On the thermal conductivity and viscosity of bionanofluid with neem (Azadirachta indica) assisted zinc oxide nanoparticles

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Abstract
Nanofluids which act as coolants in various thermal applications have been promising in accomplishing the primary objective of heat transfer. However, the impact of such fluids on flow lines in the form of enhanced friction factor through unacceptable viscosity rise is an issue to be addressed. On the other hand, these fluids are expected to deteriorate the environment when used or disposed. Hence this research focuses on preparing a bionanofluid and investigating on its primary properties, the thermal conductivity and viscosity. The bionanofluid is prepared by dispersing neem (azadirachta indica) assisted zinc oxide nanoparticles in a binary mixture of ethylene glycol-water (50:50 by volume), at volume concentrations of $\phi=0.05$, 0.2 and 0.5%. To compare the properties of these bionanofluids, additional nanofluids were prepared by dispersing combustion derived pure zinc oxide at same volume concentration. By XRD analysis, the average crystallite size of neem assisted ZnO and pure ZnO was found to be 36 nm and 32 nm. Based on the SEM images, the particles were found to be much closely packed in bioparticles than combustion derived ones. The zeta potential of the nanofluids was found to be $\pm 30$ mV at pH 6.5, at which the stability is deemed excellent. The thermal conductivity and viscosity of the nanofluids were measured under varying volume concentration and temperature ranging between 20°C and 50°C. Though the thermal conductivity of the conventional ZnO nanofluid is 3.8% higher than the ZnO bionanofluid, the viscosity is 2% lower for the latter than the former, which is highly expected from any nanofluid for an efficient thermal transport.

Keywords: Azadirachta indica, Zinc oxide, Synthesis, Ethylene glycol, Bionanofluid, Zeta potential, Iso-electric point, Thermal conductivity, Viscosity

1. Introduction

In spite of lower thermal conductivity of metal oxide nanoparticles, they are chosen over the metal based particles for nanofluid preparation, due to their oxidation resistance, lower density and lower particle settling issues (Kwak 2005; Suganthi and Rajan, 2012). Amidst many metal oxide nanoparticles, ZnO is chosen for its relative abundance and low cost of raw materials and synthesis. In nature, these oxides exist either as cubic or hexagonal wurtzite crystal structure. These particles find place as additives in various applications such as ZnO has been used in a wide range of applications such as additive in building structures, rubber materials, food processing, biomedical and gas sensing applications (Claus F. Klingshirn, 2010).

There are various factors which must be optimized before choosing a nanoparticle for synthesizing a nanofluid for being used as a coolant, such as particle size, shape, morphology, thermal conductivity, specific heat, cost, availability and environmental effects. ZnO fits mostly in to these factors and they could be synthesized using various methods (Dhanya R, 2014).
Since the research on various nanomaterials for nanofluids emerged, there are no studies to explain the environmental degradation after they are disposed. Hence, toxic nature of the nanomaterial is another challenge in its selection, especially when used for food processing industries. There are few papers which reveal the anti-microbial and hazardous nature of the ZnO nanoparticles (Brayner et al., 2006; Elshaer, 2008; Zhang et al., 2007). Hence ZnO could be a potential non-threat material for preparing nanocoolants.

Ample number of papers has been evident on the enhanced thermal conductivity of ZnO based nanofluid when compared with the commonly used base fluids such as water, glycols, glycol-water mixture (Ahmadi Nadooshan, 2017; Cabaleiro et al., 2015; Radkar et al., 2019; Suganthi et al., 2014). However, the viscosity of nanofluids plays a predominant role in the frictional effects during its flow through pipes, tubes and ducts of heat exchangers. The lowest the viscosity, lesser is the friction factor and hence the Performance Evaluation Factor (PEF) will be much higher for an efficient use in energy applications.

In order to reduce the viscosity of the nanofluids and to effectively reuse the fluids, biosynthesis of nanoparticles is a very effective method and the use of neem in the biosynthesis of ZnO nanoparticles have already been discussed by few researchers for various biological applications (Handago Dawit et al., 2019; Singh et al., 2019). However, there have been no works reported on the thermo-physical property investigations on the biosynthesized ZnO nanoparticles. Hence in this work, the ZnO nanoparticles are synthesized with and without neem using combustion synthesis and biochemical synthesis, respectively.

