

Experimental Study of the Viscosity of Water-Based Graphene Nanoplatelet Nanofluids and Comparison with Correlations

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Publication Date: 2026/10/12

Abstract: Nanofluids have attracted considerable interest because of their enhanced heat transfer characteristics. Viscosity is a key thermophysical property of nanofluids because it governs pressure drop and the pumping power required by a thermal system, yet the accuracy of existing correlations depends on the fluid composition and operating conditions. This study aims to characterise the viscosity of water-based graphene nanoplatelet (GnP) nanofluids experimentally, to assess existing viscosity correlations and to propose a modified correlation. GnP nanofluids with volume fractions of 0.01–0.05 vol.% and average particle diameters of 5, 15 and 25 μm were prepared by a two-step method without surfactant. Dynamic viscosity was measured with an SVM 3000 Stabinger viscometer at 20–60 °C. Extending the sonication time from 90 to 120 minutes changed the viscosity by less than 1.2%, indicating little further change in the measured viscosity over this interval. The viscosity increased with volume fraction and particle diameter and decreased with temperature. At 20 °C, increasing the volume fraction from 0.01 to 0.05 vol.% raised the viscosity by 14.20–17.38%, while heating from 20 to 60 °C reduced the viscosity of the 0.05 vol.% nanofluids by 46.46–47.64%. The largest increase relative to distilled water, 42.53%, occurred at 0.05 vol.%, 25 μm and 60 °C. At 50 °C, most existing correlations underpredicted the measured viscosity. A modified Brenner and Condiff model, with the intrinsic viscosity term raised to the power 1.6, was therefore compared with published data for water-based GnP nanofluids; for 2 μm GnP with specific surface areas of 300–500 m^2/g , the average deviations were about 2–8%, rising to about 14% for 750 m^2/g GnP. It agreed with the present data at 0.01 vol.% but increasingly overpredicted the viscosity of the 15 and 25 μm GnP at higher volume fractions, so further refinement is needed for larger platelets.

Keywords: Graphene Nanoplatelets, Nanofluids, Viscosity, Viscosity Correlation, Particle Size.

How to Cite: Voon Han En; Ting Tiew Wei (2026) Experimental Study of the Viscosity of Water-Based Graphene Nanoplatelet Nanofluids and Comparison with Correlations. *International Journal of Innovative Science and Research Technology*, 11(10), 301-311. <https://doi.org/10.38124/ijisrt/26oct481>

I. INTRODUCTION

Cooling is a critical requirement in automotive, electronics, manufacturing and many other industrial systems. Conventional coolants such as water, ethylene glycol and engine oil have limited thermal performance, and with increasing thermal loads it has become necessary to enhance the thermophysical properties of these fluids [1]. Early attempts to improve heat transfer by suspending millimetre- or micrometre-sized solid particles in liquids increased thermal conductivity, but problems such as clogging made them impractical. Choi [2] proposed nanofluids, suspensions of nanometre-sized particles in conventional heat transfer fluids, as a new class of engineered

heat transfer fluids, and noted that such small particles were not expected to clog flow passages. Since then, nanofluids containing metallic, oxide and carbon-based particles have been shown to enhance thermal conductivity, stability and convective heat transfer in a range of applications [3].

Among carbon-based additives, graphene has attracted particular attention since its isolation by Novoselov et al. [4]. Graphene consists of a single layer of sp^2 -bonded carbon atoms arranged in a hexagonal lattice, which gives it exceptional thermal, electrical and mechanical properties [5]. Graphene nanoplatelets (GnP) consist of short stacks of platelet-shaped graphene sheets, typically a few nanometres thick with lateral dimensions of one to several tens of

micrometres. GnP combines a high in-plane thermal conductivity with relatively simple production and can be dispersed in water and other fluids. GnP nanofluids based on water or water–ethylene glycol mixtures have shown improved heat transfer in heat sinks [6] and automobile radiators [7], and their potential for wind turbine cooling systems has been evaluated [8].

