Int. J. Nano Dimens., 11 (1): 1-11, Winter 2020

ORIGINAL ARTICLE

Thermal and electrical conductivity of Aluminium Nitride nanofluids

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Received 11 July 2019; revised 09 August 2019; accepted 03 October 2019; available online 08 October 2019

Abstract

This study was designed to experimentally measure the thermal and electrical conductivities of Aluminium Nitride/Ethylene Glycol (AlN/EG) nanofluids. Transmission electron microscopy (TEM) was used to characterize the shape of AlN nanoparticles. Nanofluids with different particle volume concentrations of 0.5%, 1%, 2%, 3%, 4%, and 5% were utilized. The thermal and electrical conductivities of the nanofluids were measured using a KD2-Pro thermal analyser and electrical conductivity meter, respectively. The obtained results revealed that the thermal conductivity of the nanofluids increased at the higher volume concentration of the nanoparticles. Thus, at 5% volume concentration, the maximum thermal conductivity enhancement of 25% was obtained. The addition of AlN nanoparticles to the EG base fluid resulted in a significant increase in the electrical conductivity of the nanofluid. An enhancement in the electrical conductivity of approximately 520 times relative to the base fluid was attained by loading a 0.5% volume concentration of AlN in EG at 28°C.

Keywords: *AlN Nanoparticles; Electrical Conductivity; Nanofluid; Stability; Thermal Conductivity.*

How to cite this article
Ezekwem C, Dare A. Thermal and electrical conductivity of Aluminium Nitride nanofluids. Int. J. Nano Dimens., 2020; 11 (1): 1-11.

INTRODUCTION

Heat transfer fluids have been extensively used in automobile [1, 2], power generation [3], and electronic industries [4] and in many diverse industrial processes. These fluids are continually developed for engineering applications owing to their importance in heat transfer. The relatively low thermal performance of heat transfer fluids requires a continuous search for new working fluids. Nanofluids are a new class of heat transfer fluids, which are prepared by dispersing nanometer-sized particles in base fluids such as ethylene glycol, water, and oil [5–9]. These nanoparticles, when carefully dispersed in base fluids, improve the thermo-physical and electrical properties of these fluids. Therefore, the investigation of nanofluid properties is an important subject. Over the last decade, many experimental studies [10–22] have been conducted on nanofluids to gain insight into the mechanism of heat transfer. In many studies, nanoparticle concentrations of < 10% were added to base fluids to understand the effect of nanoparticles on the nanofluid properties. Thus, it is essential to determine an optimal nanoparticle concentration in nanofluids to enhance the performance of thermal systems. Many experimental results have been published on the subject of nanofluids. However, promising nanofluids have not been extensively studied, and the results on several properties are inconsistent, which may be due to the experimental accuracy and differences in experimental techniques.

Aluminium nitride (AlN) is a special ceramic material, which has recently attracted considerable attention because of its promising advantages such as high surface activity, improved chemical stability [23], and low dielectric coefficient [24]. It is characterized by a combination of very high thermal conductivity (285 W m^{-1} K^{-1}), high electrical resistance, relatively low density (3.260 g/cm^3), and high corrosion and resistant properties [25]. Furthermore, AlN nanoparticles

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are commercially available and relatively inexpensive. This makes them suitable for power and microelectronics applications (e.g., heat sinks in LED lighting technology), chemical sensors for detecting toxic gases, acoustic resonators, and many other advanced applications. In addition, aluminium nanoparticles can be added to heat transfer fluids, composite materials, transparent conductive fluids, and wear resistant parts to strengthen their properties. Few investigations on the thermal conductivity have been conducted with AlN nanoparticles dispersed in base fluids [24, 26, 27]. Experimental investigations with AlN dispersed in ethanol, which utilized the transient plane source measuring technique, indicated a 20% thermal conductivity enhancement for the AlN volume fraction of 4% at 273.15 K [24]. In addition, the authors reported that the thermal conductivities of AlN nanofluids increased non-linearly with increase in the volume fraction. The thermal conductivity enhancement increased to the volume fraction of < 2.75% at 293.15 K beyond which the enhancement considerably decreased. However, when the temperature decreased below 273.15 K and volume fraction increased above 2.75%, larger values of the thermal enhancement ratio were observed. Table 1 shows an up-to-date summary of previous studies performed on the thermal conductivity of AlN nanofluids.