2. Materials and Methods

2.1 Raw materials and resources

Zinc acetate dihydrate (Product No. 5970-45-6, C6H5O4Zn.2H2O of 99% purity) was purchased from Spectrum reagents and Chemicals Private Limited, India. Glycine (Product No. 56-40-6, C2H5NO2 of 98.5% purity) is purchased from Thermo Fischer Scientific, India. The Whatman No. 1 filter paper and zinc nitrate hexahydrate (Product No. 228737, Zn(NO3)2.6H2O of 98% purity) was purchased from Merck, India.

2.2 Characterization methods and equipment

The XRD analysis of zinc oxide nanopowder samples were performed on Bruker, D8 advance rotaflex diffraction meter which contains a copper anode, Cu Kα, λ=1.5406Å. At a voltage of 45 kV and 40 mA, the X-ray tube was operated. The analysis is performed at a step scan rate of 0.02° in the 2θ range of 20 to 80°. The SEM analysis is performed using ZEISS Supra 40. The powder samples are coated with 10 nm thickness gold by sputter coating and at 8 mm working distance, the sample is analyzed at 20 kV accelerating voltage.

The powder samples were dispersed in the base fluid and sonicated with a 50 W total power using Sonicator 4000 (20 kHz). The stability investigation through zeta potential is performed using the Malvern Zeta sizer (Nano-ZS) instrument. The nanofluid viscosity was measured using a LV DV-II+PRO EXTRA Brookfield viscometer which comprises of cooling water bath based water jacket equipped around the sample holder to maintain temperature while taking measurements. The thermal conductivity of the samples are measured by placing the sample within a container enclosed by a Thermo Haake K10 water bath using the KD2 Pro Thermal Properties Analyzer of the Decagon devices, which works based on the transient hot wire method. All the fluid properties of the nanofluid samples were measured for different volume concentration (0.05, 0.2 and 0.5%) and temperature (20 to 50°C).

2.3 Synthesis of zinc oxide (ZnO) nanoparticles

Neem leaves collected and rinsed for multiple times with sterilized double distilled water were dried using a black coated vessel placed under sun shade for 3 hours. It is then ground well to fine powder and 20 g of it is dissolved in 1 litre of double distilled water and magnetically stirred at 600 rpm while maintaining the hot plate at 60 °C for 4 h. The obtained aqueous neem solution which looks like urea yellow in colour is then filtered by using Whatman filter paper and is cooled down to the ambient condition and stored in a cool condition. 100 ml of aqueous neem solution is taken and 10 g of zinc acetate dihydrate (Zn(CH3CO2)2•2H2O) is conditioned using a magnetic stirrer at 60 °C at 250 rpm for 40 min. by maintaining the pH between 6 and 7 by adding sodium bicarbonate in drops. A yellowish brown mucilage type gel is formed which is taken for drying in hot air oven and calcined within muffle furnace at 850°C for 5 hours after which yellowish powder is fine sized using ball mill.

On the other hand Solution combustion method (Suseel et al., 2018) is used to synthesize pure ZnO nanoparticles.
It is performed by stoichiometrically mixing zinc nitrate hexahydrate (Zn(NO₃)₂•6H₂O) purchased from Merck, India and glycine (C₂H₅NO₂) fuel purchased from Thermo Fischer Scientific, India, in the 100 ml of double distilled water. It is then magnetically stirred at 450 rpm for 2 hours, after which it is heated using the mantle for few hours till the combustion fumes are formed. It is ensured that a complete burning with removal of fluids happened with the by-product formed as flakes within the beaker surface. They are then collected, crushed with mortar and again taken to the ball mill for fineness. Later, it is calcined at 850°C for 3 hours within a muffle furnace.

