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Thermo-physical properties of pure ethylene glycol and water–ethylene glycol mixture-based boron nitride nanofluids

An experimental investigation

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Abstract

Nanofluids are suspensions of solid nanoparticles in conventional heat transfer fluids, and they often exhibit improved heat transfer characteristics. Different nanoparticles (metals, oxides, nitrides, etc.) have been used for the synthesis of nanofluids. The nanosized hexagonal form of boron nitride (BN) has versatile properties, such as chemical inertness, electrically insulating and high in-plane thermal conductivity ($\sim$ 600 W m^{-1} K^{-1}) making it a prospective dispersoid in nanofluids for heat transfer applications. The present study reports the synthesis of pure ethylene glycol (EG)- and ethylene glycol–water mixture (EG/W, 40/60 vol. ratio)-based nanofluids containing a dispersion of BN nanoparticles. Form the study, it emerged that with the increase in particle concentration, the BN nanofluids showed an increment in the thermal conductivity manifesting a maximum of 15.5% and 12.5% for 3 vol.% of BN dispersion in EG- and EG/W-based nanofluids, respectively. Also, the thermal conductivity enhancement of BN nanofluids was found to be nearly independent of temperature in the temperature range of 30–60 °C. The viscosity of BN nanofluids increased with the increase in particle concentration showing a maximum of 41 and 33% for 2 vol.% of BN in EG-based and EG/W-based nanofluids, respectively. Further, BN nanofluids exhibited shear-thinning behaviour at lower shear rates and a Newtonian nature at higher shear rates. A new correlation has been developed to estimate the thermal conductivity and viscosity of BN nanofluids on the basis of experimental data.

Keywords Nanofluids · Ethylene glycol–water mixture · Thermal conductivity · Dynamic viscosity · Boron nitride nanoparticles

Introduction

The ever increasing demand for improved heat transfer performance in areas of manufacturing, electronics or in power generation sectors has led to the innovation of nanofluids. Nanofluid is a stable suspension of nanoparticle (< 100 nm in size) in a base fluid (like water and ethylene glycol) [1]. Over the past two decades, extensive research has been carried out to study the thermo-physical properties of nanofluids with different nanoparticles [2–19]. Among the different base fluids used for nanofluid synthesis, water is the most common one. Water-based nanofluids, however, become difficult to use in regions with extreme temperatures. Additives like ethylene glycol are used in various ratios with water to increase their operational temperature range. Till now various researchers [20–25] have studied the thermo-physical properties of water and ethylene glycol mixture-based nanofluids. Vajjha et al. [26] come under the ones who first carried out experimental investigations on nanofluids with ethylene glycol–water mixture of ratio 60/40 (by mass) for three types of nanoparticles Al_2O_3, CuO and ZnO having different particle sizes. They reported an

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increase in the thermal conductivity of nanofluids with the increase in particle loading, as well as with an increase in temperature. They also proposed a new correlation for thermal conductivity which showed a good agreement with their experimental data. Kumaresan et al. [27] used multi-walled carbon nanotube (MWCNT) for preparing 30/70 EG/W mixture-based nanofluid and measured the thermal conductivity for different volume fractions at different temperatures (from 0 to 40 °C). With 0.45% particle loading, an increment in the thermal conductivity of 19.7% was reported at 40 °C. Moreover, their study on viscosity also showed a weak dependence on temperature. ZnO-EG and ZnO-EG/W (50/50) nanofluids were used by Suganthi et al. [28] to investigate the influence of particle loading and temperature on its thermal conductivity and viscosity. A higher thermal conductivity improvement was observed for ZnO-EG nanofluid than the ZnO-EG/W nanofluid. Also, a reduction in the viscosity of both EG- and EG–water mixture-based nanofluid with increasing particle concentrations was recorded which is contrary to many reported works of the literature [29, 30]. A difference in the synthesis of ethylene glycol-based nanofluid and enhanced perturbations in the hydrogen bonding network of ethylene glycol in ethylene glycol–water mixture-based nanofluid were proposed to be responsible for such contradictory results.

The hexagonal form of boron nitride (BN), a wide band gap material, has properties like high in-plane thermal conductivity ($\sim$ 600 W m^{-1} K^{-1}, chemical inertness and good mechanical properties. It has a structure similar to graphite. Lately, studies on the thermal-physical properties of heat transfer fluids containing BN nanoparticles were carried out. Li et al. [31] used two different particle sizes of BN nanoparticles (140 nm and 70 nm) with EG as the base fluid and studied its influence on the thermal conductivity of nanofluids. Interestingly, the larger particle size (140 nm)-based BN nanofluid showed more enhancement compared to the nanofluid with smaller sized particles (70 nm) for identical volume fraction. They also reported that lower volume fraction (0.025%) achieved a better thermal conductivity improvement when compared to the nanofluids with higher volume fraction (0.2%). Zhi et al. [32] made use of boron nitride nanotubes (BNNTs) and nanospheres (BNNSs) in a mixed combination for the synthesis of water-based nanofluids and achieved very high thermal conductivity enhancement. An increment of 2.6-fold in the thermal conductivity over base fluid was achieved with a volume fraction of 6% boron nitride nanotubes (BNNTs), whereas for the same concentration with boron nitride nanospheres, the enhancement measured was 1.6-fold. Using BNNTs and BNNSs in a mixed combination resulted in a more significant increment in thermal conductivity of the fluid, and at the same time, it also maintained the viscosity quite low. One-step synthesis of h-BN nanoflakes-based nanofluids by Taha-Tijerina et al. [33] also showed a high increase in thermal conductivity with minimal increment in viscosity.

Literature survey reveals that there are only few works on the thermal conductivity and viscosity of boron nitride nanoparticles dispersed in binary mixtures of water and ethylene glycol. Because of high in-plane conductivity, these particles can be viewed as sticks of BN flakes for heat transfer properties. The main aim of the present work is to discuss the effects of base fluid (viz. EG, EG–water mixture) on the thermos-physical behaviour of BN nanoparticles.

Materials and method

Materials

Nanosized boron nitride (BN) nanoparticles having an average particle size of 70 nm were purchased from Sisco Research Laboratories (SRL) Pvt. Ltd., Mumbai, India. Polyvinylpyrrolidone (PVP) with M.W. = 10,000 from Sigma-Aldrich was used as the surfactant during the synthesis of all nanofluids. AR-grade ethylene glycol (EG) of 99.9% purity was procured from Merck, India. Double-distilled water was used for the synthesis of nanofluids. All chemicals obtained were used without any further purification.

