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Electrical conductivity of ceramic and metallic nanofluids

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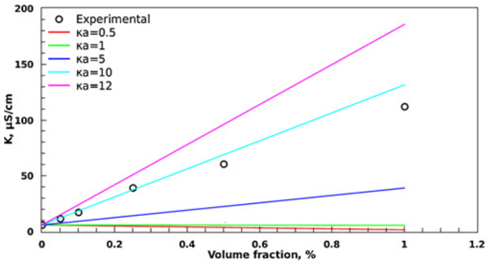
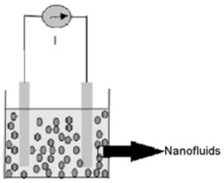
HIGHLIGHTS

- Nanofluids are prepared using water and ethylene glycol followed by ultrasonication.
- The electrical conductivity of nanofluids is studied with various parameters.
- Results are compared with existing models such as Maxwell and O'Brien model.
- The stability of nanofluids depends critically on surface charge of nanoparticles.

GRAPHICAL ABSTRACT





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ABSTRACT

An extensive experimental evaluation of electrical conductivity of nanofluids containing metallic and ceramic particles (Cu, Al_2O_3, and CuO) with different volume fractions in the dilute regime, particle sizes, electrolyte effect, temperature and base fluids has been carried out. It is observed that, in both water- and ethylene glycol (EG)-based nanofluids, the electrical conductivity increases with increasing particle concentration and reducing particle size. It is argued that the effective dielectric constant and density are at the root of the counterintuitive observation that the electrical conductivity enhancement of ceramic nanofluids is more than that of metal-based ones which is substantiated by the Clausius–Mossotti relation for the polar fluids. The influence of surfactant is found to increase the stability and decrease the electrical conductivity of the nanofluids by increasing its viscosity. There is a rise in electrical conductivity of nanofluids having low electrolyte concentration whereas a decrement is observed in nanofluids of high electrolyte concentration due to reduced surface conductance. These experimental observations on alumina nanofluids are compared with the theoretical model proposed by O'Brien [19] for electrical conductivity of dilute suspensions. It has also been observed that there is no significant effect of fluid temperature on the electrical conductivity in the range 30–60 °C. This clearly indicates that enhancement mechanism for electrical conductivity is completely different from that of thermal conductivity in nanofluids.

1. Introduction

Nanofluids are the dilute suspension of nano-sized particles in base fluids including water, ethylene glycol, transformer oil, kerosene, etc. Lasers, high power X-rays and optical fibres are essential components of present computation, scientific measurement, material processing, and medicine and communication devices. Generally the conventional base fluids which are usually used in cooling are not sufficient to meet the growth in these fields particularly in electronic chip and computing technologies. For this increasing demand, intensive research on nanofluids has been triggered using various types of nanoparticles. As the particle size decreases, the surface area increases. This property enhances the heat transfer capability of the nanoparticles which in turn enhances

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the thermal conductivity of nanofluids. Thermal conductivity of different nanofluids such as alumina [1–4], copper [5], copper oxide [2] and titanium dioxide [6] has been measured and found to be significantly enhanced. Also recently carbon nanotubes [7,8] (single walled and multi-walled) have renewed interest in heat transfer with nanofluids in which its high aspect ratio tubes form a network owing to the percolation threshold [9].

Dispersion and stability are the essential characteristics in the enhancement of the thermal conductivity of nanofluids. Uniform dispersion and stable suspension of nanoparticles in the liquids are the key to most applications of nanofluids since the final properties of nanofluids are determined by the quality of the dispersed state of the suspension [10–12]. Many researchers have reported the necessity of proper dispersion of nanofluids and various dispersion techniques [4]. 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 particle 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 [6,7].

From the above discussion on dispersion methods, it is obvious that stability of a nanofluid plays a major role in determining its thermal properties. In addition to the thermal properties, studies have also been conducted on their electrical performance. Electrical conductivity of a nanofluid is related to the ability of charged particles (ions) in the suspension to carry the charges (electrons) towards respective electrodes when an electric potential is applied. In nanofluids, the nanoparticles dispersed in a base fluid get charged due to the formation of electrical double layer (EDL) around the particle surface. These nanoparticles along with the EDL move towards oppositely charged electrode when a potential is applied. This EDL formation depends on the surface charge, size and volume fraction of the particles and ionic concentration in the base fluid. Thus the electrophoretic mobility of charged particles determines the electrical conductivity of a nanofluid.

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. [13]. They showed a linear rise of electrical conductivity with particle fraction and almost no variation with temperature. A linear rise in electrical conductivity of TiO_2 suspensions with particle fraction was observed for low ionic strength and no significant impact for high ionic concentrations by Luis and Biswas [14]. Electrical and thermal conductivities of multi-walled CNT-based fluids and electrical conductivity of graphene and gold nanofluids have been studied [15–17]. Few investigations dealt with numerical and analytical studies on electrical conductivity of concentrated and dilute colloidal suspensions [18,19]. There is scarcity in studies dealing with the electrical conductivity of mildly polar ethylene glycol (EG)-based nanofluids. The stability of a suspension depends on its electrostatic characteristics such as iso-electric point (IEP) and zeta potential which play a major role in the electrical conduction process [18,20]. The electrical conductivity of nanofluids is related to its stability [13,21]. Also, the most commonly used thermal conductivity measurement method of transient hot wire gets significantly affected by the electrical conductivity of nanofluids. Thus, this is an important parameter for characterisation of nanofluids and it needs similar attention as thermal conductivity of nanofluids. These electrically conducting fluids have a variety of applications such as field induced pattern formation in colloidal dispersion [22,23] and electrically conducting adhesive technology [24].