2.4 Preparing ZnO-EG/Water nanofluid

Six different samples of nanofluids with volume concentrations of 0.05, 0.2 and 0.5% each containing the synthesized pure (ZnOₚטעם) and neem assisted zinc oxide (ZnONeill) is prepared by two-step approach (Suseel et al., 2019). Before adopting the two-step approach, the sensitized digital weighing balance must be calibrated. The required weight of the nanoparticles based on the volume concentration, is calculated and the powders are weighed and measured accordingly. 1.75 litres of base fluid mixture which is water-ethylene glycol (aqua-antifreeze) is taken in equal proportions by volume. It is then equally distributed and stored in 7 different beakers. Except one beaker, the other beakers are dispersed with nanoparticles, continuously stirred at 350 rpm for 30 min. and ultrasonicated for 25 to 40 min. No surfactant was added in this case for fluid stability as the zinc oxide surfaces are hydrophilic due to the presence of OH groups in it. The prepared fluids are kept isolated and undisturbed from all sorts of sound and vibrations for 3 weeks to have a visual check on its stability (Carraway et al., 1994; Li et al., 1999).

3. Results and Discussion:
3.1 Powder characterization

![Fig. 1](image)

Fig. 1 (a) XRD spectra of ZnONeem (b) XRD spectra of ZnOpure (c) SEM image of ZnONeem (d) SEM image of ZnOpure

The XRD spectra of the prepared samples are shown in Fig. 1(a-b). Almost three sharp peaks could be observed at 2θ values between 30° and 40° signifies that the obtained samples are zinc oxide of wurtzite crystal structure (JCPDS: 36-1451). Also the multiple lower intensity peaks indicate the high crystalline nature of the obtained samples. The crystallite sizes of the samples were calculated using Debye-Scherrer’s relationship (West, 1984).

The average crystallite size for zinc oxide prepared from neem assisted method is 36 nm and the pure zinc oxide synthesized by combustion route is 32 nm. The SEM micrograph image depicted as Fig. 1 (c-d) signifies the spherical nature of the particles for both the powder samples and appears to be closely clustered in the case of biosynthesized product due to the water molecules existing in the neem. To be noted is that the SEM images are used to study the surface morphology of the particles and the XRD is sufficient enough to find the crystallite size. However, the size of particles appear to be lesser than 50 nm in both the cases.
3.2 Physico-chemical properties

The bulk density of the nanopowder is the ratio of its weight per unit volume which is to be tested as per ASTM D 1895. A cup which collects the sample is placed beneath a funnel which is filled with the sample after closing its bottom mouth. Without shaking either the funnel or the cup, the funnel mouth is opened for the sample to fall freely into the cup. If there is any clogging in the funnel during the flow, a smooth glass rod is used. One the cup is filled or over flows, a smooth knife edge is used to remove the excess layer of the sample over the cup. By measuring the sample mass using a sensitive weigh balance of uncertainty ±0.1 mg, the bulk density of the powder is measured as the volume of the cup is known already.

The purity of the nanopowder can be obtained by a simple titrating procedure. Dissolve 2.5 g of NH₄Cl and 1.5 g of the nanopowder into 50 ml of standard HCl. With methyl orange (C₁₄H₁₄N₃NaO₃S) as indicator, titrate the excess acid using NaOH solution. Measure the volume of NaOH used in this titration \( V_{\text{sample}} \). Repeat the same procedure without dissolving any powder sample and measure the volume of NaOH used in this blank titration \( V_{\text{blank}} \). Hence the purity of ZnO samples in mass percentage is measured by the formula, 2.71 \( (V_{\text{blank}} - V_{\text{sample}}) \). The BET surface analysis using a Micromeritics Tristar 3000 surface analyzer was adopted to measure the Surface area of the nanoparticles. With liquid N₂ temperature, the experiments were performed by N₂ adsorption.

Thermoflash 2200 laser flash apparatus was used to measure the thermal diffusivity and specific heat capacity of the nanopowder which was tested after preparing them as a compact disk shaped sample. When the sample placed within the furnace attains a steady state temperature, a laser is fired to provide a small energy pulse on the leading sample surface, which diffuses the heat towards the trailing surface of the sample. The variation in temperature with respect to time is monitored by infrared detector and logged by a data acquisition system, from which the thermal diffusivity is measured. And to know the specific heat capacity, the relative thermal response of the ZnO powder sample and a known sample, here, Pyroceram 9606, is compared, under the specific measuring conditions. Hence, the thermal conductivity of the powder samples could be measured by the product of thermal diffusivity, bulk density and specific heat. To conclude all the measured physicochemical properties of the pure ZnO and neem assisted ZnO samples are listed in Table 1.

