



Housing and Building National Research Center

HBRC Journal

<http://ees.elsevier.com/hbrcj>


## FULL LENGTH ARTICLE

# Stability and electrical conductivity of water-base $\text{Al}_2\text{O}_3$ nanofluids for different applications



M.F. Zawrah <sup>a,\*</sup>, R.M. Khattab <sup>a</sup>, L.G. Girgis <sup>a</sup>, H. El Daidamony <sup>b</sup>,  
Rehab E. Abdel Aziz <sup>a</sup>

<sup>a</sup> National Research Center, Ceramics Department, 12622 Dokki, Cairo, Egypt

<sup>b</sup> Zagazig University, Faculty of Sciences, Chemistry Department, Zagazig, Egypt

Received 10 November 2014; revised 14 December 2014; accepted 17 December 2014

## KEYWORDS

Nanofluid;  
 $\text{Al}_2\text{O}_3$ ;  
Water-base;  
Electrical conductivity

**Abstract** In this study,  $\text{Al}_2\text{O}_3$ – $\text{H}_2\text{O}$  nanofluids were synthesized using sodium dodecylbenzenesulfonate (SDBS) dispersant agent by ultra-sonication method. Different amounts of SDBS i.e. 0.1, 0.2, 0.3, 0.6, 1 and 1.5 wt.% were tested to stabilize the prepared nanofluids. The stability of nanofluids was verified using optical microscope, transmission electron microscope and Zeta potential. After selecting the suitable amount of dispersant, nanofluids with different volume fractions of  $\text{Al}_2\text{O}_3$  were prepared. Zeta potential measurement of nanofluids with low alumina and intermediate fractions showed good dispersion of  $\text{Al}_2\text{O}_3$  nanoparticles in water, but nanofluids with high mass fraction were easier to aggregate. The stabilized nanofluids were subjected for measuring of rheological behavior and electrical conductivity. The electrical conductivity was correlated to the thermal conductivity according to Wiedemann–Franz law. The results revealed that the nanofluid containing 1% SDBS was the most stable one and settling was observed for the fluid contained 0.75 vol.% of  $\text{Al}_2\text{O}_3$  nanoparticles which gave higher viscosity. The rheological measurements indicated that the viscosity of nanofluids decreased firstly with increasing shear rate (shear thinning behavior). Addition of nanoparticles into the base liquid enhanced the electrical conductivity up to 0.2 vol.% of  $\text{Al}_2\text{O}_3$  nano-particles after which it decreased.

© 2014 Production and hosting by Elsevier B.V. on behalf of Housing and Building National Research Center. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

## Introduction

Recently, due to the development of nanotechnology and surface science, many researches on nanofluids have been actively carried out. Nanofluid is a kind of new engineering material consisting of solid nanoparticles with sizes typically of 1–100 nm suspended in base fluids. It does not only solve the problems such as sedimentation, cohesion and corrosion which conventionally happened in heterogeneous solid/liquid mixture

\* Corresponding author.

Peer review under responsibility of Housing and Building National Research Center.



Production and hosting by Elsevier

with milli-meter or micrometer particles, but also increase the thermal performance of base fluids remarkably [1–9]. Dispersion and stability are the essential characteristics for enhancing the thermal conductivity of nano-fluids. Uniform dispersion and stable suspension of nanoparticles in liquids are the keys for most applications of nanofluids since their final properties are determined by the quality of dispersed state of the suspension [10–12]. Many researchers have reported the necessity of proper dispersion of nanofluids and various dispersion techniques [13]. They also measured the thermal conductivity as a function of ultra-sonication (physical technique) time and showed that long hours of ultra-sonic dispersion are required to improve particles dispersion [10]. Chemical techniques such as the use of surfactants are also discussed. It is found that surfactants can play an effective role for proper dispersion of nanoparticles without affecting nanofluid's thermo-physical properties and heat transfer performance by ensuring higher stability [14,15]. There are three methods in fluid dispersion technology: mechanical control, medium control, and agent control. Mechanical control applies disintegrator, ultrasonic oscillator, and electromagnetic stirring for particle dispersion. Medium control applies different media to different particles in terms of surface properties; like polarity to reach better dispersion effects. Agent control applies different dispersants to different particles in terms of the physical and chemical conditions of the medium to improve the rejection among particles [16,17].

Nanofluid possesses the following advantages; (a) high specific surface area and therefore more heat transfer surface between particles and fluids, (b) high dispersion stability with predominant Brownian motion of particles, (c) reduced pumping power compared with pure liquid to achieve equivalent heat transfer intensification, (d) reduced particle clogging as compared with convention slurries, thus promoting system miniaturization, and (e) adjustable properties, including thermal conductivity and surface wettability, by varying particle's concentration to suit different applications.

Very few experimental works have been reported on the electrical conductivity of water-based nanofluids. The change in electrical conductivity of alumina-based fluids with particle fraction and temperature was studied by Ganguly et al. [18]. They showed a linear increase of electrical conductivity with particle fraction and almost no variation in temperature. Modesto Lopez and Biswas [19] reported that a linear rise in electrical conductivity of  $\text{Al}_2\text{O}_3$  suspensions with particle fraction was observed for low ionic strength and no significant impact for high ionic concentration. Electrical and thermal conductivities of multi-walled CNT-based fluids and electrical conductivity of graphene and gold nanofluids have been studied [20–22].