Electrical conductivity is a property that quantifies the flow of electrical charge in the material. It is the response of free electrons of the material to an applied electrical field. It is an important property for the industrial and scientific applications of nanofluids. Currently, there are few studies on the electrical conductivity of nanofluids compared to the number of investigations performed on the thermal conductivity of nanofluids. Baby and Ramaprabhu [28] carried out investigations on graphene-based nanofluids and established that electrical conductivity had a strong dependence on volume fraction and temperature. An enhancement in electrical conductivity of 1400% was attained at 25°C for the volume fraction of 0.03%. Teng *et al.* [29] used a one-step method to prepare carbon/water nanofluids using a plasma arc system. Their findings showed that at the test temperature range of 20–50°C, there was no considerable change in the electrical conductivity enhancement ratio at the two evaluated concentrations of 0.02 wt% and 0.04 wt%. In addition, the lowest electrical conductivity enhancement ratio occurred at 50°C. Zyla and Fal [27] observed an electrical conductivity enhancement of 600 times relative to that of the base fluid for the AlN/EG nanofluid at the volume concentration of 7.9%. However, the authors did not investigate the effect of temperature variation on the electrical conductivity of AlN/EG nanofluids. Therefore, to use AlN nanofluids in heat transfer applications, extensive studies on the thermal and electrical conductivity of these nanofluids have to be conducted. The identification of the optimum volume concentration at a certain temperature to reach the maximum thermal conductivity and the comparison of thermal conductivities of various models were evaluated. In addition, the study predicts stability using the spectral analysis method.

THERMAL CONDUCTIVITY MODELS

There are many theoretical models describing the enhancement of thermal conductivity of nanofluids. One of the first classical models was given by Maxwell [30]. Maxwell [30] proposed a model to calculate the thermal conductivity of solid particle suspensions (equation 1):

$$\frac{k_{nf}}{k_{bf}} = \left[\frac{k_{np} + 2k_{bf} + 2(k_{np} - k_{bf})\varphi_v}{k_{np} + 2k_{bf} - (k_{np} - k_{bf})\varphi_v} \right] \tag{1}$$

where k_{nf} is the thermal conductivity of the nanofluid, k_{np} is the thermal conductivity of the

Table 1. Summary of available literatures on thermal conductivity of AlN nanofluid.

Source	Material	Size (nm)	Base fluid	Temperature	NPL	Measuring Technique	Thermal conductivity (TC) increase
Hu *et al.* [24]	AlN	20	Ethanol	0 &24 °C	0.5-4 % (vol. conc.)	Transient plane source method	20% increment in TC with addition of 4.0% vol. conc. NPL
Yu *et al.* [26]	AlN	50	PG EG	10-60 °C	1-10 % (vol. conc.)	Transient short hot-wire technique	38.71% & 40.2% TC enhancement ratio with 10% vol. conc. NPL in PG & EG respectively
Zyla and Fal [27]	AlN	20	EG	298.15 K	5-20 % (mass conc.)	Transient hot-wire technique	21.76% increment in TC with addition of 20% mass conc. NPL

nanoparticles, φ_v is the nanoparticle volume fraction and k_{bf} is the thermal conductivity of the base fluid. This model is applicable to suspension of randomly dispersed spherical particles.

In later years, more theoretical models were introduced. Jeffery [31] proposed a model which is applicable to suspensions of spherical particles and depends on the concentration of nanoparticles:

$$\frac{k_{nf}}{k_{bf}} = 1 + 3\left(\frac{\frac{k_p}{k_{bf}} - 1}{\frac{k_p}{k_{bf}} + 2}\right)\varphi + \left(3\left(\frac{\frac{k_p}{k_{bf}} - 1}{\frac{k_p}{k_{bf}} + 2}\right)^2 + \frac{3}{4}\left(\frac{\frac{k_p}{k_{bf}} - 1}{\frac{k_p}{k_{bf}} + 2}\right)^2 + \frac{9}{16}\left(\frac{\frac{k_p}{k_{bf}} - 1}{\frac{k_p}{k_{bf}} + 2}\right)^3\left(\frac{\frac{k_p}{k_{bf}} + 2}{\frac{k_p}{k_{bf}} + 3}\right)\ldots\right)\varphi^2 \tag{2}$$

On the basis of experimental results for thermal conductivities of AlN embedded in ethylene glycol, Zyla and Fal [27] proposed an equation to calculate the effective thermal conductivity of AlN/EG nanofluid which depends on the concentration of nanoparticles:

$$\frac{k_{nf}}{k_{bf}} = 1 + 2.54482\varphi \tag{3}$$

MATERIALS AND METHODS

The AlN nanoparticles were purchased at the US Research Nanomaterials, Incorporation. The nanoparticles is described by the manufacturer as hexagonal crystals having a particle size of 65-75 nm, specific surface area 40-80 m^2/g and purity 99.5%. The ethylene glycol was of analytical grade and supplied by Guangdong Guanghua Sci-Tech Co., China. The AlN nanoparticles were characterised for particle shape using Transmission Electron Microscope (TEM). The TEM analysis was conducted on a JEOL 2100 HRTEM 200V, Japan.