The purity of the pure ZnO is higher than that of neem assisted ZnO, as the former is synthesized by solution combustion method wherein the impurities would be burnt out. As we could infer from the SEM image that the neem assisted ZnO is closely packed and clustered, the density of it is lower than that of the pure neem which appears to looks loosely packed flakes, where the pores are slightly more, which is evident from the Surface area of the powder samples. The specific heat capacity of the neem assisted ZnO is slightly lower due to the excellent heat carrying capacity of the neem, which makes the fluid sample dispersed with it as an efficient heat transfer fluid than the conventional ZnO. And the particle with good heat carrying capacity possesses good thermal conductivity. However, the role of particle diameter on the thermo-physical properties of the nanofluid is to be deeply investigated due to the role played by the surface to volume ratio in the interfacial layering between the solid and fluid molecules.

Table 1 Physicochemical property of synthesized ZnO nanoparticles

| Properties                  | ZnO\text{pure} (32 nm) | ZnO\text{Neem} (36 nm) |
|-----------------------------|------------------------|------------------------|
| Purity [%]                  | 99.7                   | 99.3                   |
| Density [g/cm³]             | 5.712                  | 5.536                  |
| Surface Area [m²/g]         | 10.4                   | 11.7                   |
| Specific heat [J/(kg.K)]    | 501                    | 498                    |
| Thermal Conductivity [W/(m.K)] | 16.1                  | 17.8                   |

3.3 Stability

Visual inspection on the fluid samples which were kept undisturbed for 3 weeks indicated that the fluid samples were stable. However, the neem assisted sample with 0.5% concentration showed a lesser chance of agglomeration compared to its counterpart, thus signifying a better stability of the former than the latter. The highly concentrated samples were yet prepared with different pH and to test its stability through zeta potential measurement.

The zeta potential values for all pH conditions for both the samples were repeated 6 times with 30 seconds for
measuring with delay between each to be 5 seconds. The Coefficient of Variance (CoV) at all the cases were less than 3.7% and the maximum Uncertainty is ±2.95 mV or ±5.21% at 95% confidence level.

It could be observed from Fig. 2 that the iso-electric point (IEP) at which the particle starts forming large sized particles or agglomerates was 9.77 for the neem assisted ZnO was 9.45 for pure ZnO was 9.45. In addition to this, both the fluid samples were stable well near the neutral pH and at pH 12.5, which was evident from the zeta potential values of ±30 mV. Hence, all the remaining measurements were taken at pH 7.

Fig. 2 Measuring the Zeta potential of nanofluids with neem assisted and pure ZnO particles

3.4 Measuring the nanofluid properties

Before the nanofluid samples were considered for measuring the thermal conductivity and viscosity, a binary mixture of ethylene glycol and water which is the base fluid is considered. Above all, the equipment is calibrated and the system error is calculated by comparing it with the reference liquid as suggested by the manufacturers. All the measurements were taken 5 times to check the limit of coefficient of variance as per the equipment specifications.

To measure the thermal conductivity, the probe is inserted through the hole made on the cap of a vial which contains the fluid samples. The probe is heated based on the constant voltage supply for 30 seconds with additional 30 seconds to attain steady state. During these 60 seconds, the probe temperature is recorded for every 1 second interval. This temperature defines the fluid thermal conductivity. Based on the Fourier’s law of heat conduction for infinitely long line heat source, the fluid thermal conductivity is determined. Every subsequent reading was taken after 25 minutes of the temperature range obtained through a liquid bath to maintain sample temperature. Before taking the readings, the pump which is used to circulate the coolant in liquid bath is switched off to avoid vibrations leading to induced convection.