Zeta potential is an important parameter of particle suspension behavior. Due to surface energy, the well-dispersed suspended particles may agglomerate with each other, leading to precipitation. The repulsive energy of suspended nanoparticles in a solution is small in general speaking. Agglomeration may occur when the attracting energy between particles is larger than the repulsive energy. The repulsive energy, therefore, should be improved to prevent agglomeration. As a result, a relatively high zeta potential will confer stability of nanofluid [16,17,23].

The present study aims to investigate the effect of anion SDBS dispersant on dispersion, viscosity, zeta potential,

particle size, electrical properties of  $\text{Al}_2\text{O}_3$ /water nanofluid containing 50 nm alumina particles.

## Materials and experimental procedures

### Materials

Dry aluminum dioxide ( $\text{Al}_2\text{O}_3$  nanopowder with particle size  $\sim 50$  nm, SDBS acquired from sigma aldrich, and bi-distilled water were used to prepare the nanofluids. The starting alumina was characterized by X-ray diffraction (XRD) and transmission electron microscope (TEM).

### Preparation of stable nanofluids

In order to break down the large agglomerates, ultrasonication was applied for 60 min to get homogenous distribution of nanoparticles. During the preparation of  $\text{Al}_2\text{O}_3$  nanofluid, the main concern is to get homogenous and uniform suspension of nanoparticles by minimizing the diameter of agglomerated nanoparticles. The agglomerated nanoparticles are settled with time leading to poor suspension stability. So, the amount of dispersant should be carefully selected. To determine the suitable amount of dispersant, six samples having different amounts of surfactant (i.e. 0.1, 0.2, 0.3, 0.6, 1 and 1.5 mass%) were prepared with the same concentration (0.1 wt.%  $\text{Al}_2\text{O}_3$ ) of nanoparticles at pH 8. After selecting the optimum amount of dispersant required for this purpose, nanofluids having 0.1, 0.15, 0.2, 0.5 and 0.75 vol.%.  $\text{Al}_2\text{O}_3$  nanoparticles were prepared.

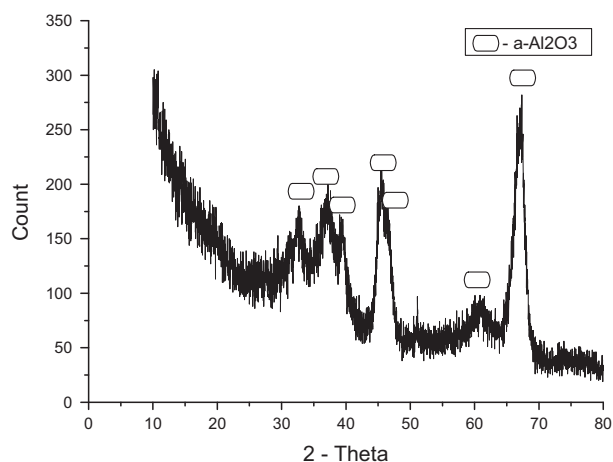
### Characterization of the prepared nanofluids

In order to study the effect of dispersant concentration on the dispersion of nanoparticles, i.e. the mass% of dispersant that exhibits minimum agglomeration and good degree of dispersion, optical microscope (OM) and transition electron microscope (TEM) were conducted for films of the dispersed solution (0.1 wt%  $\text{Al}_2\text{O}_3$  solution). For further confirmation, zeta potential of the dispersed nanoparticles was measured by Malvern ZS Nano Sizer Analyzer (Malvern Instrument Inc., London, UK). The stability is achieved by keeping the pH value away from the iso-electric point (IEP) which is the point with zero potential and maximum attraction between the particles. The viscosity and shear rate of nanofluids having different volume fractions of  $\text{Al}_2\text{O}_3$  nanoparticles were determined by using Viscometer Model DV-II+. The electrical conductivity of suspensions having different volume fraction of alumina nanoparticles was measured using the digital conductometer WTW 330I according to stmp D1125 and correlated with the thermal conductivities according to Wiedemann–Franz law.

## Results and discussion

### Characterization of starting nano alumina powder

Alumina nanoparticle was characterized by XRD for phase identification, crystallite size and crystal structure determination. Fig. 1 shows XRD of alumina nano particle. It is



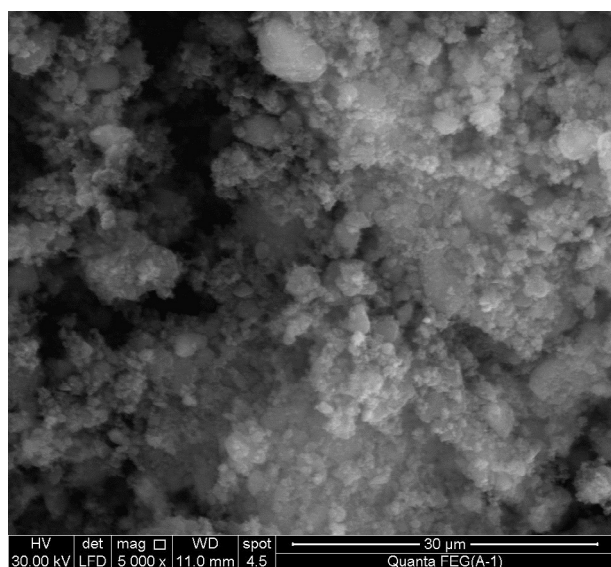
**Figure 1** XRD of alumina nanoparticles.

indicated from the pattern that the alumina is in the form of alpha-alumina single phase (cubic structure) with characteristic peaks at  $2\theta$  equal  $32.7677^\circ$ ,  $37.0404^\circ$ ,  $39.5720^\circ$ ,  $45.2826^\circ$ ,  $46.7282^\circ$ ,  $60.8500^\circ$  and  $67.4371^\circ$ .