Nanofluid synthesis

BN nanofluids were prepared by a two-step method. Two base fluids, viz. ethylene glycol (EG) and a mixture of ethylene glycol–water (EG/W) in a volumetric ratio 40/60, were used. In order to achieve a stable dispersion, 0.25–0.3 mass% of the surfactant, PVP, was mixed well in the base fluid after which a measured amount of BN nanopowder calculated through Eq. (1) for the respective volume fraction (ϕ) was added to this cumulative mixture. Stirring was allowed for 1 h at 700 rpm until complete homogenization was achieved. In the final step, sonication of the nanofluid for an optimized cumulative time of 3 h using IMECO ultrasonics water bath (120 W) was performed while maintaining the bath temperature < 30 °C. Different volume concentrations of BN nanofluids were thus synthesized in an above-mentioned manner for characterization.

$$\phi = \frac{\left(\frac{w_{BN}}{\rho_{BN}}\right)}{\left(\frac{w_{BN}}{\rho_{BN}} + \frac{w_{bf}}{\rho_{bf}}\right)} \times 100 \quad (1)$$

where w_{BN} and w_{bf} represent the weight of BN nanoparticles and bulk fluid in grams; ρ_{BN} and ρ_{bf} represent density of BN nanoparticles and bulk fluid in g cm^{-3}.

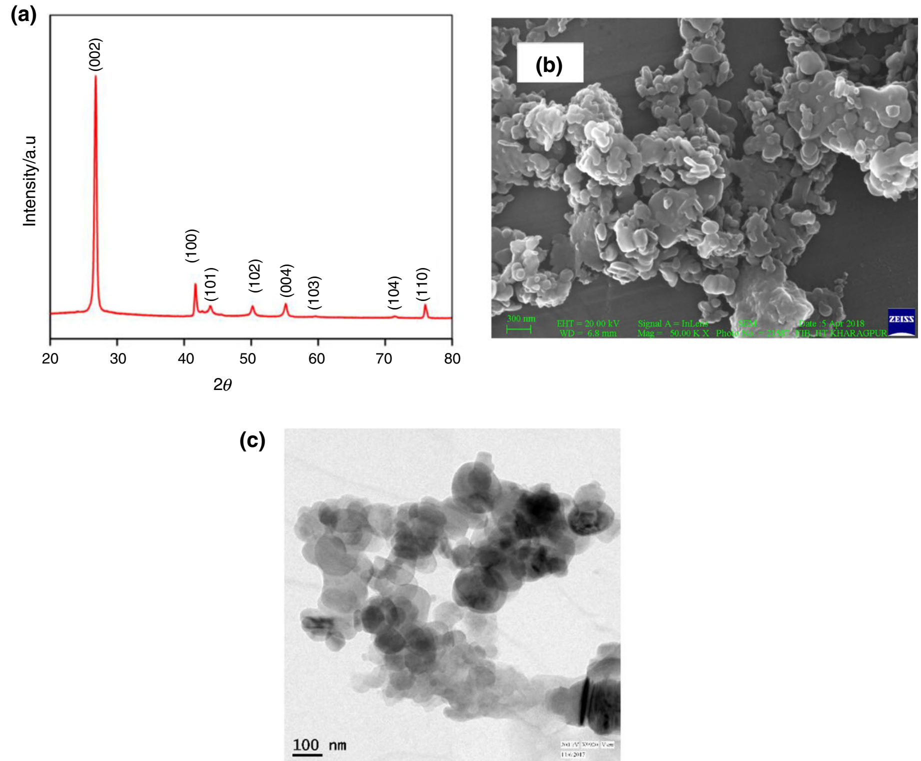

Fig. 1 **a** XRD patterns of BN nanoparticles, and **b** SEM image of BN nanoparticles **c** TEM image of BN nanoparticles

Characterization of nanofluids

The as-prepared BN nanofluids were characterized by different techniques for morphology and size. X-ray diffraction (XRD) analysis of BN was performed by BRUKER D8 Advance X-ray diffractometer using Cu-Kα radiation. The particle morphology was studied using the focussed ion beam scanning electron microscope (FIB-SEM, CARL ZEISS, AURIGA COMPACT) and transmission electron microscope (TEM, JEOL JEM 2100, Japan). Horiba particle size analyzer SZ-100 was used to study the hydrodynamic particle size distribution through dynamic light scattering method (DLS) and zeta potential of BN nanofluids. Fourier transform infrared spectrometer (FTIR, NEXUS-870) was used to study the various molecular bonding and interactions with BN. All measurements were performed at room temperature.

The thermal conductivity of the BN nanofluids was measured by transient hot wire method (THW) using LAMBDA (Flucon fluid control GmbH). The transient hot wire method is considered to be more accurate than other thermal conductivity measurement technique used for nanofluids [34]. The uncertainty of the measured values is below 2%. The thermal conductivity measurements were performed at temperatures ranging from 30 to 60 °C, which was attained using the Julabo temperature-controlled bath (F12). The Brookfield DV-II + Pro viscometer along with a water bath was used to measure the viscosity of BN nanofluid. The viscometer consisting of a rotating spindle is immersed in the sample fluid which thereby experiences a viscous drag force against the spindle. The viscosity is measured at temperatures ranging from 30 to 60 °C. The uncertainty in the viscosity measurements is approximately 3%. The thermal conductivity and viscosity measurements are performed for both the EG- and EG–water mixture-based BN nanofluids having concentrations from 0.5 to 2 vol.%. A sufficient time of 20 min was given before every thermal conductivity and viscosity measurement at the desired temperature.

Results and discussion

Figure 1a shows the X-ray diffraction pattern recorded in the range between 20° and 80° for BN nanoparticles. The diffraction peaks at 26.76°, 41.60°, 43.87°, 50.14°, 55.16°, 59.56°, 71.41° and 75.93° can be readily indexed as the diffraction from crystal planes of (0 0 2), (1 0 0), (1 0 1), (1 0 2), (1 0 3), (0 0 4) and (1 1 0) from hexagonal symmetry of BN (JCPDS card no. 34-0421), thereby demonstrating that the products are highly crystalline and mainly composed of h-BN crystals without any impurity phase. Using the Williamson-Hall method [35], the average crystallite size of BN nanoparticles has been estimated to be ~ 21.2 nm.