The experimental studies on electrical conductivities of nanofluids are limited to only certain types of particles so far (Al_2O_3, TiO_2, Au and CNT) with water as base fluid. The parameters studied are particle concentration and temperature. This brings out only a limited picture of the physics of electrical conduction process which needs more extensive investigation into the dependence of electrical conductivity in the parametric space. Thus the objective of this work is to reveal experimentally in detail the dependence of electrical conductivity of nanofluids on particle concentrations, base fluids, particle size, temperature, influence of electrolyte and surfactant and the underlying physics behind the conduction of charge in them. Two kinds of nanoparticles, namely metallic (copper) and ceramic (alumina and CuO), are chosen and their effects on the electrical conductivity of nanofluids are analysed. These particles are used in different particle concentrations with water and EG as base fluids. The behaviour of electrical conductivity of alumina–water nanofluids has been studied for different temperature, particle sizes, and electrolyte concentrations to give a comprehensive picture of the ion transport behaviour in nanofluids. The results have been compared with the theoretical model of O'Brien [19].

2. Materials and methods

2.1. Preparation and characterisation of nanofluids

Nanoparticles with different particle sizes used in this study are purchased commercially. Alpha alumina nanopowders (α-Al_2O_3) with particle size of ~150 nm were procured from Inframat Advanced Materials, USA whereas particles with sizes 20–30 nm and 80 nm were from Nabond, China. Copper and copper oxide nanoparticles, with size ~80 nm were bought from NT base, South Korea. Deionised water (DI) and EG are used as the base fluids, sodium dodecyl sulfate (SDS) as a surfactant and hydrochloric acid (HCl) is used as electrolyte. The nanoparticles are characterised for its morphology by transmission electron microscopy (TEM). The TEM images (Fig. 1) of the nanoparticles show that alumina, copper and CuO nanoparticles are spherical in shape and properly dispersed. However, in the present study, the particle shape is not considered as a parameter and the study is concentrated only on the state of dispersion for estimating the electrical conductivity. The metals form a thin layer of oxide on its surface in atmosphere and the rate of oxidation depends on the temperature, humidity and level of pollution of the surroundings. The purity of Cu is confirmed by X-ray diffraction (XRD) in Fig. 2. The peaks corresponding to 43.63°, 50.6°, and 74.3° are the characteristics peaks of copper as given by JCPDS data software. The other two peaks at 36.7° and 61.6° are due to oxides and their presence is relatively less. The pure metal powder should be taken care that it is not exposed to open atmosphere for long periods and there should be minimum rise in temperature while sonicating to avoid oxidation of nanofluids so that the oxidation is minimum as in the present case.

Nanofluids with various particle concentrations (0.05, 0.1, 0.25, 0.5, and 1 vol%) are prepared weighing the particles accurately and mixing with base fluid in a clean glass beaker, followed by ultra-sonication. The effect of electrolyte has been studied using three different concentrations (1 M, 0.5 M, and 0.05 M) of HCl alumina–water nanofluids. Alumina with various particle sizes has been used to estimate the variation in electrical conductivity with particle size. The dependence of electrical conductivity on temperature is analysed in the temperature range of 30–60 °C and the effect of surfactant is also studied.

2.2. Experimental setup and measurement details

The electrical conductivity is measured by a 4-Cell conductivity electrode meter (CYBERSCAN CON 11) with inbuilt automatic temperature compensation (ATC). Experimental setup is shown in Fig. 3. Fig. 3(a) shows the electrical circuit which has four circular