AlN/EG nanofluids of volume concentration between 0.5 and 5% were carefully prepared using the two-step method (Fig. 1). AlN nanoparticles were dispersed into the base fluid at different volume concentration. The mass of the nanoparticles and the base fluid is calculated using equation 4.

$$\varphi = 100 \times \frac{\left(\frac{m}{\rho}\right)_{AlN}}{\left(\frac{m}{\rho}\right)_{AlN} + \left(\frac{m}{\rho}\right)_{EG}} \tag{4}$$

where φ is the percentage of nanoparticles volume concentration, ρ is the density and *m* is the mass. AlN nanoparticles were weighed using a weighing balance of readability accuracy of 0.01mg (PA4102 OHAUS) and added into 50 ml volume of EG contained in a clean glass beaker before stirring using a magnetic stirrer. An ultrasonic processor (FS-300N, 300W 24 Hz) was then used to homogenize the mixture to ensure proper dispersion and adequate stability (Fig. 1). Ultrasonic agitation was done for 15 hours on each sample to attain prolonged stability. Photographic image of prepared AlN/EG nanofluids showed no sedimentation after 48 hrs (Fig. 2). Stability checks

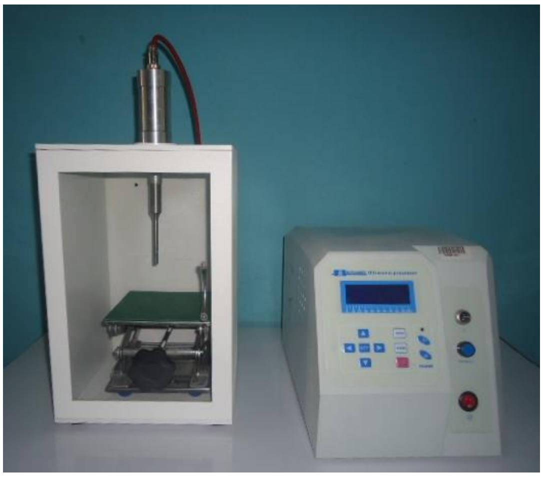

Fig. 1. Ultrasonic Processor.

Fig. 2. Photographic image of just prepared AlN/EG nanofluids (0.5, 1, 2, 3, 4 and 5% vol. conc. from left to right).

were performed on the prepared nanofluids using spectral analysis technique. Properties of the nanofluids namely thermal conductivity and electrical conductivity were measured afterwards.

For the analysis of nanofluid stability, the supernatant concentration of nanofluid suspension was measured quantitatively against the sedimentation time. The dispersion stability of nanofluid suspension was evaluated using a Lambda 25, PerkinElmer precisely UV/VIS spectrometer. The absorbance measurements were taken as the stability responses over a period of time after nanofluid preparation. The UV–Vis spectrophotometer works on the principle that the intensity of light becomes different by absorption and scattering of light passing through a fluid. A pair of cuvette was filled with reference solution (blank) and an initial background scan was first recorded. When the samples are too concentrated (very large absorption) it could prevent light from passing through the solution. Therefore, a pipette (Acura 825 Autoclavable 10µl-100µl) set to a dilution factor of 10 of each sample was added with base fluid in front curvette and second scan was recorded. Thus, prepared nanofluids were periodically analyzed. The inspection range was from 190 nm to 900 nm.

The thermal conductivity of the nanofluid sample was measured with a KD_2 Pro Thermal Properties Analyzer (Decagon Device Inc., USA). This device was designed on the principle of transient hot wire method. It consists of a handheld controller and needle sensors. The KD_2 Pro uses the transient-heated needle to measure thermal properties of solid and fluid media. In this technique, a small amount of heat pulse is applied to the needle sensor, and the temperature response with time is monitored. The nature of the temperature response is a result of the thermal properties of the material. For a given applied heat input (q), the thermal conductivity (k) was computed as $k=\left[\frac{q}{4\pi(T_2-T_1)}\right]In\left(\frac{t_2}{t_1}\right)$ where T_1 and T_2 and are temperatures at times t_1 and t_2. The KS-1 needle (60 mm in length and 1.3 mm in diameter) served as the most suitable as it was primarily designed for liquid samples and could be used to measure thermal conductivity in the range of 0.02-2 W/m.K with an accuracy of ±5%. For correct results, glycerine solution was provided for calibration of the sensor. The estimated accuracy for thermal conductivity was less than 1%. Afterwards, the thermal conductivity of AlN/EG nanofluids was measured. A 50 mL test tube containing nanofluid sample was placed in a water bath (Lemfield Medical England model DK-420) equilibrated to 28 °C. Thereafter, the probe was completely immersed vertically in the nanofluids. Ten readings were taken at interval of 15 minutes and the average value was reported. The sensor was calibrated each time before taking the thermal conductivity measurement.

An electrical conductivity meter manufactured by Lutron Electronic Enterprise CO., LTD (Model: CD-4317SD) and has been calibrated by the manufacturer was used to measure the electrical conductivity of the nanofluids. The accuracy of the meter stated by the manufacturer is ±2% (full scale + 1 digit). For accurate results, the conductivity meter was calibrated using standard solutions with known electrical conductivities of 165 and 1514 µS/cm. Measurements gave less than 2% deviation from the values of the standard solutions. The electrical conductivity was measured by immersing the probe into the sample such that the sensing head is wholly immersed within the solution. The probe was then shaken to let the internal air bubble drift out from the sensing head. The electrical conductivity of the samples was first measured at temperature of 28°C. For measurements above 30°C, the nanofluid samples were heated at various temperature levels up to 60°C using the water bath. At each temperature, the measurements were repeated for 5 times, and the average value was taken.