Fig. 3 Validating the measuring equipment with standard ASHRAE data
To measure the viscosity, take the fluid sample in the prescribed container and place it in the water bath. Place the viscometer spindle into the sample container in such a way that the air bubbles are not formed. Maintain a slow stirring for an hour to maintain the required temperature by controlling the water bath. Once the steady state is attained, measure the fluid viscosity. To be noted that the accuracy of the RTD thermocouples are ±0.1°C, for any property measurement.

The measured thermal conductivity and viscosity of ethylene glycol-water is plotted and compared with the ASHRAE standards as shown in Fig. 3. It could be noted that the deviation between them were lesser than 1%, which is very well agreeable. In addition, the maximum coefficient of variation for the thermal conductivity and viscosity based on all the fluid samples was 0.41% and 2.88% respectively.

### 3.4.1 Thermal conductivity

In general, the heat or mass transfer is found to be hindered by internal resistances in the fluid. The kapitza resistance or the thermal resistance existing between solid-fluid layer is defined as the heat flow resistance offered by the interfacial layers during the heat transport from solid to fluid. But, in the case of nanofluids, the solid-fluid interface provides a good support for heat transfer. As there is an orderly structure for solids, they possess effective thermal conductivity than the liquids. So, when they are dispersed into the base fluid, the effective arrangement of the fluid molecules around the nanoparticles results in a positively significant interfacial layers, thus enhancing the nanofluid thermal conductivity.

The thermal conductivity of the nanofluid was found to increase with increase in the volume concentration and temperature, as expected, which is observed from Fig. 4. This is due to the fact that more particle dispersion promotes enhanced interfacial layering of the base-fluid molecules around the nanoparticles and this increasing the kapitza resistance for enhanced thermal conductivity in the case of high particle concentrated fluid. It must also be inferred that the thermal conductivity of pure ZnO is higher due to comparably higher Brownian motion and hence the micro-convection effects which is possibly due to its lesser particle size and high surface to volume ratio.

In addition to this, the trends of the plots are nearly linear which indicates that there is no interaction between particles within the fluid. The thermal conductivity was found to increase with nanoparticle concentration in a linear fashion, which indicates absence of significant particle–particle interactions. The better stability of the nanofluid and the use of ethylene glycol as base fluid have been significant in avoiding the particle interactions.

![Fig. 4 Thermal conductivity under varying temperature and volume concentration](image-url)

However, the lower viscosity of the nanofluids at higher temperature can reduce the thickness of liquid layer, which could decrease the thermal conductivity too. At the same time, the rise in temperature could increase the Brownian motion of the particle, thus enhancing the thermal conductivity. Hence, we could note that the thermal conductivity of pure ZnO is higher than neem assisted ZnO, as the former possesses higher viscosity than the latter, during the change in temperature, in addition the lower particle size of pure ZnO, possessing better surface area than
neem assisted particle. The neem assisted ZnO and pure ZnO provided 10% and 6% enhancement in the thermal conductivity when compared with the base fluid. Hence it is to be noted that the thermal conductivity of the nanofluid is signified by the particle shape, particle size, particle surface area, particle density, particle thermal conductivity and the particle interaction with the fluid molecules. But the contributing proportion of each parameter over the thermal conductivity could not be established by a mere set of data.

We inferred that the smaller size particle possesses higher surface to volume ratio which enhances the thermal conductivity. Higher surface area of the particle will generate a significant particle-fluid interaction, accounting for enhanced thermal conductivity. Sometimes the density of particle accounts for additional Brownian velocity resulting in high thermal conductivity, but can cause stability issues in addition to creeping viscous effects. We can read from the Table 1 that the density of ZnO_{Neem} is lesser than ZnO_{pure}, whereas the particle size, surface area and thermal conductivity of ZnO_{Neem} are slightly higher than ZnO_{pure}. So based on all the inferences except the density comparison, nanofluids with ZnO_{Neem} should have possessed much higher thermal conductivity than ZnO_{pure}. But it was evident that the maximum thermal conductivity of nanofluids with ZnO_{pure} is higher than that of ZnO_{Neem}. This could be attributed to the less density of the neem assisted particles which might be due to the clustered nature with existence of pores within it and that these pores might have captured a part of heat within it, thus failing to conduct the heat to the annexed fluid molecules, causing such deterioration in the thermal conductivity.