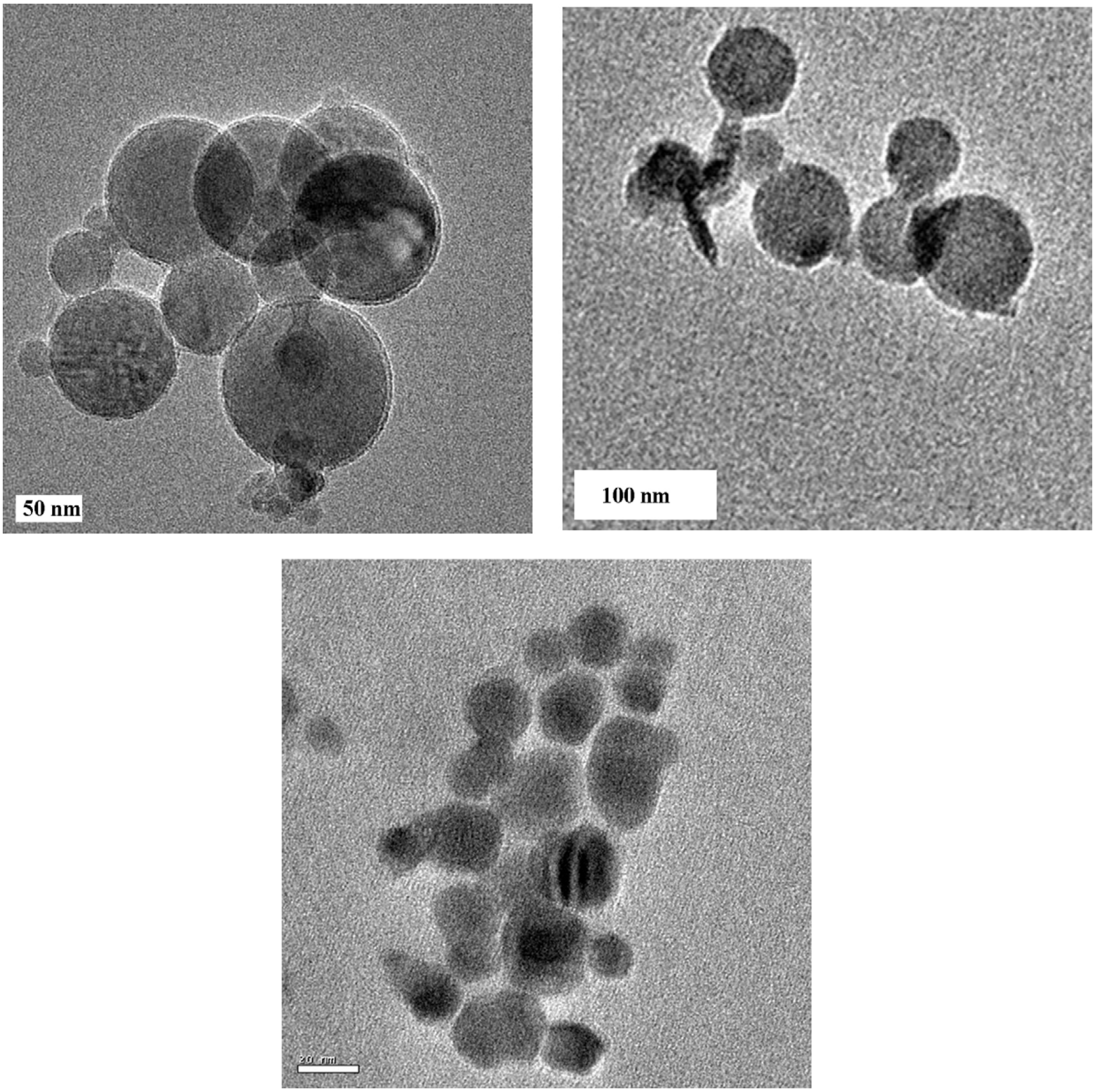

Fig. 1. Transmission electron microscope (TEM) images of nanoparticles: (a) Al_2O_3, (b) Cu, and (c) CuO.

electrodes and Fig. 3(b) shows the measuring setup with the sample. The display shows the electrical conductivity values with instantaneous temperature. The electrode meter gives both temperature and conductivity values simultaneously at a given instant. The instrument is calibrated with de-ionised (DI) water and ethylene glycol, and the consistency of readings is checked by repeating measurements and is found to agree with the standard values. The zeta potential of the particles is measured using Zetasizer Nano ZS 90 Malvern in the measurement range of 3.8 nm to 100 μm. A water proof pH meter Testr30 (Eutech Instruments – Oakton) with inbuilt ATC has been used to measure pH of the solution, which is having the range of −1.00 to 15.00 pH and relative accuracy is 0.01.

The error in the experimental data can be given as the total of the instrumental and the measurement error. The measurement error is attributed to the deviation from the actual results (from repeatability) due to experimental conditions. It is found to be ±1%. The instrumental uncertainty for electrical conductivity and temperature measurement is ±1% (full scale + 1 digit) and 0.1 K in the conductivity range is 0–1999 μS/cm. Thus, the total experimental error is limited to 2%. The deviation due to the error is shown in the form of error bars in Figs. 4 and 6.

The experimental setup is used to measure the electrical conductivity of few known fluids and is compared with the standard values in the literature [25]. The values are tabulated in Table 1.

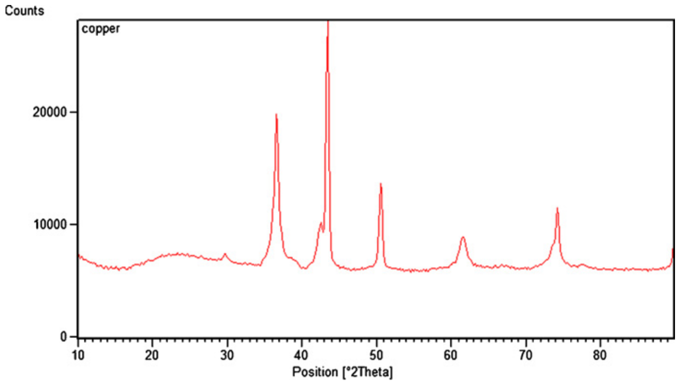

Fig. 2. X-ray diffraction (XRD) of Cu.