RESULTS AND DISCUSSION

Results on investigation of AlN nanoparticle microstructure

Fig. 3 shows the TEM result of AlN nanoparticles. From the image, AlN nanoparticles have spherical

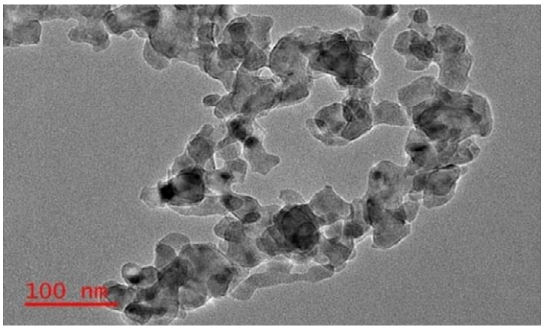

Fig. 3. TEM image of AlN nanoparticles.

shape and they are aggregated while individual ones are bonded and generate a colloidal network.

Stability of nanofluids

The UV-Vis spectra of as-prepared AlN/EG nanofluids (1% vol. conc.) are shown in Fig. 4, and it is observed that the maximum absorbance occurred at 271 nm. Fig. 5 shows a linear trend between different nanofluid volume concentration and the absorbance at constant wavelength of 271 nm. The increase in absorbance at wavelength of 271 nm is due to increase in concentration which is simply described by beers Lambert law where absorbance is directly related to concentration. Thus, nanofluid stability can be examined via absorbance.

The absorbance with respect to the wavelength for 1% vol. conc. of AlN/EG nanofluid which were recorded after different number of days after preparation is shown in Fig. 6. It was determined that absorbance decreased as the number of days increased. The settling behaviour showed that two days post preparation, the absorbance decreased by 28% at 271 nm wavelength. This is because

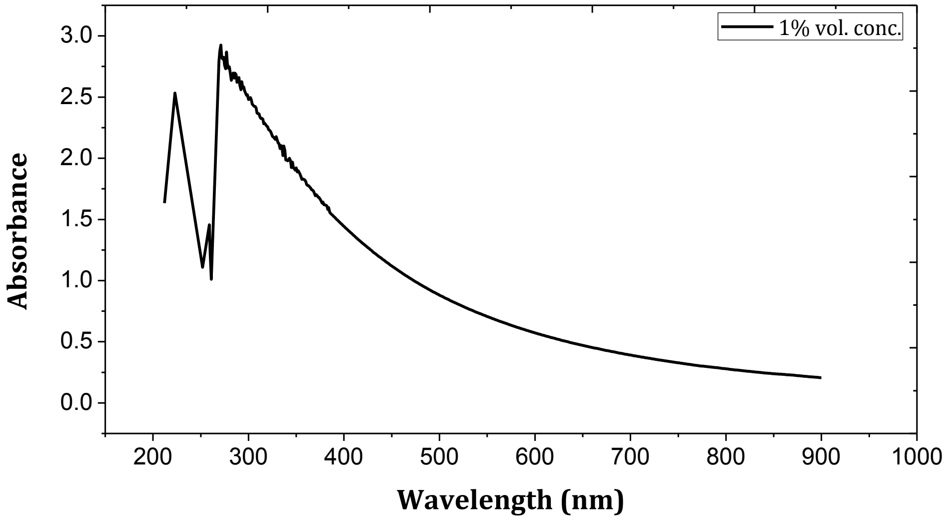

Fig. 4. UV-Vis spectrum of AlN/EG nanofluid.

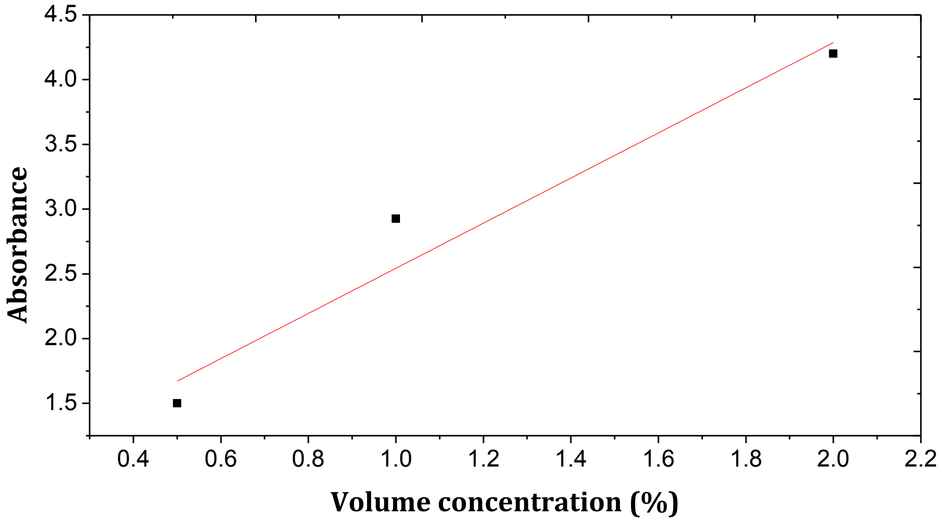

Fig. 5. Absorbance and concentration of AlN/EG nanofluid at wavelength of 271 nm.