SEM is a powerful tool to characterize the shape, size and distribution of nanoparticles. Fig. 2 exhibits SEM micrograph of alumina nanoparticle. The primary alumina nanoparticles are approximately spherical with an average diameter of about 20–30 nm. However, due to strong Van der Waals attractive force, nearly all nanoparticles are in the form of dried agglomerates with larger dimensions than the primary particles. In order to break down the large agglomerates, ultrasonication is applied.

#### Characterization of the prepared Al<sub>2</sub>O<sub>3</sub> nanofluids

The agglomeration of nanoparticles results in not only settlement and clogging but also the decrement of thermal conductivity of nanofluids. So, stability analysis is a matter of



**Figure 2** SEM of alumina nanoparticles.

importance in context to its application. Sedimentation, centrifugation, spectral analysis and zeta potential analysis are the four basic methods for evaluating stability of nanofluids. The stability of nanofluids can be also detected by the electron and optical microscopes. Optical spectroscopy uses the interaction of light with matter as a function of wavelength or energy in order to obtain information about the material. Optical spectroscopy is attractive for materials characterization because it is fast, non destructive and of high resolution. TEM is reckoned as the most important tool to determine the size distribution and the morphology of the synthesized nanoparticles. It uses electron beam to create the image of samples. Figs. 3 and 4 depict, respectively, the TEM and optical micrographs of 0.1 wt.% Al<sub>2</sub>O<sub>3</sub>/water nanofluid having different dispersant concentrations. As indicated in the TEM images (Fig. 3), the alumina nanoparticles are rod-like in shape. However, the figures (Figs. 3 and 4) portray that the sample with 0.1, 0.3 and 0.6 wt.% dispersant have the most severe agglomeration, while the sample with 1 wt.% dispersant reached better suspension. The maximum agglomeration and settling rate are obtained for the nanofluids with 1.5 wt.%. This is due to the over loading of dispersant which agglomerates the particles. Owing to the agglomeration and precipitation of Al<sub>2</sub>O<sub>3</sub>/water nanofluid with 1.5 wt.% SDBS dispersant, 1 wt.% SDBS is selected as the optimum amount for the present work.

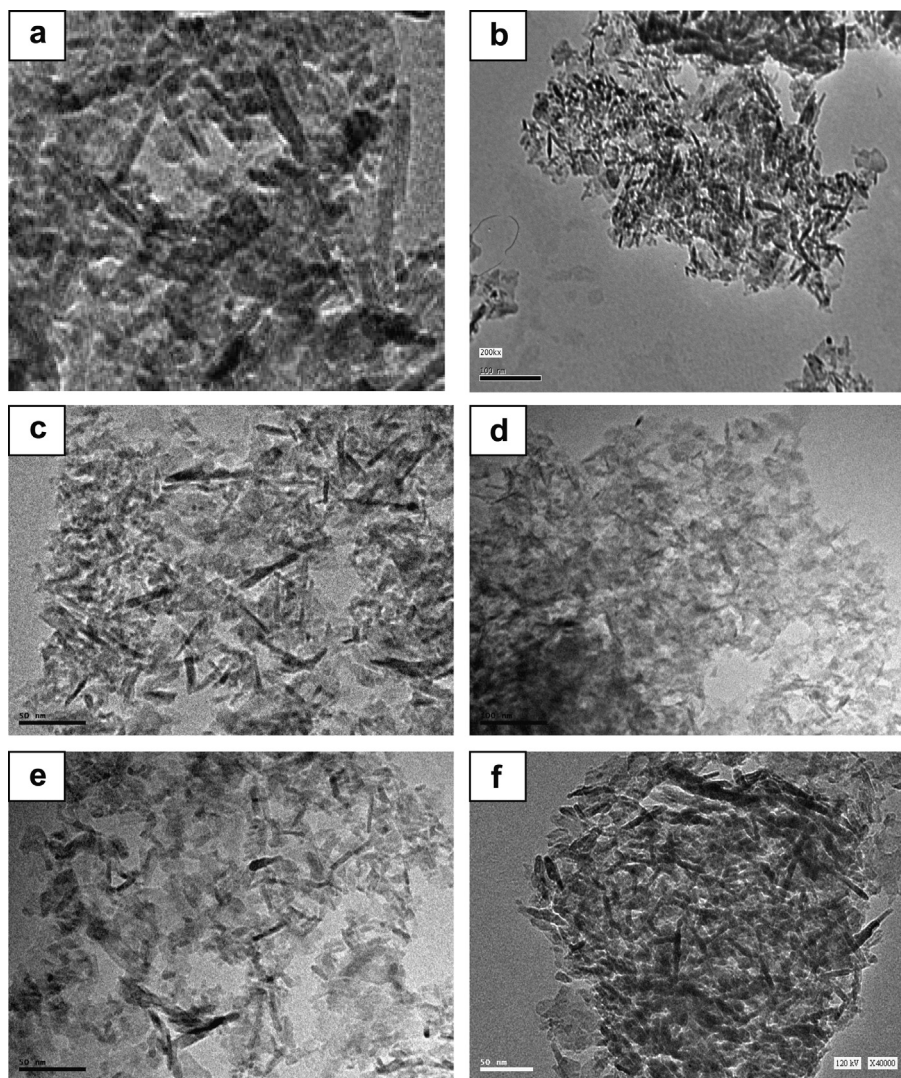
#### Zeta potential of alumina nanoparticles

Major factors influencing the extraordinary enhancement of electrical conductivity are pH value (surface charge), monodispersity and iso electric point (IEP). The effect of particle surface charge and IEP is also exposed in varying thermal conductivity experimental sets conducted by Lee et al., [24]. They reported that the colloidal particles get more stable and enhance thermal conductivity of nanofluid when the pH of the solution goes far from the IEP of particles.