The heat transfer benefit of a nanofluid depends on its thermophysical properties, and viscosity is among the most important because it directly affects the pressure drop, pumping power and convective heat transfer of the system [1]. Numerous experimental studies on GnP nanofluids have reported that viscosity increases with nanoparticle loading and decreases with temperature. Mehrali et al. [9] and Sadeghinezhad et al. [10] measured the viscosity of water-based GnP nanofluids at 0.025–0.1 wt% between 20 and 60 °C. Mehrali et al. [9] attributed the increase with loading to particle agglomeration, which raises the internal shear stress, and both studies attributed the decrease with temperature to weaker inter-particle and inter-molecular adhesion forces. Similar trends were reported for triethanolamine-treated GnP [11], functionalised GnP [8,12], GnP hybrid nanofluids containing silver or platinum [13,14] and GnP in water–ethylene glycol mixtures [7,15]. Several of these studies also found that temperature has the strongest effect on viscosity [9,10,16], and Vakili et al. [17] likewise reported a strong dependence of viscosity on temperature. Particle size is a further important parameter, although its influence on nanofluid viscosity is less well established [18].

On the theoretical side, the classical model of Einstein [19] and its extensions by Brinkman [20] and Batchelor [21] assume rigid spherical particles and do not account for particle shape, size or temperature. Empirical correlations for GnP nanofluids have since been proposed by modifying classical suspension models, including the correlations of Sarsam et al. [11], Bahaya et al. [22] and Toh and Ting [23]. However, published comparisons show that classical correlations, such as those of Einstein [19], Brinkman [20] and Batchelor [21], underpredict measured GnP nanofluid viscosity [8], and no classical model has been found to estimate nanofluid viscosity accurately across different conditions [24]. Reliable experimental data spanning volume fraction, temperature and particle size, together with an assessment of the available correlations, are therefore needed.

In this study, the viscosity of water-based GnP nanofluids was measured for volume fractions of 0.01–0.05 vol.%, temperatures of 20–60 °C and particle diameters of 5, 15 and 25 µm. The measurements were compared with ten existing viscosity correlations, and a modified correlation was proposed and compared with the present and published data.

II. METHODOLOGY

➤ Materials

Grade M graphene nanoplatelets (xGnP®) were purchased from XG Sciences [25]. Three average particle diameters, 5, 15 and 25 µm, were investigated. The specifications of the GnP are given in Table 1. Distilled water (DW) was used as the base fluid, and no surfactant was added.

Table 1 Specifications of the Grade M GnP [25]

Property	Specification
Average particle diameter	5, 15 and 25 µm
Average thickness	6–8 nm
Specific surface area	120–150 m ² /g
Density	2.2 g/cm ³

➤ Preparation of GnP nanofluids

The nanofluids were prepared by a two-step method. The mass of GnP powder required for each volume fraction was calculated using (1):

$$W_{\text{GnP}} = \frac{\phi}{100 - \phi} \times \frac{\rho_{\text{GnP}}}{\rho_{\text{bf}}} \times W_{\text{bf}} \quad (1)$$

Where W_{GnP} is the mass of GnP to be added (g), ϕ is the volume fraction of GnP (vol.%), ρ_{GnP} and ρ_{bf} are the densities of the GnP and base fluid, and W_{bf} is the mass of base fluid (g). The densities used were $\rho_{\text{GnP}} = 2.2 \text{ g/cm}^3$ and $\rho_{\text{bf}} = 1 \text{ g/cm}^3$.

The GnP powder was weighed using an HR-250AZ analytical balance (A&D Company). The powder was then added directly to the distilled water and stirred for 10 minutes on a digital stirring hotplate (Fisher Scientific Isotemp) at 30 °C and 500 rpm to reduce agglomeration. The suspension was subsequently sonicated in a digital ultrasonic bath operating at 40 kHz and 360 W with the bath temperature set

to 50 °C. To avoid overheating the equipment, the ultrasonic bath was rested for 2 minutes after every 5 minutes of operation. Each suspension was sonicated for a total period of 120 minutes, including the rest intervals; this duration was chosen on the basis of the sonication-time measurements presented in the Results and Discussion section. Nanofluids were prepared at volume fractions of 0.01, 0.02, 0.03, 0.04 and 0.05 vol.% for each of the three particle diameters, giving 15 samples in total. These volume fractions correspond to mass fractions of approximately 0.022, 0.044, 0.066, 0.088 and 0.110 wt%.