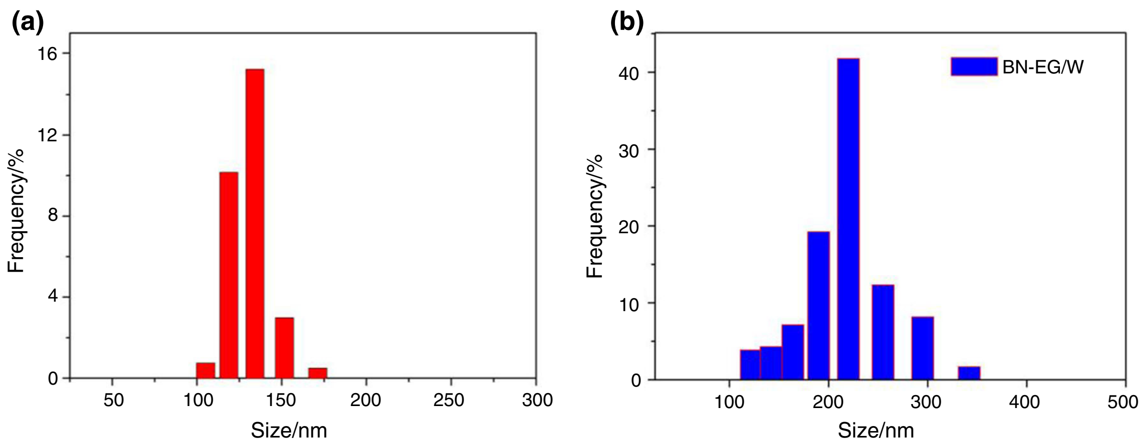

Fig. 2 **a** Particle size distribution from BN nanoparticles in **a** EG, **b** EG/W

From the TEM micrograph, (Fig. 1c) it is observed that the particles are in the nanometre range having almost a spherical morphology. Also these particles have a size distribution ranging from 90 to 170 nm. The hydrodynamic particle size distribution of the BN nanoparticles in the base fluids is shown in Fig. 2.

BN nanoparticles suspended in ethylene glycol (Fig. 2a) gave a narrow distribution over the range of 105–171 nm with a mean hydrodynamic size of 134 nm. From Fig. 2b, the mean hydrodynamic size of BN in ethylene glycol–water mixture (EG/W) is 220 nm with a wider size distribution in the range of 122–340 nm. Higher particle size is apparently due to the long chain surfactant layers (PVP) present on the nanoparticles during synthesis of nanofluids.

Although a detailed study on the stability of nanofluids at high temperature was not conducted in this work, the basic evaluation method which involves zeta potential measurements was performed at room temperature and visual observation was performed at room temperature and high temperature. The zeta potential for EG- and EG/W-based BN nanofluid was − 54.6 mV and − 38.3 mV, respectively. It is in well agreement with the visual observation of the EG-based BN nanofluid (Fig. 3) which showed no phase separation up to minimum 15 days, and phase separation began to appear for EG/W-based BN nanofluid within 8 days of synthesis. An attempt to study the stability of BN nanofluids at higher temperature has been made by holding a 0.5 vol.% EG- and EG/W-based BN nanofluid at the maximum temperature of this study (i.e. 60 °C) for increasing time. From Fig. 4, it is evident that for both EG- and EG/W-based BN nanofluid, the phase separation and sedimentation begin to appear after 4 h of holding time. High temperature gives rise to increased Brownian motion and reduced viscosity of the fluid resulting in more frequent collisions between nanoparticles. Also, the surfactant that forms a protective layer on the nanoparticle tends to dissociate at high temperature

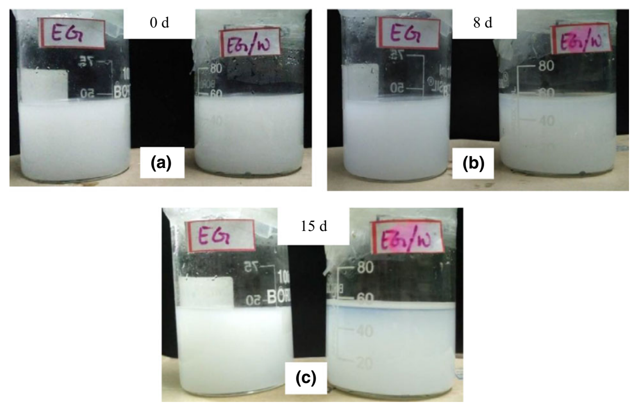

Fig. 3 EG- and EG/W-based BN nanofluid on **a** 0th day **b** 8 days and **c** 15 days

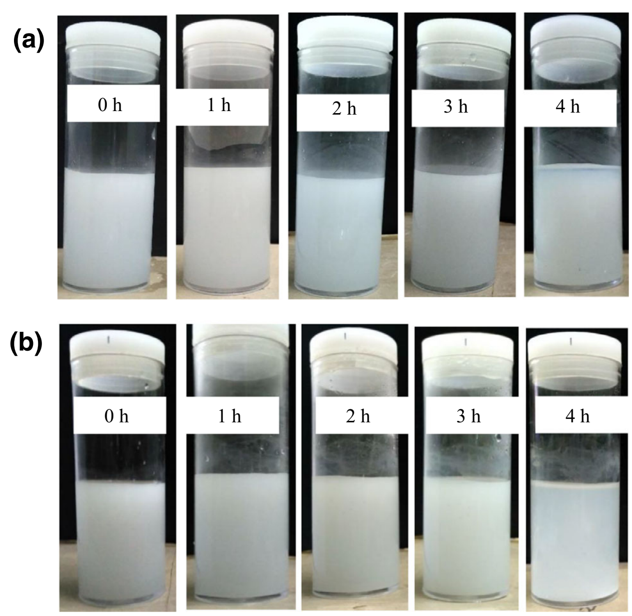

Fig. 4 **a** EG-based and **b** EG/W-based BN nanofluid after holding at 60 °C for increasing hours

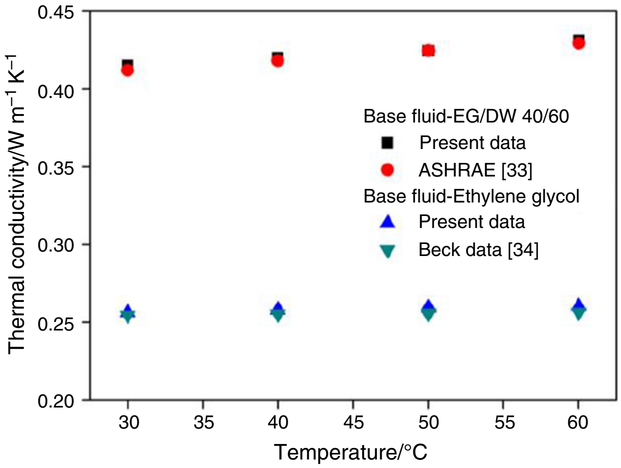

Fig. 5 Thermal conductivity of ethylene glycol and ethylene glycol–water mixture at different temperatures

leading to aggregation and instability within hours. However, a more detailed study would be required to investigate and analyze the stability of nanofluids at higher temperatures.