The pH control as an important role in stability control, determines the IEP of suspension in order to avoid coagulation and instability. A repulsion force between suspended particles is caused by zeta potential which increases with the increase of surface charge of the particles suspended in the base fluid [25,26].

The suspension stability of Al<sub>2</sub>O<sub>3</sub> nanofluids with different pH values is analyzed via Zeta potential. The pH value of Al<sub>2</sub>O<sub>3</sub> nanofluids is adjusted by HCl and NaOH solutions and then their zeta potentials were measured. As shown in Fig. 5, for the fluid without dispersant, the zeta potential is zero when the pH of Al<sub>2</sub>O<sub>3</sub> fluid is 8, which is the isoelectric point (iep). When the pH value is greater than 8, the particle surfaces begin to have a negative charge. The original pH value of the prepared Al<sub>2</sub>O<sub>3</sub> nanofluid is about five. For the fluids having 0.3 and 0.6% dispersant, iep is decreased to be at pH 6.8 and 6.2, respectively, after which the particles' surfaces are completely negative charged i.e. more stable. The suspension has electrostatic stability due to the strong repulsive force among charged particles which reduces the probability of coalescing, thus forming more stable suspension in the alkaline media. So, the pH value of these nanofluids is adjusted to be high. The higher pH value creates strong surface charges on the nanoparticles and prevents aggregations. The mechanism





**Figure 3** TEM images of alumina nanofluids having different amounts of SDBS dispersant, (a) 0.1, (b) 0.2, (c) 0.3, (d) 0.6, (e) 1.0, (f) 1.5 vol. %.

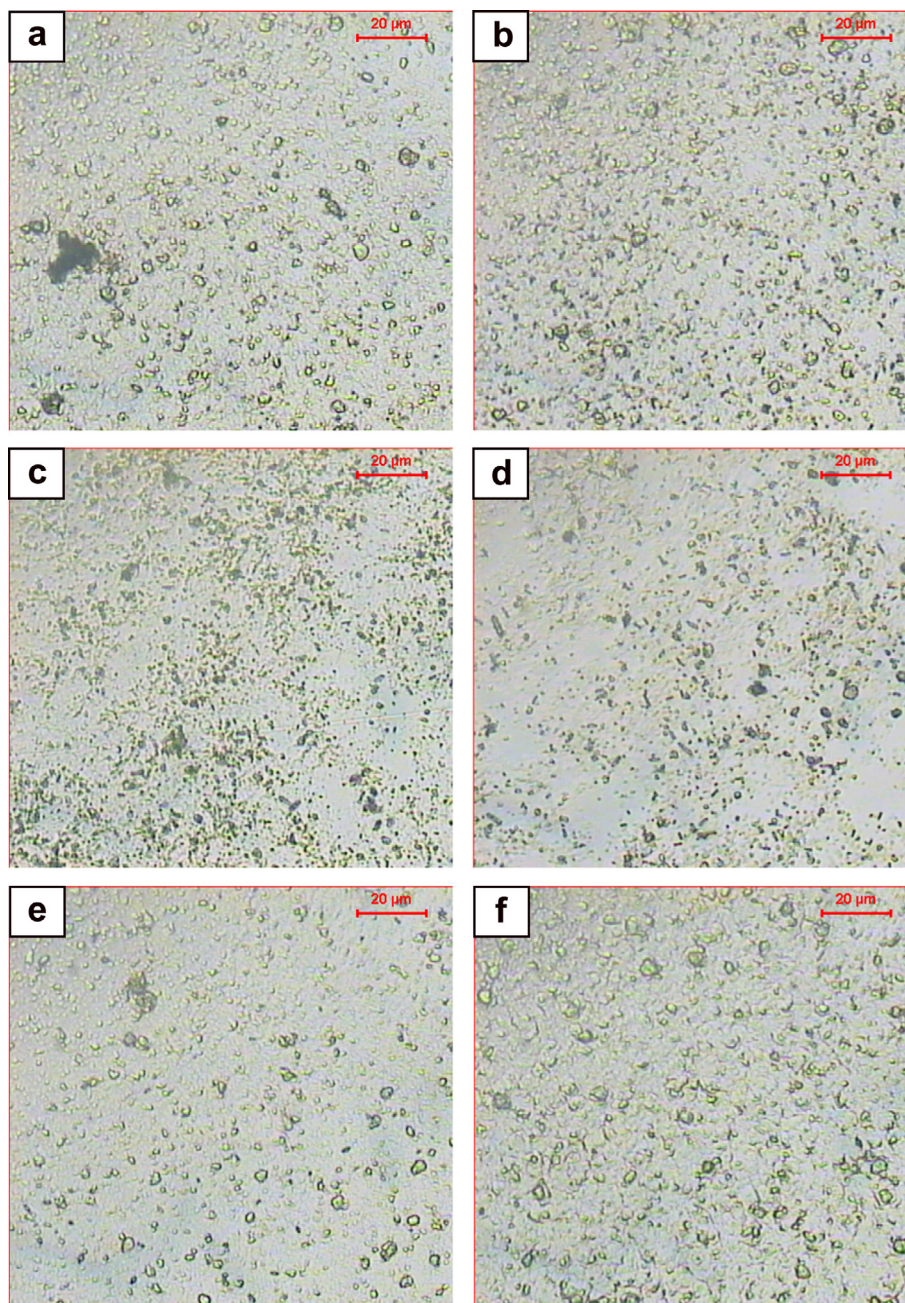
of reaction between alumina nanoparticles and SDBS dispersant is shown in Fig. 6.