3.4.2 Viscosity

There is always a need to investigate the change in viscosity of the nanofluid with reference to change in temperature, as these fluids are employed as coolants which are susceptible to cyclic heating and cooling conditions over a period of time. In addition to the above said, the Brownian motion effects is significantly introduced upon the change in viscous nature of nanofluids while the temperature changes. This is why the nanofluid viscosity appears to decrease with increase in temperature and increases with increase in the volume concentration of the particle as noted from Fig. 5. In other words, when the temperature increases, the intermolecular attraction between the fluid and particle reduces due to the increase in energy of the particles, which makes it flow freely and hence the viscosity starts reducing. In addition to the above said, the increased particle size contributes to a reduced viscosity which is due to higher interface resistance between the particles with lower surface area, and the fluid layer (P. K. Namburu, 2007; Pastoriza-Gallego et al., 2011). In other words, the surface to volume ratio of pure ZnO is much higher than that of neem assisted ZnO, which is why the viscosity of the latter fluid is higher than the former, as observed from Fig. 5. This inference is much important to be considered when nanofluids are investigated for transport properties. The viscosity enhancement appears to be higher for pure ZnO which accounts for 15% enhancement over the base fluid, whereas neem assisted ZnO is 10% higher than the base fluid.

![Fig. 5 Viscosity under varying temperature and volume concentration](image-url)
5. Conclusion

Pure ZnO and neem assisted ZnO nanoparticles synthesized by combustion and biological synthesis routes were 32 nm and 36 nm were average sized as per the Debye-Scherrer relation. They were spherical in shape and were lesser than 50 nm as per the SEM image. The neem assisted ZnO nanoparticles appear to be closely clustered than the pure ZnO. At volume concentrations of $\phi=0.05$, 0.2 and 0.5%, the nanoparticles were dispersed in the binary mixture of ethylene glycol and water (50:50 volume percentage) and magnetically stirred and ultrasonicated to obtain stable nanofluids, without adding any surfactants. The stability was visually inspected after 3 weeks and by zeta potential measurements. The iso-electric point (IEP) of both the samples was close to pH 9.5 and the best stability was noted at neutral pH. The increase in the temperature and volume concentration of nanoparticles has enhanced the thermal conductivity of the nanofluid. On the other side, there was a reduction in viscosity for rise in temperature and enhancement in viscosity for particle addition. All these changes were attributed to the liquid layering, Brownian movement and intermolecular attraction between fluid and particle molecules. It was well evident from the results that the neem assisted ZnO has equally enhanced desirable properties in addition to a well reduced viscous property when compared with pure ZnO, which makes the former a replacement for conventional ZnO in thermal transport based applications.

Conflict of Interest
The authors declare that they have no conflict of interest.