To make sure whether PVP added to the BN nanofluids for improving stability does not cause any reaction and change in its final composition, FTIR analysis was performed on base fluids, surfactant–base fluids mixture and finally BN nanofluids with surfactant. Results show that for the kind of PVP concentration used in the present case, there was no presence of extra peaks in FTIR spectrum (Fig.S1) of the base fluids and BN nanofluids depicting no change in the composition of the base fluids. More detailed information is provided in the Supporting Information.

Thermal conductivity of nanofluids

For obtaining a proper dispersion of nanoparticles, ultrasonication [36] has been carried out for an optimum time of 3 h to completely disperse the BN nanoparticles in the base fluid. Figure 5 shows the variation of thermal conductivity of base fluid EG and EG–water mixture (40/60) with temperature measured in the present study in close agreement with experimental data reported in the literature [37, 38]. The measured data and the literature data have a maximum deviation of not more than 1.5%.

Having achieved a proper dispersion of nanoparticles in the base fluid, its thermal conductivity is measured. The thermal conductivity enhancement of the nanofluids is determined using the following equation:

$$\text{Enhancement}(\%) = \left(\frac{k_{\text{nf}} - k_{\text{bf}}}{k_{\text{bf}}}\right) \times 100 \qquad (2)$$

where k_{nf}—measured thermal conductivity of nanofluid and k_{bf}—thermal conductivity of base fluid.

In order to study the effect of the surfactant (i.e. PVP) on the measured values of thermal conductivity and viscosity of nanofluids, the thermal conductivity and viscosity of base fluids and nanofluids of 1 vol.% concentration were measured with and without the addition of PVP. From Fig. 6a, b, the thermal conductivity and viscosity of both

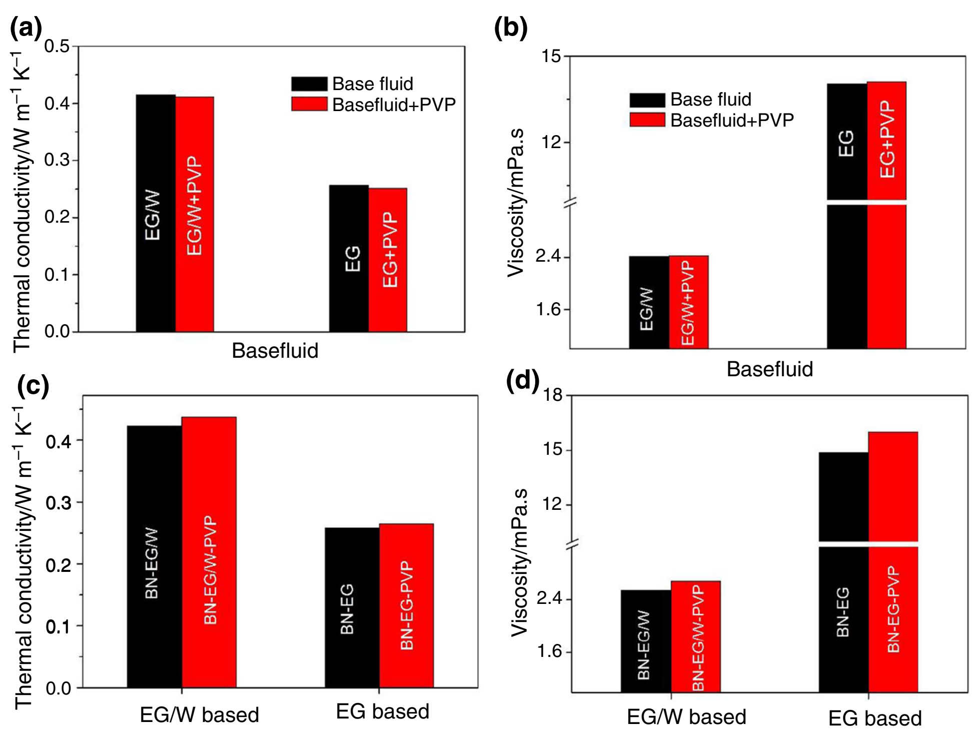

Fig. 6 **a** Thermal conductivity and **b** viscosity of base fluids with and without PVP **c** Thermal conductivity and **d** viscosity of 1 vol.% BN nanofluids with and without PVP

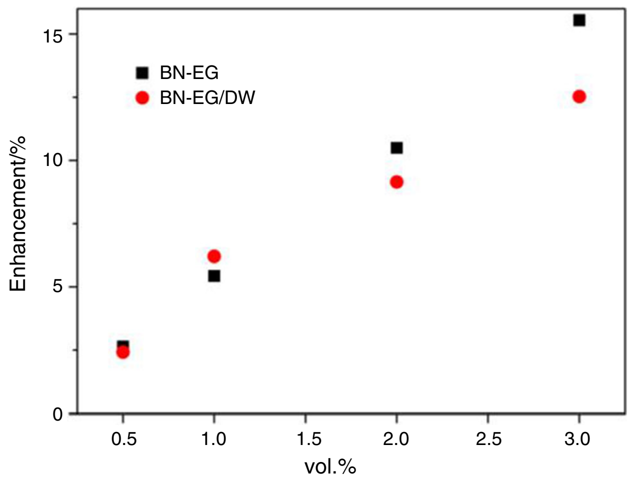

Fig. 7 Experimental thermal conductivity enhancement with respect to particle concentration of EG-based and 40/60 EG/W-based BN nanofluid at 30 °C

the base fluids with and without the addition of PVP show only a minute difference. Also, the thermal conductivity of EG- and EG/W-based 1 vol.% BN nanofluids with the addition of PVP has a better improvement than the nanofluids without the addition of PVP (Fig. 6c). This is due to the better dispersion provided by PVP, while in the case of viscosity (Fig. 6d), the presence of PVP in the base fluids has caused an increase in the viscosity which is due better dispersion of BN nanoparticles in the base fluids. The viscosity of EG- and EG/W-based BN nanofluids with PVP present is little higher than their corresponding nanofluids without PVP. Hence, keeping this in mind, the enhancement in thermal conductivity and viscosity has been calculated by taking into consideration the effective thermal conductivity and viscosity of base fluids in the presence of surfactant.