#### *Viscosity of alumina nanofluids*

Viscosity is another important property of nanofluids for all thermal applications involving fluid flows since it characterizes the inertial resistance when fluid flows in the pipe or other system. Quantitative information of viscosity of nanofluids is essential for industrial applications to establish adequate pumping power as well as the convective heat transfer coefficient. For example, industries will be reluctant to use nanofluids if the benefits associated with the heat transfer enhancement of nanofluids bring heavy penalties in terms of pumping power [27]. It is believed that viscosity is as critical as thermal conductivity in engineering systems because the nanofluid increases in thermal conductivity without drop in pressure, which in turn is related to fluid viscosity. However, the effective viscosity of nanoparticles' suspension depends on many

factors, such as surface chemistry of the particle, the size and shape of primary particle, base fluid, pH, temperature and the dispersion method. These factors affect strongly the morphology of suspension of nanoparticles/nanofluids [28,29] by changing the structure of electrical double layer around particles/aggregates (electro-viscous effect) [30] and the interaction between particles/aggregates due to attractive van der Waals force and repulsive electrostatic force (DLVO forces) [31]. As indicated from our study,  $\text{Al}_2\text{O}_3$ -water mixture increases the viscosity compared to that of water alone. Fig. 7 shows also the dynamic viscosity as function of shear rate for different concentration of nanoparticles (0.1–0.75 vol.%). It is observed that the nanofluids with higher concentrations of nanoparticles show shear thinning behavior but at lower concentration, neglected effect of shear rate on viscosity is observed. In the colloidal suspension study, the reason that the Newtonian viscosity of a fluid is mostly modified to be non-Newtonian comes from the complex interactions between the fluid and particles and between particles themselves. Recently, it has been pointed





**Figure 4** Optical microscope images of alumina nanofluids having different amounts of SDBS dispersant, (a) 0.1, (b) 0.2, (c) 0.3, (d) 0.6, (e) 1.0, (f) 1.5 vol.%.

out that there are possible particle aggregations and formation of extended structures of linked nanoparticles in nanofluid [32–35]. The viscosity of nanofluids has been affected by the aggregations where the sizes of aggregates are between 3 and 4 times the diameter of nanoparticles [32–33]. It seems that the existence of aggregation process can be responsible for the present results. This can be clarified as follow; (i) The aggregation can explain the non-Newtonian viscosity of nanofluids, i.e. the presence of a Newtonian plateau is followed by a shear-thinning behavior at high shear rate where the aggregate is possibly destroyed under shear, (ii) It can explain why the non-Newtonian character of the nanofluids is more obvious at higher volume fraction where the chance of aggregation is

higher, and (iii) It can also explain why nanorods nanofluids with an aspect ratio higher than spherical nanoparticles have a higher viscosity and a much more pronounced non-Newtonian character. Rods are much more subject to form aggregates or superstructures, significantly decrease with increasing shear rate indicating strong possibility that nanofluid may be non-Newtonian.

It is well known that, for a non-Newtonian fluid behaving either shear thinning or shear thickening features in its shear viscosity, the low shear rate viscosity (LSV) is different from high shear rate viscosity (HSV). In the forced convective heat transfer flow, the thermal fluid flows at a high speed (and high shear rate in consequence). Thus the high shear rate viscosity is

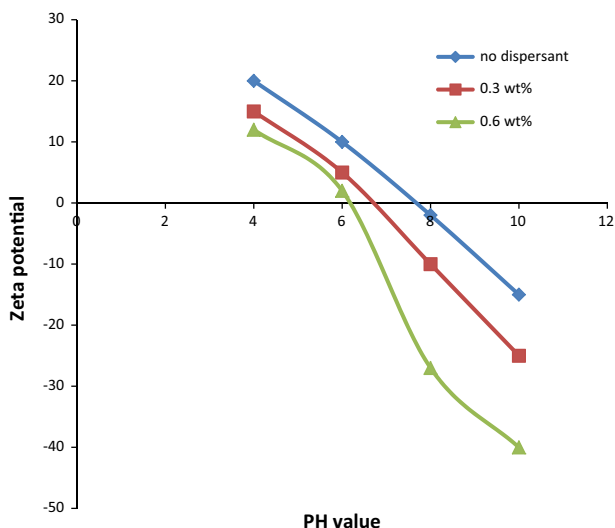


Figure 5 Zeta potential of alumina nanofluids versus PH value.

more practical and important from the engineering point of view. Fig. 7 shows the measured HSV of Al<sub>2</sub>O<sub>3</sub> nanofluids with different concentration of volume fraction of nanoparticles. The increase of volume fraction of Al<sub>2</sub>O<sub>3</sub> nanoparticles increases the HSV.