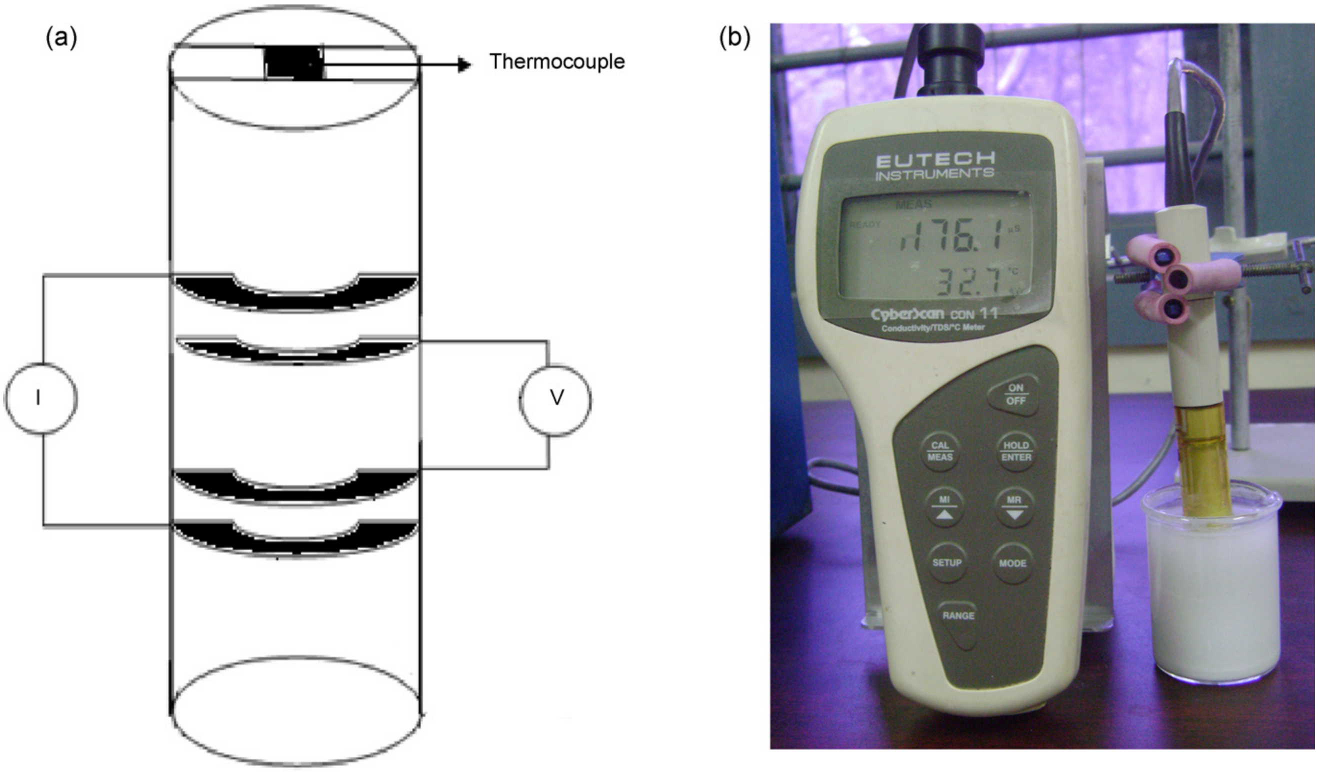

Fig. 3. Experimental setup of electrical conductivity measurement: (a) electrical circuit with circular electrodes and (b) measurement setup with sample.

Table 1
Comparison of electrical conductivities of known fluids with the standard values.

Fluids	K (μS/cm) (measured)	K (μS/cm) (standard)
Isopropyl alcohol	5	6
10 mM KCl	1408	1400

3. Results and discussion

The contribution of electrical properties in nanofluids is revealed in this work. There is a significant dependence on the dispersed particles and its concentration. A detailed study on electrical conductivity of nanofluids with various parameters is thoroughly analysed in the following sections.

3.1. *Effect of system (nanoparticles and base fluid combination)*

The present work investigates the effect of different nanoparticles in base fluids. The electrical properties of the base fluid get altered on the dispersion of nanoparticles. The electrical conductivity of the base fluid (DI water) is measured as 6 μS/cm. Fig. 4 shows the electrical conductivity values of water-based nanofluids with various particle concentrations and compared with Maxwell model. It is observed from the figure that the electrical conductivity increases linearly with concentration for ceramic (CuO and Al_2O_3) nanofluids and increases in a nonlinear fashion for metallic nanofluids (Cu). Also it is observed that the metallic nanofluids show less conductivity enhancement than oxides which is counterintuitive, keeping the higher conductivity of metals into consideration.

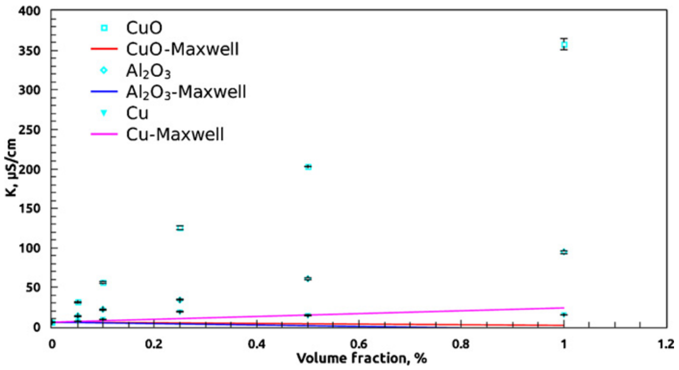

Fig. 4. Electrical conductivity of water nanofluids.