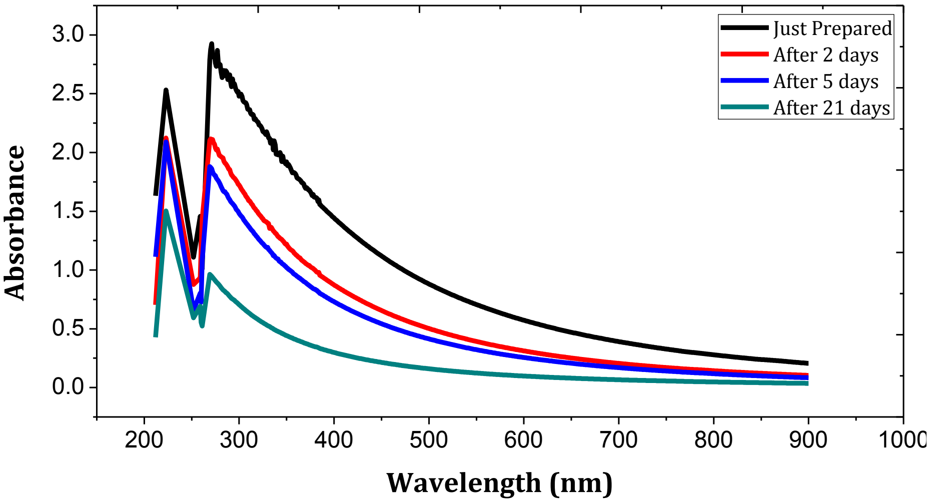

Fig. 6. UV-Vis spectra of AlN/EG nanofluids (1% vol. conc.) at different sedimentation periods.

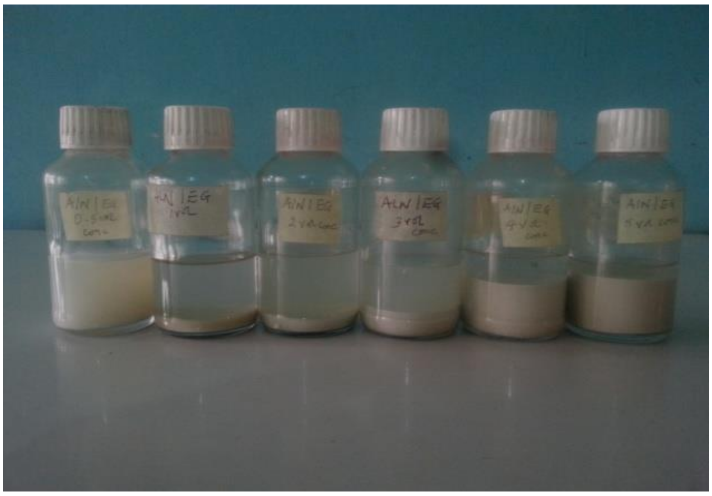

Fig. 7. Photographic image of dispersed AlN/EG nanofluids after six months (0.5, 1, 2, 3, 4 and 5 % vol. conc. from left to right).

rapid agglomeration occurred and led to fast sedimentation. However, between the 2nd and 5th day post preparation, the absorbance decreased slowly by 11%. After 21 days, the absorbance did not change until 6 months when complete settling was observed (Fig. 7). Also, maximum absorbency was maintained in the same wavelength which indicates that the nanofluid possessed good stability. This could be as a result of the long hours of ultrasonic agitation of the nanofluid.

Thermal conductivity of nanofluids

The thermal conductivities of AlN/EG nanofluids as a function of the AlN nanoparticle volume concentration of 0.5–5% at the temperature of 28 °C were measured and are presented in Fig. 8(a). Fig. 8(a) shows that the thermal conductivities of nanofluids containing the abovementioned amounts of AlN nanoparticles are significantly higher than that of the base fluid. The thermal conductivity of AlN/EG nanofluids at 28 °C ranged from 0.281 W m^{-2} K^{-1} to 0.308 W m^{-2} K^{-1} for the volume concentration of 0.5–5%. These values are obtained owing to the thermal conductivity of the nanoparticles and the increase in particle interactions.