*Electrical conductivity of alumina nanofluids*

The major focus of the research work, so far, has been on the estimation of thermo-physical properties, primarily on the

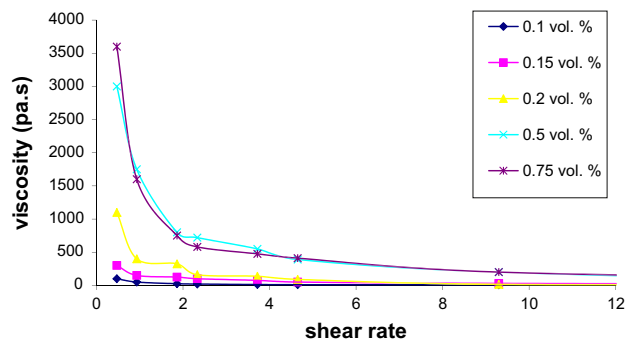


Figure 7 Apparent viscosity behavior of the prepared alumina nanofluids versus applied shear rate.

effective thermal conductivity. Despite the vast scientific and technological importance of electrical conductivity characteristics of nanoparticle suspensions, studies concerning the issue of the effective electrical conductivities of nano-fluids have been largely ignored. Also, there is very few data published on the electrical properties of nanofluids. On the other hand, among the transport properties, electrical conductivity might bring information on the state of dispersion and stability of the particulate suspension. The electrical conductivity was investigated by conducting experiments at different volume fractions of nanofluids. The electrical conductivity of Al<sub>2</sub>O<sub>3</sub>–water nanofluid was first measured at room temperature. Fig. 8 shows the effective electrical conductivity of alumina nanofluids with different volume fractions. It is indicated that the electrical conductivity of alumina nanofluid increases with

Al<sub>2</sub>O<sub>3</sub>+SDBS:

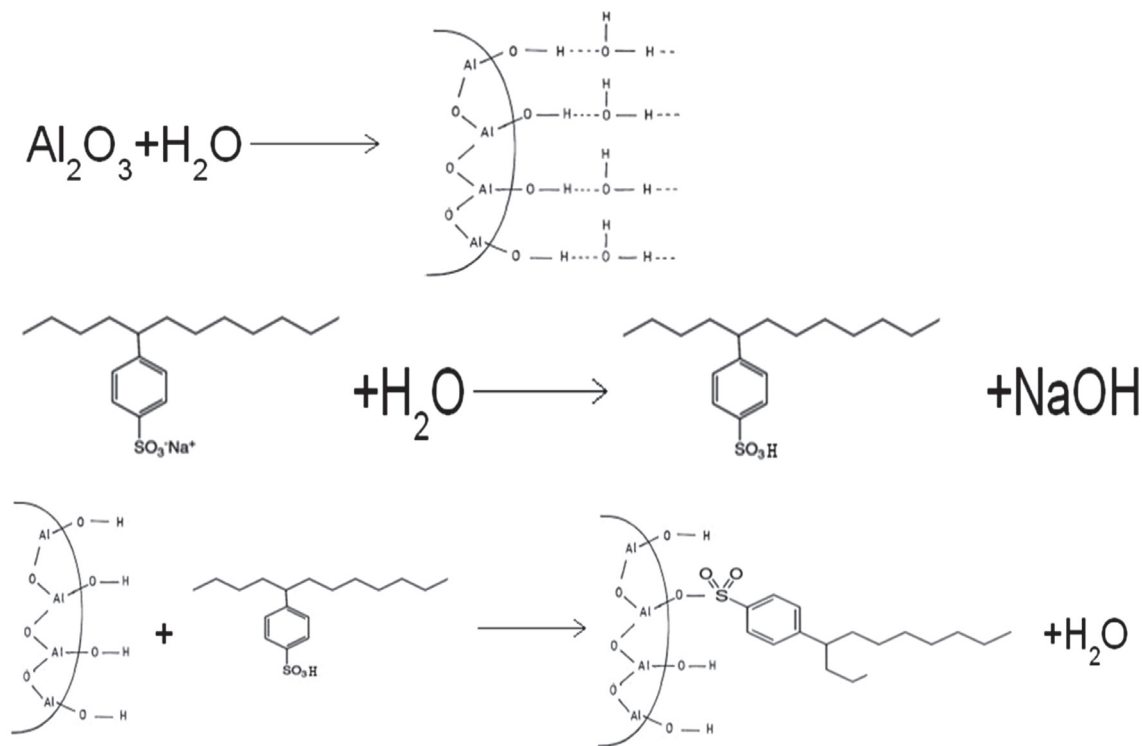
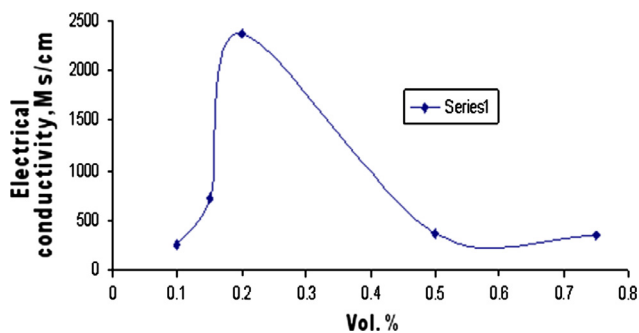


Figure 6 Mechanism of reaction between alumina nanoparticles and SDBS dispersant.