The main cause for the enhancement in the above observation is the formation of surface charges by polarisation of nanoparticles when dispersed in the base fluid of water which is polar. The polarisation process is quantified by the effective dielectric constants and the densities of both the particles and the base fluid as given in Table 2.

The dielectric constant [26] and density [27] of base fluid get altered when the nanoparticles are dispersed in it. The effective values of the properties are given by Eqs. (1) and (2).

$$\varepsilon_{\text{eff}} = \varepsilon_1 + \frac{3\varepsilon_1(\varepsilon_2 - \varepsilon_1)}{2\varepsilon_1 + \varepsilon_2}\phi \tag{1}$$

$$\rho_{nf} = \rho_p\phi + \rho_{bf}(1 - \phi) \tag{2}$$

where subscripts p, nf, and bf refer to the particle, nanofluid and base fluid, respectively, ρ is the density, ϕ is the particle volume

Table 2
Properties of nanoparticles and base fluids used in this work.

System	Dielectric constant, ε	Density, ρ (g/cm^3)
Water	80	0.999
Ethylene glycol	38	1.1085
CuO	18.1	6.3
Al_2O_3	9.1–9.3	4
Cu	6.1	9

Table 3
Increment in dielectric constant with density of particles.

Nanofluids	ρ_{nf}	ε_{eff}	$d\varepsilon/d\rho$
CuO	3.65	38.3	137.27
Al_2O_3	2.5	29.8	122.11
Cu	5	26.6	49.15

fraction, and ε_1 and ε_2 are the dielectric constants of the base fluid and particle, respectively.

The change in dielectric constant ($d\varepsilon$) for a change in the concentration or density ($d\rho$) of particles is given by Clausius–Mossotti relation as

$$\frac{d\varepsilon}{d\rho} = \frac{(\varepsilon_{\text{eff}} - 1)(\varepsilon_{\text{eff}} + 2)}{3\rho_{nf}} \tag{3}$$

From Eq. (3), the increase in effective dielectric constant of nanofluids with density can be found. Table 3 shows $d\varepsilon/d\rho$ values of water nanofluids for a particular concentration ($\phi = 0.5$) of particles.

From Table 3, it is observed that the effective increment of dielectric constant with density is high for oxide nanofluids and for copper nanofluids it is low due to its high particle density. In general, the electric field (E) experienced by the particles (considered as dielectric here) present in a medium is reduced due to the polarisation as given by

$$E = \frac{q}{\varepsilon} \tag{4}$$

and the polarisation density (P) is given by

$$P = q\left(1 - \frac{1}{\varepsilon_{\text{eff}}}\right) \tag{5}$$

where q is the charge of the carrier. The polarisation (P) increases due to the effective dielectric constant of the dispersion (Eq. (5)). To relate the polarisation to the conductivity (K) of the fluid, from the basic principles it is known that the conductivity is the ratio of total current density (J_{tot}) to the applied electric field (E) given by

$$K = \frac{J_{\text{tot}}}{E} = \frac{J_b}{E} \tag{6}$$

and total current density is the sum of current densities due to free (electrons, holes) carriers (J_f) and bound (polarised) charge carriers (J_b). In nanofluids, we assume only the presence of bound carriers, J_f being zero.

$$J_{\text{tot}} = J_b = \frac{\partial}{\partial t}\int \rho_b \; dV = -\int \nabla . P \, dV \tag{7}$$

Using Gauss theorem volume integral is changed to surface integral where the surface S is the area bounded by the volume V:

$$-\int \nabla \cdot P \, dV = -\int P \cdot da \tag{8}$$

where ρ_b is the density of bound charges in volume V.

Thus from the above discussion, it is clear that polarisation is responsible for the current flux across the interface of the particles surface S. The polarisation current density is found and applied electric field being known, the electrical conductivity of polarised particles in the aqueous medium is found by Eq. (6). The results are compared with the Maxwell model based on 'effective medium' theory which relates the electrical conductivity of the nanofluids with the concentration of the particles (ϕ) alone. This model does not include the polarisation effect of the particles and the effective values of its properties and hence the experimental results do not match with the model as shown in Fig. 4. The electrical conductivity increment with effective dielectric constant is shown in Fig. 5. It shows the increase in the conductivity values with dielectric constant and also with volume fractions. The results are consistent with the above explanation.

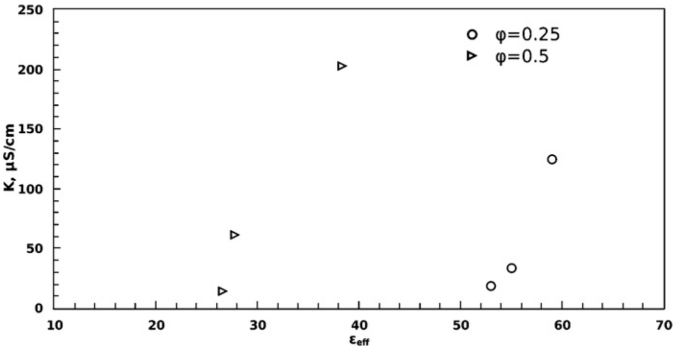

Fig. 5. Effect of dielectric constant on the electrical conductivity of water nanofluids.