Figure 7 shows the thermal conductivity enhancement of EG- and 40/60 EG/W-based BN nanofluids with a particle concentration ranging from 0.5 to 3 vol.% at 30 °C. It is found that with the increase in particle concentration the thermal conductivity enhancement increases linearly which is in agreement with the results reported in the literature [17, 39]. A maximum thermal conductivity enhancement of 15.5% and 12.5% has been obtained for EG- and 40/60 EG/W-based nanofluids, respectively, with for 3 vol.% BN loadings. Also, the EG-based BN nanofluid showed a slight better thermal conductivity enhancement than 40/60 EG/W-based BN for the same particle concentration and temperature.

Figure 8 shows the thermal conductivity enhancement of EG- and EG–water mixture-based BN nanofluids for different particle concentrations with their absolute values given in Tables 1 and 2. Although a very high thermal conductivity increment reported by Zyla et al. [40] for EG- or water-based BN nanofluids were not evident in the present experiments, the theoretical reasons for such high values of thermal conductivity increment are not well understood.

Although the absolute thermal conductivity of the BN nanofluid increased with temperature, its thermal conductivity enhancement calculated by Eq. 2 showed an almost temperature-independent nature ranging from 30 to 60 °C (Fig. 8). The observed increase in the absolute thermal conductivity of BN nanofluid with temperature is mainly due to the base fluid's temperature-dependent thermal conductivity. Even though a lot of researchers [41, 42] have reported temperature dependence on the thermal conductivity enhancement of nanofluids, the contrary has also been observed in recent literature [18, 28, 42–44]. Suganthi et al. [28] while studying the effect of temperature on thermal conductivity of ZnO nanofluids observed a similar trend as observed in the present case. Reduction in the thickness of the base fluid molecule's layered structure around the nanoparticle attempts to counterbalance the effect of the enhanced Brownian motion with a rise in temperature which was considered to be responsible for such temperature-independent behaviour of thermal conductivity of ZnO nanofluids.

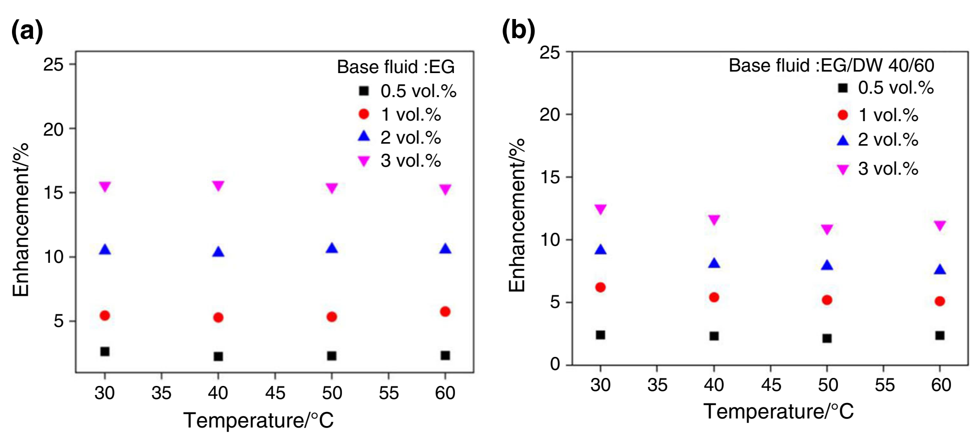

Fig. 8 Experimental thermal conductivity enhancement with respect to temperature of **a** EG-based **b** EG/W-based BN nanofluid

Table 1 Absolute thermal conductivity for EG-based BN nanofluid

Temperature/°C	0.5 vol.%/W m^{-1} K^{-1}	1 vol.%/W m^{-1} K^{-1}	2 vol.%/W m^{-1} K^{-1}	3 vol.%/W m^{-1} K^{-1}
30	0.25806	0.26508	0.27779	0.29051
40	0.25918	0.26689	0.27963	0.2931
50	0.26165	0.26943	0.2829	0.29529
60	0.26285	0.27164	0.284	0.29628

Table 2 Absolute thermal conductivity for 40/60 EG/W-based BN nanofluid

Temperature/°C	0.5 vol.%/W m^{-1} K^{-1}	1 vol.%/W m^{-1} K^{-1}	2 vol.%/W m^{-1} K^{-1}	3 vol.%/W m^{-1} K^{-1}
30	0.42148	0.4371	0.44916	0.46308
40	0.42712	0.44001	0.45101	0.46617
50	0.43	0.4429	0.45426	0.468
60	0.43837	0.45005	0.46055	0.47626

Viscosity of nanofluids

A lot of research work tends to focus on the enhanced thermal properties of nanofluid, but its rheological behaviour also needs to be investigated for its technological application. Most studies [13, 14, 29, 42, 45, 46] show that nanofluids have a greater viscosity than their corresponding base fluids which increases with increasing particle concentration. On the contrary, Suganthi et al. [28] observed a decrease in effective viscosity of nanofluid with increasing volume concentration of nanoparticles presumably due to the disruption caused by the hydroxyl groups present on the nanoparticle surface. As per the literature, nanofluids have shown both Newtonian and non-Newtonian kind of behaviour. In the present study, the viscosity of BN nanofluids has been measured at different temperatures ranging from 30 to 60 °C over shear rates between 0.3 and 122 s^{-1}.

The viscosity of base fluids, viz., EG and EG/W 40/60, measured at different temperatures are in agreement with the data reported in [8, 37] (Fig. 9). The viscosity of the base fluids was measured at increasing shear rates from 0.36 to 122 s^{-1} for temperatures between 30 and 60 °C and exhibited the Newtonian-type behaviour as shown in Fig. 10.