**Figure 8** The corresponding values of electrical conductivity with different vol.% of alumina nanoparticles.

the increase in volume fraction of alumina nanoparticles up to 0.2 vol.% and then begins to decrease with 0.5 and 0.75 vol.%. The highest value of electrical conductivity, 2370  $\mu$ S/cm, is recorded for a volume percent of 0.2 at a temperature of 25.9 °C which underpredicts the conductivity increase in nano-particle fluid mixtures. This is due to the fact that, apart of the physical properties of fluid as well as conductivity of particles and fluids, the effective electrical conductivity of colloidal nanosuspensions in a liquid exhibits a complex dependence on the electrical double layer (EDL) characteristics, volume fraction, ionic concentrations and other physicochemical properties. In fact, the observed enhancement in electrical conductivity of the suspension with respect to the base fluid is a consequence of net charge effect of the solid particle and the pertinent EDL interactions [36,37]. When alumina particles are suspended in a polar liquid (water in the present case), electric charges develop on their surfaces. Ions of charge opposite to that of the particle surface are attracted, causing the development of a charged diffuse layer surrounding the particle. This layer is known as electrical double layer [36] and is commonly characterized by a parameter  $\kappa^{-1}$  (Debye length). For the present case when the ionic strength of the solution is very low, the amount of ions in solution is insufficient to compensate the electric charges, and hence the net electric charge density is high on particle surfaces. The surface charge of the particles, together with ion-cloud that constitutes the EDL, actively contributes for the enhancement in conduction mechanisms through the suspension. In addition, the presence of uniformly dispersed nanoparticles is characterized with reduced equivalent particulate masses, leading to increase electrophoretic mobility, which consequently increases the effective electrical conductivity of the nanofluid suspension. With an increase in particle volume fraction, the availability of conducting path-ways increases in the solution, which in turn increases the overall electrical conductivity of the solution. The decrease of electrical conductivity for 0.5 and 0.75 vol.% is due to the reduction of particle diameter produced from the increase of surface area and the number of particles. As the number of particles increases, the charges available for the formation of EDL are insufficient for particles. So, electrostatic attraction force becomes more than repulsion force between nanoparticles in alumina nanofluids.

## Conclusion

This paper is concerned with the dispersion behavior and electrical conductivity of Al<sub>2</sub>O<sub>3</sub>-H<sub>2</sub>O nanofluids under different

concentrations of sodium dodecylbenzenesulfonate (SDBS) as a dispersant. The appropriate amount of dispersant is used to prepare Al<sub>2</sub>O<sub>3</sub>/water nanofluids having different volume concentration of alumina. The followings are the concluded remarks:

- The dispersion of alumina nano fluids is increased with increasing the amount of dispersion. The most stable fluid was with 1% dispersant.
- The effect of pH on the stability of alumina suspension was critical. A good dispersion of alumina particles was obtained with increasing the pH after iep. This is attributed to charge build up on the surface of alumina particles.
- The viscosity of nano-fluids displayed strong dependence on Al<sub>2</sub>O<sub>3</sub> loading. Viscosity of nanofluids increased dramatically with the increase of particle concentration. Higher viscosity was obtained for the fluid containing 0.75 vol.%.
- The addition of alumina nanoparticles on the base liquid enhances the electrical conductivity up to 0.2 vol.% of Al<sub>2</sub>O<sub>3</sub> nanoparticles after which it decreased.

## Conflict of interest

There is no conflict of interest.

## References

- [1] S.U.S. Choi, Enhancing thermal conductivity of fluids with nanoparticles: developments Applications of Non-Newtonian flows, ASME 231 (1995) 99–105.
- [2] T.K. Hong, H.S. Yang, C.J. Choi, Study of the enhanced thermal conductivity of Fe nanofluids, J. Appl. Phys. 97 (2005) 1–4.
- [3] S.M.S. Murshed, K.C. Leong, C. Yang, Investigations of thermal conductivity and viscosity of nanofluids, J. Thermal Sci. 47 (2008) 560–568.
- [4] S.K. Das, N. Putra, P. Thiesen, W. Roetzel, Temperature dependence of thermal conductivity enhancement for nanofluids, J. Heat Transfer (2003) 567–574.
- [5] Y.M. Xuan, Q. Li, W. Hu, Aggregation structure and thermal conductivity of nanofluids, AIChE J. 49 (2003) 1038–1043.
- [6] A. Eastman, S.U.S. Choi, S. Li, L.J. Thompson, Proceedings of the Symposium on Nanophase and Nanocomposite Materials II, vol. 457, Materials Research Society, USA, 1997, pp. 3–11.
- [7] J.A. Eastman, S.U.S. Choi, S. Li, W. Yu, L.J. Thompson, Anomalously increased effective thermal conductivity of ethylene glycol-based nanofluids containing copper nanoparticles, Appl. Phys. Lett. 78 (2001) 718–720.
- [8] S. Lee, S.U.S. Choi, S. Li, J.A. Eastman, Measuring thermal conductivity of fluids containing oxide nanoparticles, ASME J. Heat Transfer 121 (1999) 280–289.
- [9] X. Li, D. Zhu, X. Wang, N. Wang, J. Gao, H. Li, Thermal conductivity enhancement dependent pH and chemical surfactant for Cu-H<sub>2</sub>O nanofluids, Thermochim. Acta 469 (2008) 98–103.
- [10] J.H. Lee, K.S. Hwang, S.P. Jang, B.H. Lee, J.H. Kim, S.U.S. Choi, C.J. Choi, Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al<sub>2</sub>O<sub>3</sub> nanoparticles, J. Heat Mass Transfer 51 (2008) 2651–2656.
- [11] T.K. Hong, H.S. Yang, Nanoparticle-dispersion-dependent thermal conductivity in nanofluids, J. Kor. Phys. Soc. 47 (2001) 321–324.