Fig. 6 shows the electrical conductivity variation of EG nanofluids with particle concentration. Electrical conductivity of EG is 1.07 µS/cm which is a mild polar liquid. The polarisation process is very weak compared to the water nanofluids as there is less availability of polar molecules. Thus the increase in electrical conductivity values is very low with particle concentration. The results are also compared with the Maxwell model which considers the concentration of particles. The model fits well for the conducting particles (Cu) in the limit of infinite particle electrical conductivity which reduces the model to depend on concentration alone. It does not agree for non-conducting particles (Al_2O_3 and CuO). The Clausius–Mossotti (C–M) relation holds good only for polar fluids. A correction term for mildly polar fluids is included in the C–M equation that takes the dipole moment interaction and their fluctuations between the neighbouring molecules into account which complicates the term and usually found only by molecular dynamic simulations [28].

3.2. Effect of stabilisation of alumina–water nanofluids

The effect of electrolytes on the nanofluids in the formation of electrical double layer (EDL) is studied by adding three different concentrations (1 M, 0.5 M, and 0.05 M) of hydrochloric acid to alumina–water nanofluids and the results are shown in Fig. 7. From the figure it can be observed that for each HCl concentration, the electrical conductivity decreases with the fraction of nanoparticles and shows a slight rise after a particular (critical) concentration of particles. The critical concentration increases with increasing electrolyte concentration.

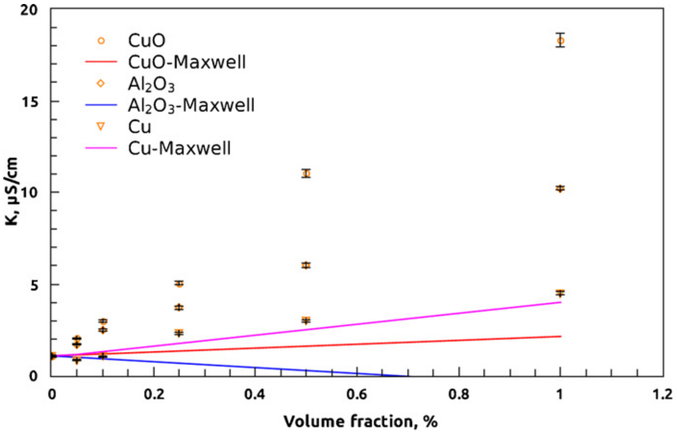

Fig. 6. Electrical conductivity of EG nanofluids.

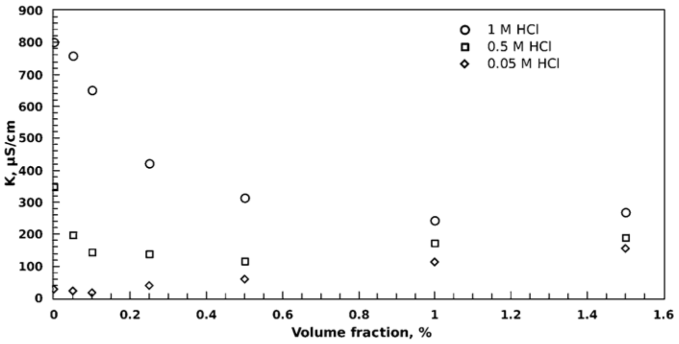

Fig. 7. Effect of electrolyte (HCl) on the electrical conductivity of alumina–water nanofluids.

This feature can be explained on the basis of EDL formation. The dispersed particles forms surface charges which are compensated by a dense layer of counter ions close to the surface, followed by diffuse layer of both type of ions. The potential measured from the surface of the particle to the bulk solution where the potential becomes less is termed as zeta potential and this layer is called electrical double layer. The thickness of this layer is termed as Debye length ($1/\kappa$). Zeta potential is measured to be 51 mV, 33.4 mV and 32 mV for three HCl concentrations, respectively. Fig. 8 shows the zeta potential curve for 0.5 M HCl in alumina–water nanofluids. For low ionic concentration, the surface conductance is more than the bulk fluid which increases the electrical conductivity and with higher ionic concentrations the diffuse layer becomes thicker and the electrical conductivity is reduced.

The experimental values of electrical conductivity are compared with the theoretical model proposed by O'Brien [19] for dilute suspensions given by Eq. (9):

$$\frac{K^*}{K_{bf}} = 1 - 3\Phi - \left[\frac{L(\kappa a)I_3 e\zeta}{kT} - \left\{I_4 M(\kappa a) + N(\kappa a)\left(\frac{\sum_{j=1}^{j=N} z_j^2 n_j^\infty}{\sum_{j=1}^{j=N} z_j^2 (n_j^\infty/m_j)}\right)\right\}\left(\frac{e\zeta}{kT}\right)^2\right] \qquad (9)$$

where

$$I_3 = \frac{z_1(\omega_1 - \omega_2)}{(\omega_1 + \omega_2)}$$

$$I_4 = (z_1^2)$$

$$\frac{\sum_{j=1}^{j=N} z_j^2 n_j^\infty}{\sum_{j=1}^{j=N} z_j^2 (n_j^\infty/m_j)} = \frac{2m_1 m_2}{m_1 + m_2}$$

and $L(\kappa a)$, $M(\kappa a)$, and $N(\kappa a)$ are mathematical functions given in terms of exponential integrals, ω_1 and ω_2 are the ionic mobility of the suspensions and m_1 and m_2 are ionic drag coefficients of the species.