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References

Ahmadi Nadooshan, A., An experimental correlation approach for predicting thermal conductivity of water-EG based nanofluids of zinc oxide, Physica E: Low-dimensional Systems and Nanostructures, Vol.87, (2017), pp.15-19.
American Society of Heating, R., and Engineers, A.-C., ASHRAE Handbook: Fundamentals: American Society of Heating, Refrigeration and Air-Conditioning Engineers (2009).
Brayner, R., Ferrari-Iliou, R., Brivois, N., Djediat, S., Benedetti, M. F., and Fiévet, F., Toxicological Impact Studies Based on Escherichia coli Bacteria in Ultrafine ZnO Nanoparticles Colloidal Medium, Nano Letters, Vol.6, No.4, (2006), pp.866-870.
Cabaleiro, D., Colla, L., Agresti, F., Lugo, L., and Fedele, L., Transport properties and heat transfer coefficients of ZnO/(ethylene glycol+water) nanofluids, International Journal of Heat and Mass Transfer, Vol.89, (2015), pp.433-443.
Carraway, E. R., Hoffman, A. J., and Hoffmann, M. R., Photocatalytic Oxidation of Organic Acids on Quantum-Sized Semiconductor Colloids, Environmental Science & Technology, Vol.28, No.5, (1994), pp.786-793.
Claus F. Klingshirn, A. W., Axel Hoffmann, Jean Geurts. , Zinc Oxide: From Fundamental Properties towards Novel applications: Springer-Verlag Berlin Heidelberg (2010).
Dhana R, S. K., Rajan KS., Studies on Scale-up of ZnO Nanoparticles, Asian Journal of Chemistry, Vol.26, No.14, (2014), pp.4273-4276.
Elshaer, A. A. M., Molecular Beam Epitaxy Growth and Characterization of ZnO-based Layers and Heterostructures (2008), Cuvillier Verlag.
Handago Dawit, T., Zereffa Enyew, A., and Gonfa Bedasa, A., Effects of Azadirachta Indica Leaf Extract, Capping Agents, on the Synthesis of Pure And Cu Doped ZnO-Nanoparticles: A Green Approach and Microbial Activity, Open Chemistry, (2019), pp. 246-253.
Kwak, K., Kim, C., Viscosity and thermal conductivity of copper oxide nanofluid dispersed in ethylene glycol. Korea
Australia Rheology Journal, Vol.17, No.2, (2005), pp.35-40.
Li, W.-J., Shi, E.-W., Zhong, W.-Z., and Yin, Z.-W., Growth mechanism and growth habit of oxide crystals, Journal of Crystal Growth, Vol.203, No.1, (1999), pp.186-196.
P. K. Namburu, D. P. K., A. Dandekar, D. K. Das., Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids, Micro & Nano Letters, Vol.2, No.3, (2007), pp.67-71.
Pastoriza-Gallego, M. J., Casanova, C., Legido, J. L., and Piñeiro, M. M., CuO in water nanofluid: Influence of particle size and polydispersity on volumetric behaviour and viscosity, Fluid Phase Equilibria, Vol.300, No.1, (2011), pp.188-196.
Radkar, R. N., Bhanvase, B. A., Barai, D. P., and Sonawane, S. H., Intensified convective heat transfer using ZnO nanofluids in heat exchanger with helical coiled geometry at constant wall temperature, Materials Science for Energy Technologies, Vol.2, No.2, (2019), pp.161-170.
Singh, A., Neelam, and Kaushik, M., Physicochemical investigations of zinc oxide nanoparticles synthesized from Azadirachta Indica (Neem) leaf extract and their interaction with Calf-Thymus DNA, Results in Physics, Vol.13, (2019), Article ID: 102168.
Suganthi, K. S., Leela Vinodhan, V., and Rajan, K. S., Heat transfer performance and transport properties of ZnO–ethylene glycol and ZnO–ethylene glycol–water nanofluid coolants, Applied Energy, Vol.135, (2014), pp.548-559.
Suganthi, K. S., and Rajan, K. S., Temperature induced changes in ZnO–water nanofluid: Zeta potential, size distribution and viscosity profiles, International Journal of Heat and Mass Transfer, Vol.55, No.25, (2012), pp.7969-7980.
Suseel Jai Krishnan, S., Nagarajan, P. K., Mamat, R., Loganathan, V. D., Sathyamurthy, R., Synthesis, characterisation and thermo-physical investigations on magnesia nanoparticles dispersed in ethylene glycol–DI water (50:50), Micro and Nano Letters, Vol.13, No.3, (2018), pp.335-340.
Suseel Jai Krishnan, S., Nagarajan, P. K., Convective thermal performance and entropy generation analysis on Solution Combustion synthesis derived magnesia nano-dispersion flow susceptible by a micro-fin tube, Experimental Thermal and Fluid Science, Vol.101, (2019), pp.1-15.
West, A. R., Solid state chemistry and its applications (1984), London, John Wiley & Sons.
Zhang, L., Jiang, Y., Ding, Y., Povey, M., and York, D., Investigation into the antibacterial behaviour of suspensions of ZnO nanoparticles (ZnO nanofluids), Journal of Nanoparticle Research, Vol. 9, No.3, (2007), pp.479-489.