Fig. 8(b) shows the variation in the thermal conductivity ratio (i.e., the thermal conductivity of nanofluid divided by the thermal conductivity of the base fluid) of AlN/EG nanofluids as a

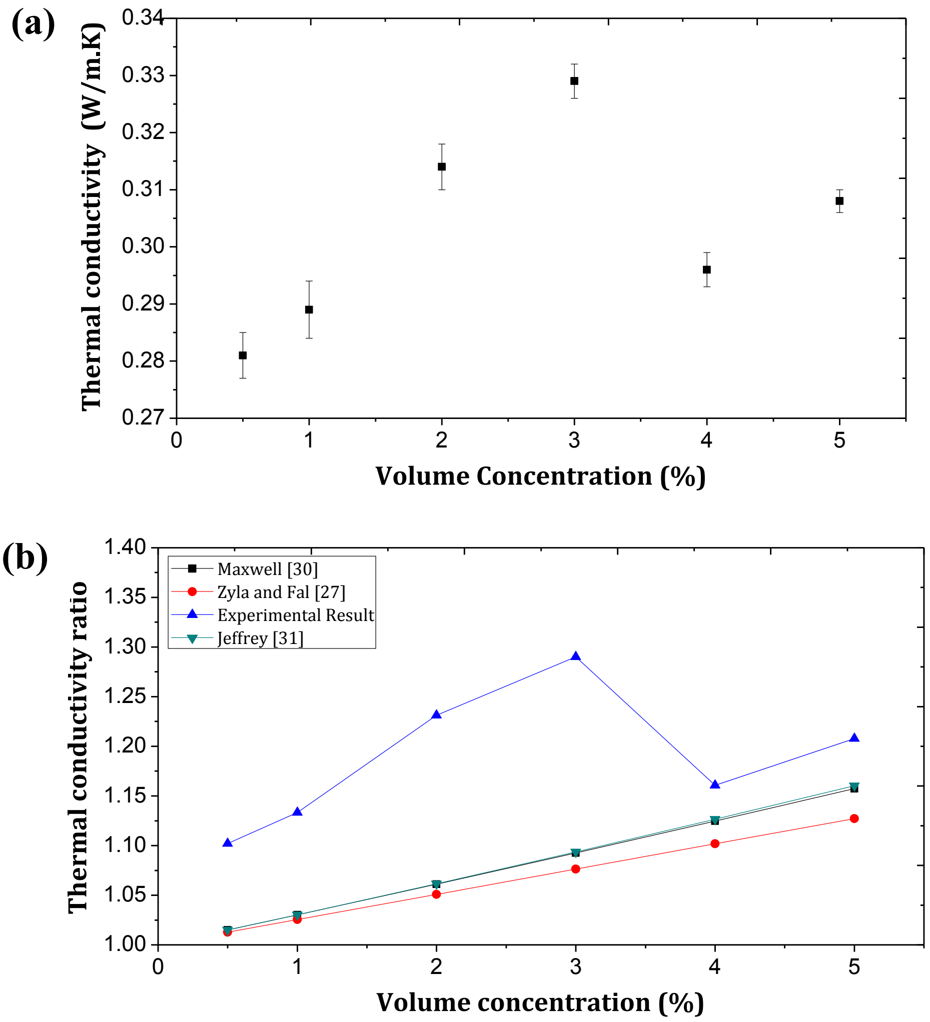

Fig. 8. (a) Thermal conductivity of AlN/EG nanofluids for varying nanoparticle volume concentrations (b) Thermal conductivity ratio of AlN/EG nanofluids for varying nanoparticle volume concentrations compared with works of Maxwell [30]; Zyla and Fal [27] and Jeffery [31].

function of volume concentration. The plot shows that at the low volume concentration of 0.5%, the thermal conductivity ratio increased to 1.10. Similarly, at the maximum volume concentration of 5%, the ratio increased to 1.21. Furthermore, the thermal conductivity ratio increased up to the volume concentration of 3% beyond which the thermal conductivity decreased as concentration increased to 4% and 5%. The thermal conductivity ratio decreased owing to the aggregation (because nanoparticles do not disperse well in the fluid) and high viscosity of the mixture, which reduced the Brownian velocity of the particles. Thus, the volume concentration of 3% is the saturation concentration at which the optimal thermal conductivity is obtained for the AlN/EG nanofluids at 28°C. Hu *et al.* [24] reached a similar conclusion, which was discussed in the introduction. The authors indicated that the thermal conductivity ratio increased as the volume fraction increased up to 2.75%; above this value, the enhancement ratio decreased.

The measured thermal conductivity ratio are compared with the results from theoretical models of Maxwell [30] and Jeffery [31] as well as recently developed experimental models by Zyla and Fal [27] and plotted in Fig. 8(b). The results of Maxwell [30] under-predicted the measured thermal conductivity ratio of the nanofluids with a maximum deviation of 15.3 %. This was