Figure 11a–f presents the flow curves for EG- and 40/60 EG/W-based BN nanofluids for particle concentrations from 0.5 to 2 vol.% in the temperature ranging from 30 to 60 °C. For the EG-based nanofluid when the BN concentration is as low as 0.5 vol.% (Fig. 11a), the viscosity seems to be almost independent of the shear rate at all measured temperatures which is typical of Newtonian-type behaviour. With an increase in the particle concentration to 1 vol.%, the viscosity decreases with the increase in the shear rate up to 3.67 s^{-1} after which it remains constant

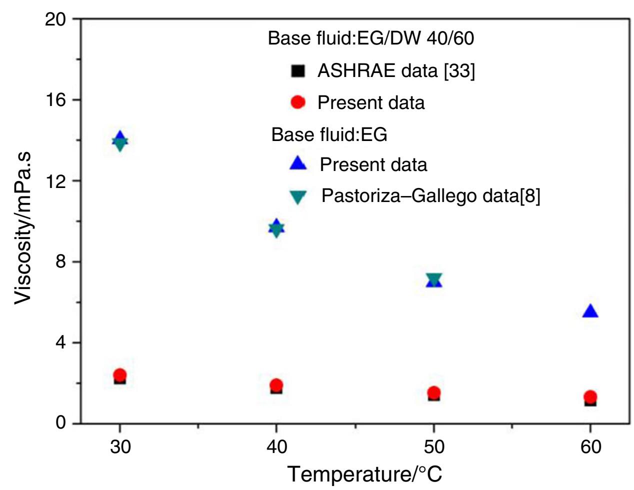

Fig. 9 Viscosity of EG and EG/W at different temperatures

and hence displaying both Newtonian and non-Newtonian kind of behaviour. A similar trend was also observed for 2 vol.% EG-based BN nanofluids. On examining the results for 40/60 EG/W-based BN nanofluids in Fig. 11d–f) for all the concentrations, the viscosity initially decreases with the increase in the shear rate up to a certain point, i.e. 36.7 s^{-1} after which it stays constant, thus displaying both Newtonian and non-Newtonian nature, similar to as observed for EG-based BN nanofluids. This kind of behaviour possibly results from the loosely formed clusters of nanoparticles in the fluid. In the presence of low shear rates, these nanoparticle clusters resist any kind of alignment resulting in higher viscosity. With increasing shear rates, the clusters possibly slowly align themselves in the flow direction, which would result in lower viscosity and hence displaying a shear-thinning behaviour. Similar results were also

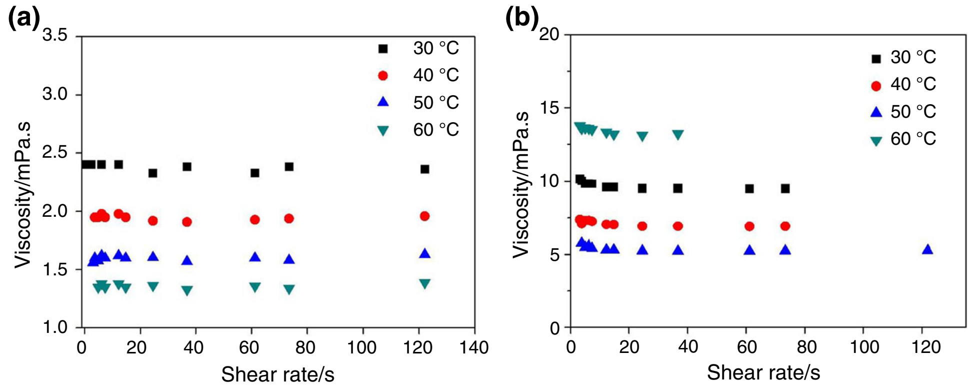

Fig. 10 Viscosity versus shear rate for base fluid **a** EG and **b** EG/W (40/60) at different temperatures

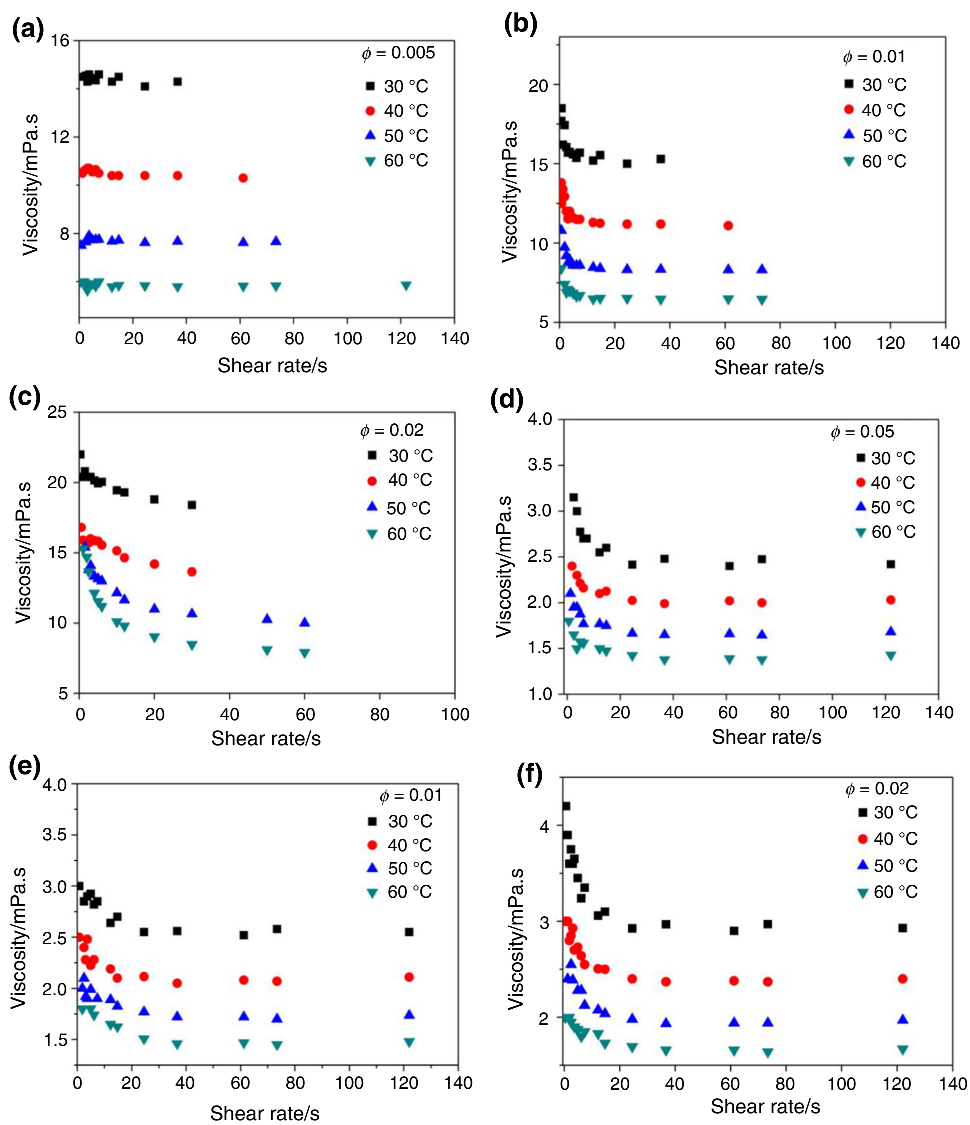

Fig. 11 Viscosity versus shear rate for **a**–**c** EG-based BN nanofluid **d**–**f** 40/60 EG/W-based BN nanofluid for different particle concentrations

reported by Ijam et al. [47] who studied the rheological properties of graphene oxide dispersed in ethylene glycol–water mixture (40/60).