➤ Viscosity Measurement and Calibration

The dynamic viscosity was measured using an SVM 3000 Stabinger viscometer (Anton Paar). This instrument is a rotational viscometer with cylindrical geometry based on a modified Couette principle, in which a rapidly rotating outer tube drives a more slowly rotating inner measuring bob. The dependence of viscosity on shear rate was not examined. The viscometer and syringes were rinsed periodically with Decon 90 to remove contaminants. Each reading was taken once the

measured value had stabilised; three readings were taken at each condition and the mean value is reported. The relative standard deviation of the three readings was 0.32% on average and did not exceed about 1%. Because each nanofluid was prepared once, this variability reflects repeat measurements and does not include variability between separate preparations. Measurements were made at 20, 30, 40, 50 and 60 °C.

The accuracy of the viscometer was checked by measuring the viscosity of distilled water between 20 and 60 °C and comparing the results with reference values reported by White [26]. The measured values agreed with the reference data with a mean deviation of about 2% and a maximum deviation of about 3% at 20 °C, which was considered acceptable for the present measurements.

➤ Viscosity Correlation Models

The measured viscosities were compared with the ten correlation models listed in Table 2. All models are expressed in terms of the relative viscosity C_μ defined by (2):

$$C_\mu = \frac{\mu_{nf}}{\mu_{bf}} \quad (2)$$

Where μ_{nf} and μ_{bf} are the dynamic viscosities of the nanofluid and base fluid, respectively, at the same temperature. The models were selected because they represent different dependencies: the Brenner and Condiff [27] and Corcione [28] models account for particle size; the Einstein [19], Brinkman [20], Batchelor [21], Sarsam et al. [11], Buongiorno [29] and Maiga et al. [30] models depend on volume fraction only; the Bahaya et al. [22] model

includes a temperature dependence; and the Toh and Ting model [23], which was validated against experimental data for GnP and graphene nanofluids, was developed for GnP nanofluids at concentrations up to 0.5 vol.% and temperatures of 30–90 °C.

In the Brenner and Condiff [27] and Toh and Ting [23] models, the intrinsic viscosity is $\sigma = 0.312\beta/(\ln 2\beta - 1.5) + 2 - 0.5/(\ln 2\beta - 1.5) - 1.872/\beta$, where $\beta = d_p/t_p$ is the axis ratio, d_p is the platelet diameter and t_p its thickness. This expression was derived by Brenner and Condiff [27] for rod-like spheroids in simple shear flow at high shear rates; here, it is applied empirically to platelets by taking β as the ratio of platelet diameter to thickness. Most of these correlations were developed for spherical nanoparticles; for example, the Corcione [28] correlation is based on data for particles of 25–200 nm, and the Buongiorno [29] and Maiga et al. [30] correlations were fitted to alumina nanofluid data, so their application to micrometre-sized platelets is an extrapolation.

In the Corcione [28] model, $d_{bf} = 0.1(6M/N\pi\rho_{bf})^{1/3}$ is the equivalent diameter of a base-fluid molecule, where $M = 18$ g/mol is the molecular weight of water, $N = 6.022 \times 10^{23}$ mol⁻¹ is the Avogadro number and ρ_{bf} is the density of the base fluid at 293 K; in the Bahaya et al. [22] model, T is the nanofluid temperature in K. In the present calculations ϕ was expressed as a fraction, t_p was taken as 8 nm, the upper value of the manufacturer's thickness range, and the model predictions of μ_{nf} were obtained by multiplying C_μ by the reference viscosity of water [26]. The experimental viscosity increases relative to distilled water were instead calculated using the measured viscosity of the distilled water, which was about 2% lower than the reference value at 50 °C.