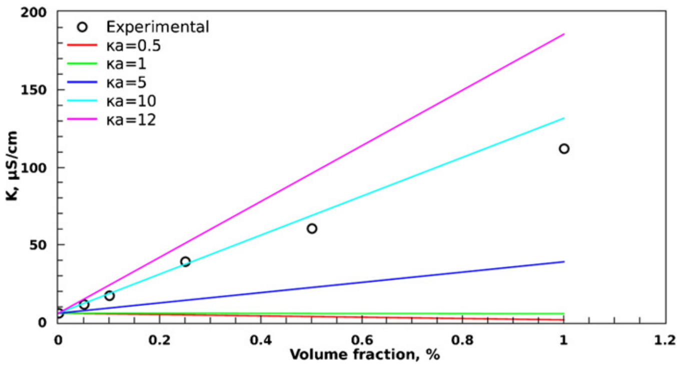

Fig. 9. Comparison of experimental results of alumina water nanofluids with O'Brien model of dilute suspensions.

The O'Brien model is explained using double layer thickness (κa) and zeta potential (ζ) values. Theoretical calculations are done for different κa values and compared with the experimental values of electrical conductivity as shown in Fig. 9. It is observed that the theoretical values are comparable with experiments for a double layer thickness (κa) of 10 where 'a' is the radius of the particle (80 nm). The Debye length ($1/\kappa$) is calculated using the concentration of ions (I) by the equation,

$$\kappa = (32.87 \times 10^8 \sqrt{I})\,\mathrm{m}^{-1} \qquad (10)$$

This model can be used for finding the double layer thickness of a given nanofluid if the ionic concentration is not known.

3.3. *Effect of surfactants on alumina–water nanofluids*

The surfactant used in the stabilisation of nanofluids has a crucial effect on the electrical conductivity of nanofluids. Sodium dodecyl sulfate (SDS) is used as a surfactant. These surfactants, below the critical micelle concentration (CMC) are in the form of monomers and at CMC they form micelles (aggregates) and further addition increases the viscosity of the nanofluids. The experiments have been done below the CMC of the surfactant. The monomer attaches to the particles surface, stabilises them and thus increases the electrical conductivity of the nanofluids. Fig. 10 shows the influence of surfactant on the electrical conductivity of alumina nanofluids. Two different concentrations (0.1 mM and 0.5 mM) of

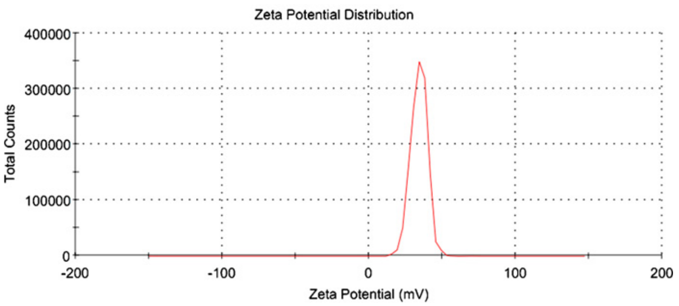

Fig. 8. Zeta potential of 0.5 M HCl added alumina water nanofluids (34 mV).

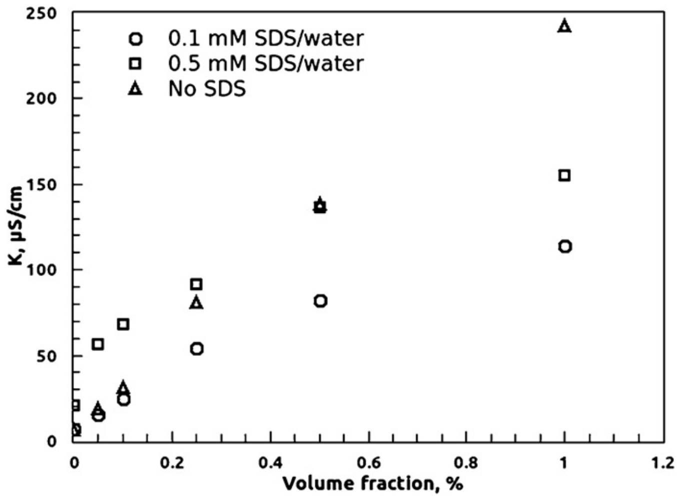

Fig. 10. Influence of surfactant on the electrical conductivity of alumina nanofluids.

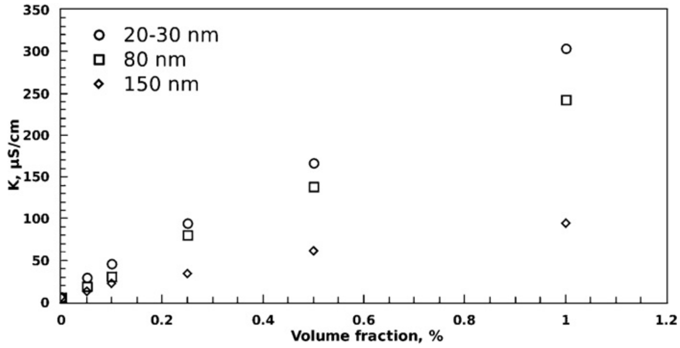

Fig. 11. Electrical conductivity variation of alumina water nanofluids with particle size.