Figure 12 shows the viscosity of BN nanofluids measured at temperatures between 30 and 60 °C. The viscosity of nanofluids is higher than the base fluid and increases with the particle concentration. This increase is apparently

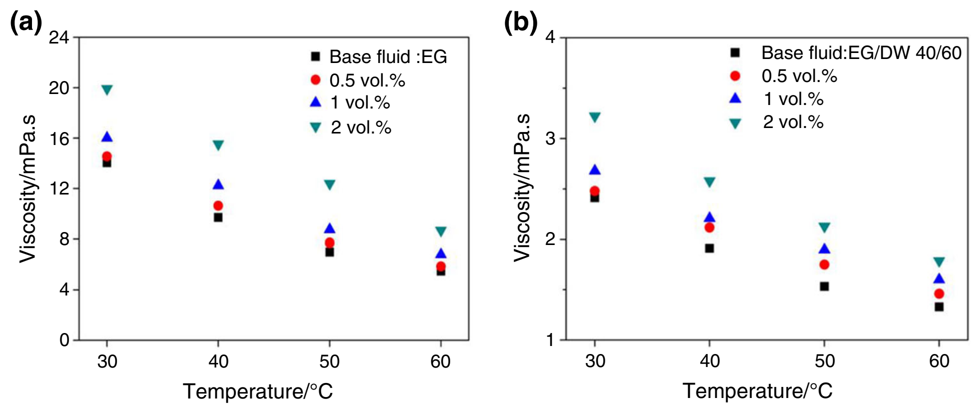

Fig. 12 Effect of temperature on viscosity of **a** EG-based **b** EG/W-based BN nanofluid

due to the resistance between the layers of fluid caused by the presence of nanoparticles, which thereby increases with an increase in the particle concentration. For heat transfer applications of nanofluids where temperature variations are uncontrollable, studying the effect of temperature on its rheological properties becomes very important. At 60 °C 2 vol.% of BN in EG- and 40/60 EG/W-based nanofluids exhibit a 56.4% and 44.4% reduction in viscosity, respectively. Similar kind of results was reported by other researchers too [5, 28, 48]. Figure 12 evidences that the viscosity decreases with increasing temperature following the behaviour of its base fluid. Intermolecular forces become weaker with the increase in temperature resulting in a decrease in viscosity of nanofluids [14].

Figure 13 presents the effect of increasing volume concentration on the relative viscosity of BN nanofluids. The relative viscosity of BN nanofluids increases with increasing particle concentration which is as expected and already cited in the previous literatures. The maximum relative viscosity of 1.41 and 1.33 is observed for 2 vol.% EG- and 40/60 EG/W-based BN nanofluid at room temperature.

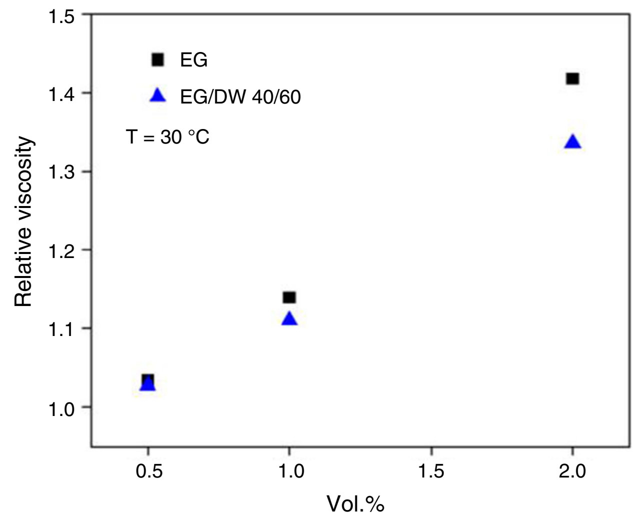

Fig. 13 Effect of volume concentration on the relative viscosity of BN nanofluids

Comparison with classical models

The present thermal conductivity and viscosity results are compared with the already available well-established classical models. Figure 14a shows the plot for experimental thermal conductivity data for EG-based BN nanofluids along with results predicted by Maxwell [38], Hamilton and Crosser [39], Timofeeva [29], Buongiorno [40], Jeffrey [41] and Mintsa [42]. It is clear that the present data are visibly higher than the results predicted by the classical models.

Similarly, Fig. 14b shows the comparison of viscosity results measured experimentally with the result from established literature models. The present viscosity ratio is larger than the one predicted by Einstein [49], Batchelor [50], Roscoe [51], Brinkman [52] and Wang [53] model. Clearly, it can be stated that these models underestimate the thermal conductivity and viscosity of nanofluids which might be due to not considering many important factors like particle size, Brownian motion, and nanoparticle aggregation etc. which are significant in nanofluids.

Proposed correlation

The already developed different classical models do not fit well with the present experimental data; therefore, a new correlation was proposed for estimating the thermal conductivity and viscosity for BN nanofluids at different volume fractions and temperatures. This correlation which was obtained by curve-fitting method can estimate thermal conductivity and viscosity up to 3 vol.% particle concentration at temperatures of 30–60 °C. For EG-based nanofluids,

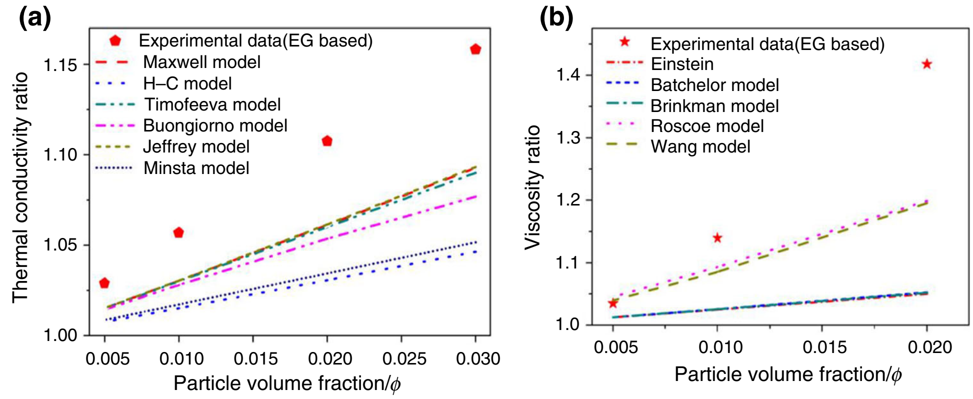

Fig. 14 Comparison of experimental data of **a** thermal conductivity and **b** viscosity with classical models for BN nanofluids