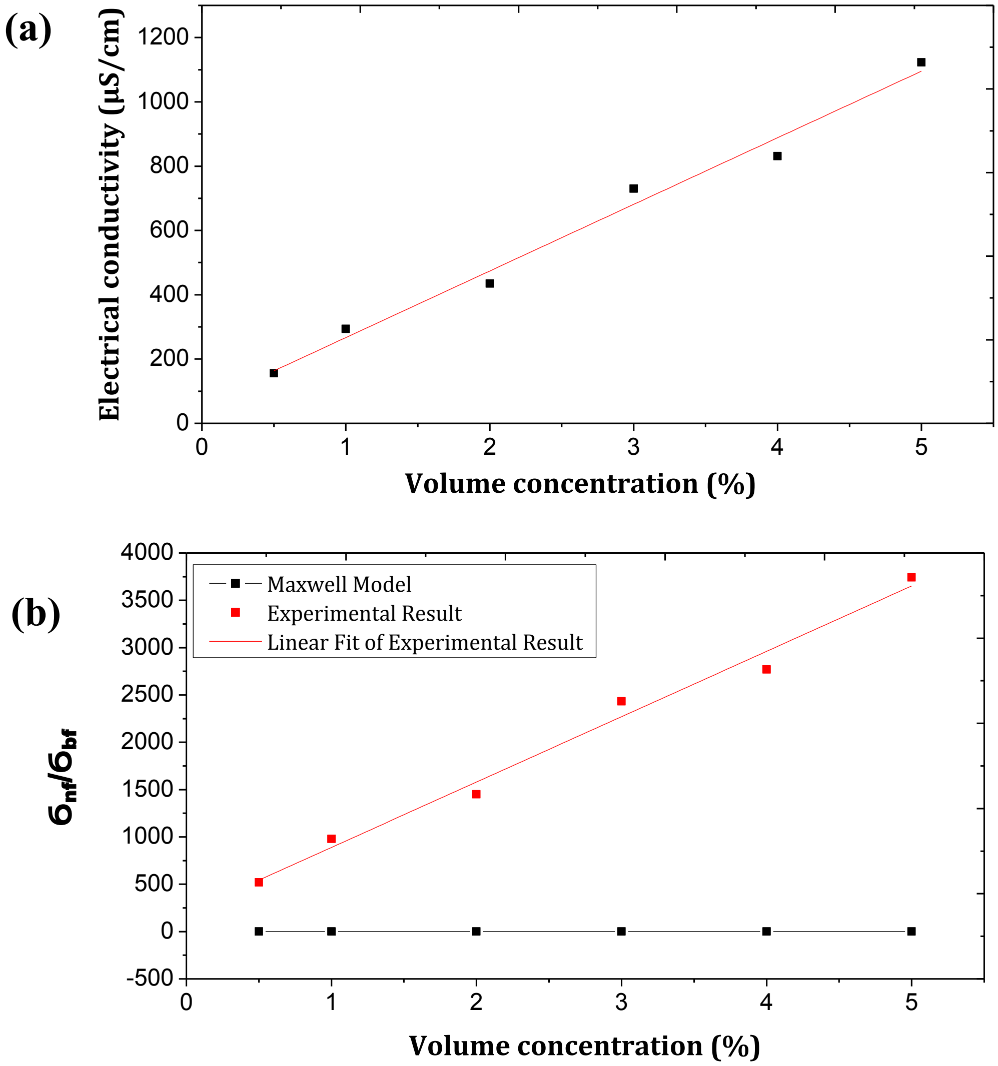

Fig. 9. (a) Electrical conductivity of AlN/EG nanofluids as a function of volume concentration (b) Electrical conductivity enhancement of AlN/EG nanofluids as a function of volume concentration.

also reported by other researchers [14, 19, 23, 24, 32–35]. This is because the model is only a function of the k_{np}, k_{bf} and φ and does not take into consideration important factors like particle size, temperature and interfacial layer [24,35]. Moreover, thermal conductivity ratio from this study depicts larger values compared to Zyla and Fal [27] and Jeffery [31]. This shows that larger values of thermal conductivity ratio can be attained indicating further experimental work. The inconsistency in thermal conductivity enhancements for same nanofluid by different experiments is common in nanofluid studies and may be caused by different particle size, preparation method, stabilization method etc.

Electrical conductivity of nanofluids

Effect of volume concentration

The electrical conductivities of AlN/EG nanofluids as a function of the AlN nanoparticle volume concentration of 0.5–5% at the temperature of 28°C were measured and are presented in Fig. 9(a).

It is clear that the electrical conductivity increased in a linear fashion with volume concentration. The plot shows that at the low volume concentration of 0.5%, the electrical conductivity increased to 156 µS/cm. Similarly, at the maximum volume concentration of 5%, the electrical conductivity increased to 1123 µS/cm. This is because increase in nanoparticle

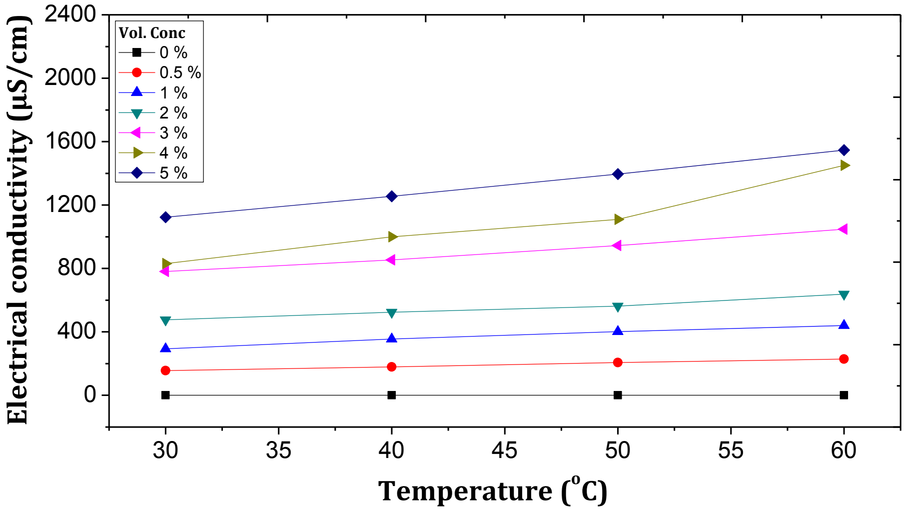

Fig. 10. Electrical conductivity variations for AlN/EG nanofluids as a function of temperature.