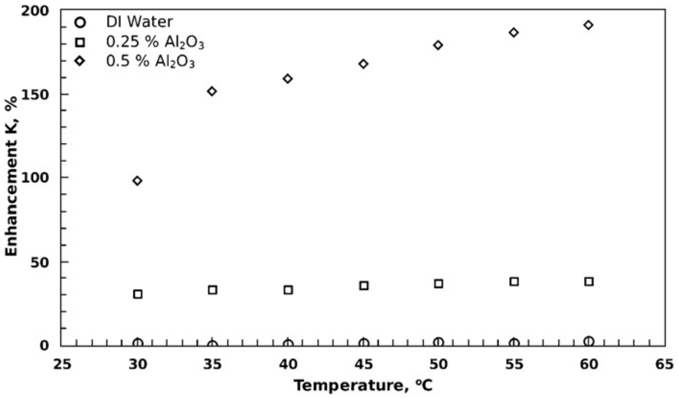

Fig. 12. Influence of temperature on electrical conductivity of nanofluids.

SDS are used with various particle fractions. It can be observed that the enhancement of the conductivity in presence of the particles with SDS is more than water with SDS alone. It is also observed in the graph that the conductivity is contributed greatly by the particles at higher concentrations (>0.25%), whereas at low concentrations contribution of free ionic monomers are more to the electrical conductivity of nanofluids. The presence of the surfactants confirms the stability of nanofluids but the electrical conductivity of them is reduced slightly in their presence which can be clearly seen from Fig. 10.

3.4. *Effect of particle size of alumina–water nanofluids*

Particle size determines the surface area, pH and dispersion properties in nanofluids. It was observed that the surface reactivity and iso electric point (IEP) are size-dependent [25]. The zeta potential decreases with reducing particle diameter, due to increase in surface area and the number of particles. As the number of particles increases, the charges available for the formation of EDL are not sufficient for particles and thus there is a reduction in zeta potential. Fig. 11 shows the variation of electrical conductivity of alumina nanofluids with particle size. The effect of particle size is explained and the effective particle volume fraction is given by Larson [29]:

$$\phi_{\text{eff}} = \frac{d_{\text{eff}}}{2a}\phi \qquad (11)$$

where ϕ is the particle volume fraction (%), ϕ_{eff} is the effective particle volume fraction (%), a is the particle radius (nm), d_{eff} is the effective particle diameter (nm) of the nanoparticles.

From the above equation, it can be seen that for the same volume fraction of nanofluids having different sizes of nanoparticles, the effective volume fraction is higher for smaller particle sizes. The electrophoretic mobility increases with reduced particle size. Hence it is observed that particle size reduction has a positive effect on the electrical conductivity of nanofluids.

3.5. *Effect of temperature on nanofluids*

The effect of temperature on the electrical conductivity of alumina–water nanofluids has been studied and the results are shown in Fig. 12. There is no appreciable enhancement of electrical conductivity with temperature for low volume fractions (less than 0.5%). It has been stated that aggregation is a time-dependent phenomena and the aggregation time decreases significantly for decreasing nanoparticles size and with the increasing temperature [30]. In this work the particle size is same and even though aggregation takes place with temperature, there is an electrical conductivity enhancement with the same. This is because the aggregated particle forms contact (percolation) with each other which facilitates the charge transport between the electrodes with increase in particle fractions. This also brings out the fact that the mechanism of charge transport is different from that of heat transport where perceptible increase in thermal conductivity with temperature is observed due to the increase Brownian motion of the particles [31]. This also indicates that the classical Maxwellian effective medium theory for microsuspensions which is applicable to both thermal and electrical conductivity does not apply to nanofluids.

4. Conclusion

An experimental study has been performed to bring out the influence of various physico-chemical factors on the electrical conductivity of nanofluids with ceramic and metallic nanoparticles. The nanoparticles used in the present study are copper, alumina and copper oxide. It is shown that there is a nearly linear rise in electrical conductivity of water- and EG-based nanofluids with particle volume fraction. It is argued that the effective dielectric constant and density are at the root of the counterintuitive observation that the electrical conductivity enhancement of ceramic nanofluid is more than that of metals which is substantiated by the Clausius–Mossotti relation for the polar fluids. The presence of surfactant increases the stability and decreases the electrical conductivity of the nanofluids. The decrease in the size of alumina nanoparticles increases the electrical conductivity of water-based nanofluids which is attributed to the increased surface area and electrophoretic mobility of the particles. There is no significant rise in electrical conductivity of water nanofluids with temperature. The electrical double layer formation around the particles is studied by adding different molar concentrations of HCl to the alumina water nanofluids. It is found that nanofluids with low ionic strength have an enhancement in electrical conductivity while it decreases for high ionic strength. This is due to the variation in the surface conductance of the particles. The experimental values are compared with O'Brien [19] model of electrical conductivity of dilute suspensions. This model explains the electrical conductivity from the electro kinetic radius (κa) and zeta potential (ζ) of the dispersed particles. From this theoretical model, κa values of alumina nanofluids have been found out. This work will also be useful for studying the stability criteria of the nanofluids since the stability of nanofluids depends critically on surface charges on the nanoparticles.

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