- [12] X.-J. Wang, X. Li, S. Yang, Influence of pH and SDBS on the stability and thermal conductivity of nanofluids, *Energy Fuels* 23 (2009) 2684–2689.
- [13] E.V. Timofeeva, A.N. Gavrilov, J.M. McCloskey, Y.V. Tolmachev, S. Sprunt, L.M. Lopatina, J.V. Selinger, Thermal conductivity and particle agglomeration in alumina nanofluids: experiment and theory, *Phys. Rev. E* 76 (2007) 1–16.
- [14] S.M.S. Murshed, K.C. Leong, C. Yang, Enhanced thermal conductivity of TiO<sub>2</sub>–water based nanofluids, *Int. J. Therm. Sci.* 44 (2005) 367–373.
- [15] Y. Hwang, H. Park, J. Lee, W. Jung, Thermal conductivity and lubrication characteristics of nanofluids, *Curr. Appl. Phys.* 1 (2006) 67–71.
- [16] R. Mondragon, J.E. Julia, A. Barba, J.C. Jarque, Characterization of silica–water nanofluids dispersed with an ultrasound probe: a study of their physical properties and stability, *Powder Technol.* 224 (2012) 138–146.
- [17] D.D. Ebbing, S.D. Gammon, *General Chemistry*, Cengage, 2013.
- [18] S. Ganguly, S. Sikdar, S. Basu, Experimental investigation of the effective electrical conductivity of aluminium oxide nanofluids, *Powder Technol.* 196 (2009) 326–330.
- [19] L.B. Modesto Lopez, P. Biswas, Role of the effective electrical conductivity of nano suspensions in the generation of TiO<sub>2</sub> agglomerates with electro spray, *J. Aerosol. Sci.* 41 (2010) 790–804.
- [20] J. Glory, M. Bonetti, M. Helezen, M. Mayne l’Hermite, C. Reynaud, Thermal and electrical conductivities of water based nanofluids prepared with long multiwalled carbon nanotubes, *J. Appl. Phys.* 103 (2008) 1–7.
- [21] T.T. Baby, S. Ramaprabhu, Investigation of thermal and electrical conductivity of graphene based nanofluids, *J. Appl. Phys.* 108 (2010) 1–6.
- [22] F. Fang, Y.F. Zhang, DC electrical conductivity of Au nanoparticles/chloroform and toluene suspensions, *J. Mater. Sci.* 40 (2005) 2979–2980.
- [23] S.K. Das, S.U.S. Choi, W. Yu, T. Pradeep, *Nanofluids Science and Technology*, John Wiley & Sons, 2008.
- [24] D. Lee, J.W. Kim, B.G. Kim, A new parameter to control heat transport in nanofluids: surface charge state of the particle in suspension, *J. Phys. Chem. B* 110 (2006) 4323–4328.
- [25] Y. Hwang, J.K. Lee, C.H. Lee, Y.M. Jung, S.I. Cheong, C.G. Lee, B.C. Ku, S.P. Jang, Stability and thermal conductivity characteristics of nanofluids, *Thermochim. Acta* 455 (2007) 70–74.
- [26] H. Jin, W. Xianju, L. Qiong, W. Xueyi, Z. Yunjin, L. Liming, Influence of pH on the stability characteristics of nanofluids, in: *Symposium on Photonics and Optoelectronics*, 2009, pp. 1–4.
- [27] M. Kole, T.K. Dey, Viscosity of alumina nanoparticles dispersed in car engine coolant, *Exp. Therm. Fluid Sci.* 34 (2010) 677–683.
- [28] E.V. Timofeeva, D.S. Smith, W. Yu, D.M. France, D. Singh, J.L. Routbort, Particle size and interfacial effects on thermo-physical and heat transfer characteristics of water-based a-SiC nanofluids, *Nanotechnology* 21 (2010) 215703.
- [29] P. Ding, A.W. Pacek, Effect of pH on de-agglomeration and rheology/morphology of aqueous suspensions of goethite nanopowder, *J. Colloid Interface Sci.* 325 (2008) 165–172.
- [30] F. Booth, The electroviscous effect for suspensions of solid spherical particles, *Proc. Roy. Soc. Lond. Ser. A* 203 (1950) 533–551.
- [31] Z. Zhou, P.J. Scales, D.V. Boger, Chemical and physical control of the rheology of concentrated metal oxide suspensions, *Chem. Eng. Sci.* 56 (2001) 2901–2920.
- [32] H. Chen, S. Witharana, Y. Jin, C. Kimd, Y. Ding, Predicting thermal conductivity of liquid suspensions of nanoparticles (nanofluids) based on rheology, *Particuology* 7 (2009) 151–157.
- [33] H.S. Chen, Y. Ding, Y. He, C. Tan, Rheological behaviour of ethylene glycol based titania nanofluids, *Chem. Phys. Lett.* 444 (2007) 333–337.
- [34] G.R. Vakili-Nezhaad, A. Dorany, Investigation of the effect of multiwalled carbon nanotubes on the viscosity index of lube oil cuts, *Chem. Eng. Commun.* 196 (2009) 997–1007.
- [35] Y. Yang, Z. Zhang, E. Grulke, W. Anderson, G. Wu, Heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in laminar flow, *J. Heat Mass Transfer* 48 (2005) 1107–1116.
- [36] R.J. Hunter, *Zeta potential in colloid science, Principles and Applications*, Academic Press, London, 1981.
- [37] J. Lyklema, *Fundamentals of Interface and Colloid Science*, Academic Press, London, 1991.