$$\mathrm{TC} = 0.2485 + \left(0.00714 * T^{0.2686}\right) * \left(\phi^{0.74905}\right)$$
$$\mu_{\mathrm{nf}} = 28.37 + \phi^{2.150} - T^{0.77037} \tag{3}$$

where TC and μ_{nf} are the thermal conductivity and viscosity of nanofluid, T is temperature and ϕ is the volume fraction. The correlation developed for EG/W-based nanofluids is:

$$\mathrm{TC} = 0.35271 + \left(0.0438 * T^{0.1871}\right) * \left(\phi^{0.2230}\right)$$
$$\mu_{\mathrm{nf}} = 5.538 + \phi^{0.34905} - T^{0.39116} \tag{4}$$

Figure 15 shows the comparisons of measured thermal conductivity and viscosity of BN nanofluids with those predicted by the proposed correlation. From Fig. 15, the thermal conductivity and viscosity of BN nanofluids estimated through this proposed correlations are in good agreement with the measured data.

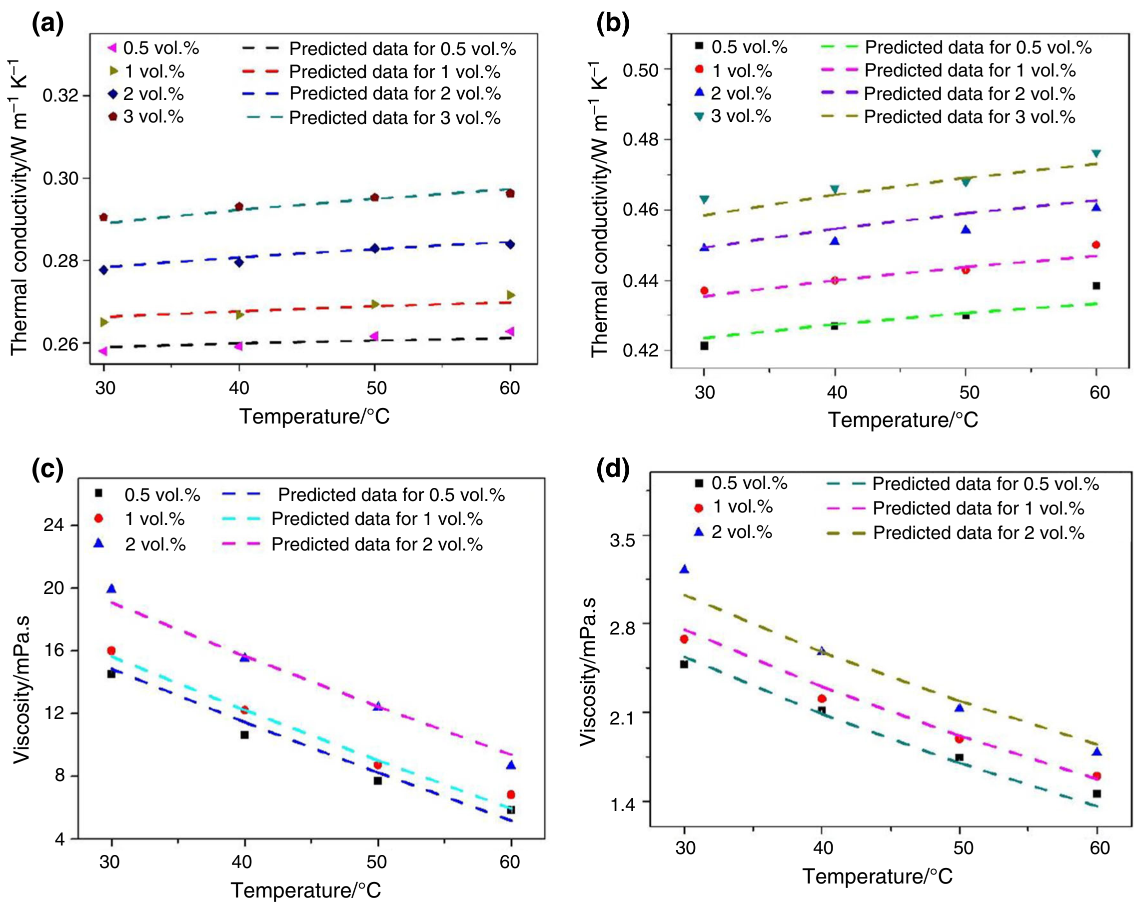

Fig. 15 Comparison of measured thermal conductivity and viscosity of **a**, **c** EG-based **b, d** EG/W-based BN nanofluid with proposed correlation

Conclusions

Thermal conductivity and viscosity of boron nitride nanofluids, synthesized using ethylene glycol and ethylene glycol–water mixture (volumetric ratio of 40/60) as base fluid, were investigated experimentally. Following are the conclusions based on the results obtained:

- Boron nitride nanofluids with particle concentration varying from 0.5 to 3 vol.% indicated that the thermal conductivity enhancement increases with an increase in the particle concentration. A maximum thermal conductivity enhancement of 15.5% and 12.5%, respectively, was obtained for 3 vol.% BN loading in EG- and 40/60 EG/W-based nanofluid.
- Thermal conductivity enhancement of BN nanofluid was almost independent of temperature in the range of 30–60 °C for EG- and 40/60 EG/W-based nanofluid.
- In the case of rheological properties of BN nanofluids, the viscosity of BN nanofluids was found to be dependent on both particles concentration and temperature. The viscosity ratio of both EG-based and EG/W-based BN nanofluid increased with particle concentration and attained a maximum of 1.41 and 1.33, respectively, at 30 °C. In addition, a significant decrease in viscosity with the increase in temperature over the range of 30–60 °C was observed, which can be attributed to the lowering of the viscosity of base fluids.
- The synthesized BN nanofluids showed initially non-Newtonian nature possibly due to the formation of loose clusters of nanoparticles in the fluid which in the presence of low shear rates resists any kind of alignment resulting in higher viscosity. With the increase in shear rates, these clusters possibly slowly align themselves in the flow direction which results in lower viscosity and hence displaying shear thinning. After reaching a specific shear rate, the BN nanofluids begin to exhibit a Newtonian nature.
- The new correlation developed to predict the thermal conductivity and viscosity of BN nanofluids shows good agreement with the present experimental results.

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