concentration, led to increased interaction between nanoparticles resulting in an enhancement in the electrical conductivity. Some literatures [12, 27] have reported linear trends between nanofluid concentration and electrical conductivity. For example, Zyla and Fal [27] observed a linear relation between electrical conductivity and volume fraction of AlN nanoparticles embedded in ethylene glycol. Similar results were reported by Shoghl *et al*. [12] for Al_2O_3, CuO, MgO, TiO_2, and ZnO nanofluids.

The enhancement in electrical conductivity (σ_{nf} / σ_{bf}) has also been compared with the Maxwell's theoretical model [36] which was proposed for the measurement of electrical conductivity of suspension (equation 5):

$$\frac{\sigma_{nf}}{\sigma_{bf}} = 1 + \frac{3(\alpha - 1)\varphi}{(\alpha + 1) - (\alpha - 1)\varphi} \quad (5)$$

where $\alpha = \frac{\sigma_{np}}{\sigma_{bf}}$, φ is the volume fraction, σ_{nf} is the electrical conductivity of nanofluid and σ_{bf} is the electrical conductivity of base fluid. From Fig. 9 (b), the model clearly falls below the electrical conductivity of the present study and has been observed by other researchers [12, 14]. This is because the Maxwell's theoretical model does not take into account factors like Brownian motion, aggregation or electrical double layer [14, 27]. The electrical conductivity of the base fluid was 0.3 µS/cm at 28°C. Therefore, 520 times enhancement in electrical conductivity, relative to the base fluid, was observed for volume concentration 0.5% of AlN at 28°C. This firm dependence of volume concentration of nanoparticles on electrical conductivity of nanofluid has also been observed by other researchers [13, 27, 35].

Regression analysis of the experimental data was carried out which illustrates a linear fit with R^2 value of 0·983 expressed as follows:

$$\frac{\sigma_{nf}}{\sigma_{bf}} = 690.65\varphi + 198.60 \quad (6)$$

Effect of temperature

The electrical conductivity for the present nanofluids with respect to volume concentration for different temperature has also been measured. Fig. 10 shows the electrical conductivity variations for the AlN/EG nanofluids as a function of temperature (30 to 60°C). Similar to the observations made by Adio *et al*. [36], the electrical conductivity of the base fluid showcased an almost unvarying value with rise in temperature which is mainly due to the poor ionization of pure ethylene glycol owing to its mild polarity. The addition of AlN nanoparticles indicated considerable increment in the electrical conductivity of the nanofluid as temperature is raised. For example, at volume concentration of 0.5%, the electrical conductivity increased from 156 µS/cm to 229 µS/cm (47% enhancement) as temperature increased from 30 to 60°C respectively. Also, at volume concentration of 5%, the electrical conductivity increased from 1123 µS/cm to 1546 µS/cm (38% enhancement) as temperature increases from 30 to 60°C respectively. The enhancements are higher at lower volume concentrations because nanoparticles are less sensitive to temperature compared with base fluid [14]. Increasing the temperature, increases the thermal fluctuations of the solvent and the nanoparticles experience stronger Brownian motion, the collision frequency of nanoparticles increases and more nanoparticles are likely to collide with each other causing increase in the electrical conductivity of the nanofluids.

CONCLUSION

Nanofluid of AlN embedded in EG has been studied for characteristics namely thermal conductivity and electrical conductivity. The results of this research paper are summarized below:

- The maximum absorbency for AlN/EG nanofluids occurred at wavelength of 271 nm.
- The thermal conductivity of nanofluid is increased with an increase in the volume concentration of nanoparticles. Further, AlN/EG at 3% volume concentration gave the highest thermal conductivity ratio of 1.29.
- Similar to the thermal conductivity, electrical conductivity is also increased with an increase in the volume for both nanofluids. An enhancement of about 520 times in electrical conductivity, relative to the base fluid, was observed for volume concentration 0.5% of AlN at 28°C.

DISCLOSURE STATEMENT

All authors declare that they have no conflict of interest in the publication of this manuscript.

NOMENCLATURE

EG	ethylene glycol
PG	propylene glycol
SEM	scanning electron microscope
TEM	transmission electron microscope
AlN	aluminium nitride
NPL	nanoparticle loading

Greek symbol

φ	volume concentration (%)
σ	electrical conductivity (µS/cm)
ρ	density (kg/m^3)

Subscripts

bf	basefluid
nf	nanofluid
np	nanoparticle

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