copper oxide nanofluid respectively, it is then decreased in the region of $0.1 \text{ wt\%} < \text{SDBS} < 0.2 \text{ wt\%}$ for alumina and $0.15 \text{ wt\%} < \text{SDBS} < 0.2 \text{ wt\%}$ for copper oxide. Obviously, for the Al_2O_3 /water and CuO/water nanofluids, the addition of more surfactant into the system resulted in a rapid decrease in the thermal conductivity ratio and higher concentration of nanoparticles observed to have higher thermal conductivity ratio. This may be because the heat transfer area becomes narrower, due to the amount of surfactant on the surface of the particles [35].

Fig. 14. Effect of SDBS additive and nanoparticles weight fraction on thermal conductivity ratio of Al_2O_3 /water nanofluids at a constant temperature of 298 K.

Fig. 15. Effect of SDBS additive and nanoparticles weight fraction on thermal conductivity ratio of CuO /water nanofluids at a constant temperature of 298 K.

Bearing in mind the joint effect of viscosity, thermal conductivity and dispersion behaviour, 0.1 wt% SDBS was chosen as the optimal concentration for Al_2O_3 nano-suspensions. For the CuO /water nanofluids, a very similar thermal conductivity trend was obtained and 0.15 wt% SDBS was selected as the optimal concentration. Moreover, from Figs. 14 and 15, the thermal conductivity of the nanofluids increased nonlinearly with increasing weight concentration of nanoparticles, with the maximum increase of 10% for Al_2O_3 and 14% for CuO observed for 0.15 wt% nanoparticles in thermal conductivity. These results are in good agreement with those of the maximal enhancement for alumina nanofluids observed in previous studies [36]. By controlling and optimising the value of SDBS concentration and pH for the both nanofluids, the electrostatic repulsion force between particles becomes adequate to prevent from the collision and attraction between particles triggered by Brownian motions. Higher electrostatic force also directed to more free particles by enhancing particle to particle distance so that the distance exceeds the hydrogen bonding range between particles and further decreases the feasibility of particles coagulation and increases dynamism of nanoparticles; as a result the heat transport process is improved. Thus, the stability has a good corresponding relationship with the increment of thermal conductivity of nanofluids.

4. Conclusion

In the present study, the effects of weight concentrations of nanoparticles as well as SDBS on pH, zeta potential, particle size distribution, viscosity and thermal conductivity of $\text{Al}_2\text{O}_3/\text{DI}$ -water and CuO/DI -water nanofluids were studied in detail. The conclusion derived in this work highlights that:

- The aggregation is studied in terms of zeta potential and particles size distribution. This was done by varying the surfactant (SDBS) and nanoparticles weight concentrations. The reduction in SDBS concentration led to decrease in stability because of the increased aggregation. In contrast, completely opposite result was found for nanoparticle concentration. The increase in concentration has led to increase aggregation and therefore the stability was found to decrease.
- The optimum values has been derived for the SDBS and nanoparticle concentrations to improve stability and thermal conductivity and to reduce viscosity (and thus pumping power) of both copper and aluminium oxide nanofluids.

Therefore, the treatment with chemical dispersant was recommended to improve the stability and in turn viscosity and thermal conductivity of nanofluids for practical applications. As shown here, the value of pH, zeta potential, particle size distribution, as well as viscosity and thermal conductivity are tied together and are the most important parameters for efficiency improvement of a heat transfer fluid. Hence, the performance of a heat exchanger system can be enhanced by implementing nanofluids at optimum weight concentration of anionic surfactant as well as nanoparticles. This study could be given a good basis for highly homogeneous, industrially improved heat transfer fluids.

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(a)

(b)

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Product name	Molecular formula	Mean particle size	Surface area	Density
Aluminum oxide	Al ₂ O ₃	10 nm	160 m ² /g SSA	3.7 g/cm ³ at 20 °C
Copper (II) oxide	CuO	30-50 nm	13 m ² /g SSA	6.3-6.49 g/cm ³ at 20 °C