Table 2 Viscosity Correlation Models Used in this Study

No.	Model	Correlation
1	Einstein [19]	$C_\mu = 1 + 2.5\phi$
2	Batchelor [21]	$C_\mu = 1 + 2.5\phi + 6.2\phi^2$
3	Brinkman [20]	$C_\mu = 1/(1 - \phi)^{2.5}$
4	Brenner and Condiff [27]	$C_\mu = 1 + \sigma\phi$
5	Sarsam et al. [11]	$C_\mu = 1 + 550\phi$
6	Corcione [28]	$C_\mu = 1/[1 - 34.87(d_p/d_{bf})^{-0.3}\phi^{1.03}]$
7	Bahaya et al. [22]	$C_\mu = 1 + 2151\phi(T/298)^3$
8	Buongiorno [29]	$C_\mu = 1 + 39.11\phi + 533.9\phi^2$
9	Maiga et al. [30]	$C_\mu = 1 + 7.3\phi + 123\phi^2$
10	Toh and Ting [23]	$C_\mu = 1 + \sigma^{1.675}\phi$

III. RESULTS AND DISCUSSION

➤ Effect of Sonication Time

To assess whether the GnP were adequately dispersed, the viscosity of every volume fraction and particle size was measured at 50 °C after sonication periods of 30, 60, 90 and 120 minutes (Fig. 1). For all particle sizes, the viscosity increased as the sonication time was extended from 30 to

90 minutes, by 3.55–10.39%, consistent with progressive dispersion of the platelets. Extending the sonication from 90 to 120 minutes changed the viscosity by no more than 1.11%. This indicates a plateau in the measured viscosity, with changes comparable to the repeat variability. Long-term sedimentation stability was not assessed in this study. The viscosity measurements at 20–60 °C reported below were therefore performed on the nanofluids after 120 minutes of sonication.

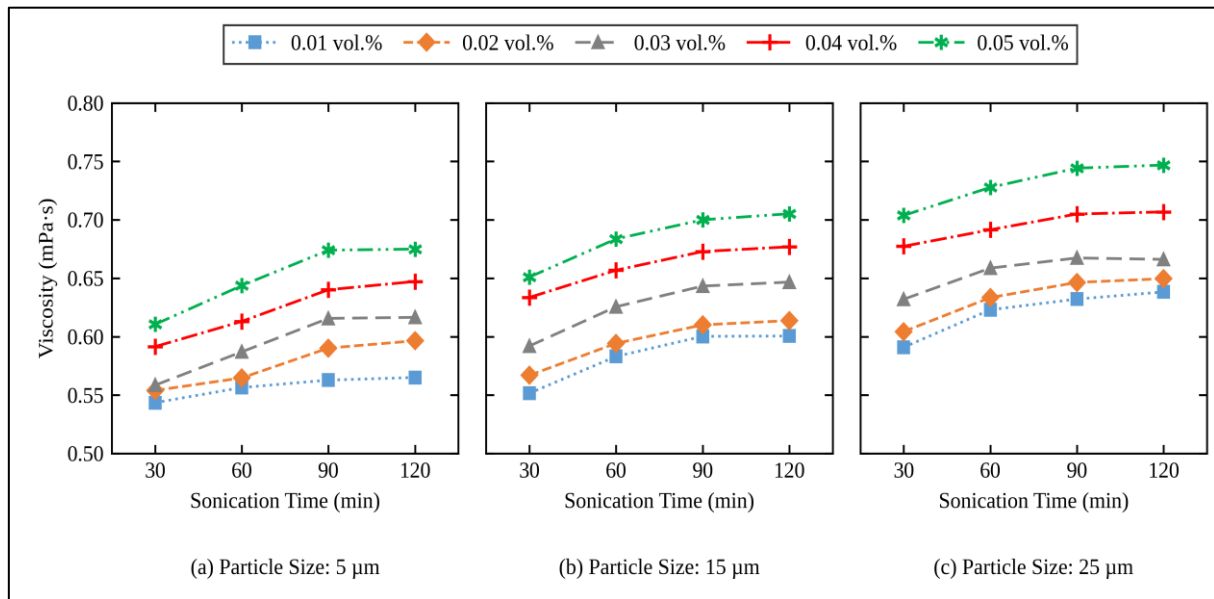


Fig 1 Variation of Viscosity with Sonication Time at 50 °C for GnP Diameters of (a) 5 µm, (b) 15 µm and (c) 25 µm

The levelling-off of viscosity after about 90 minutes of sonication is consistent with the literature on graphene nanofluids, in which sonication time strongly influences dispersion and thermophysical properties [31]. Zheng et al.

[32] found that 90 minutes of ultrasonication was sufficient for proper dispersion of few-layer graphene nanofluids under their conditions, and noted that the optimal ultrasonication process is material-dependent.

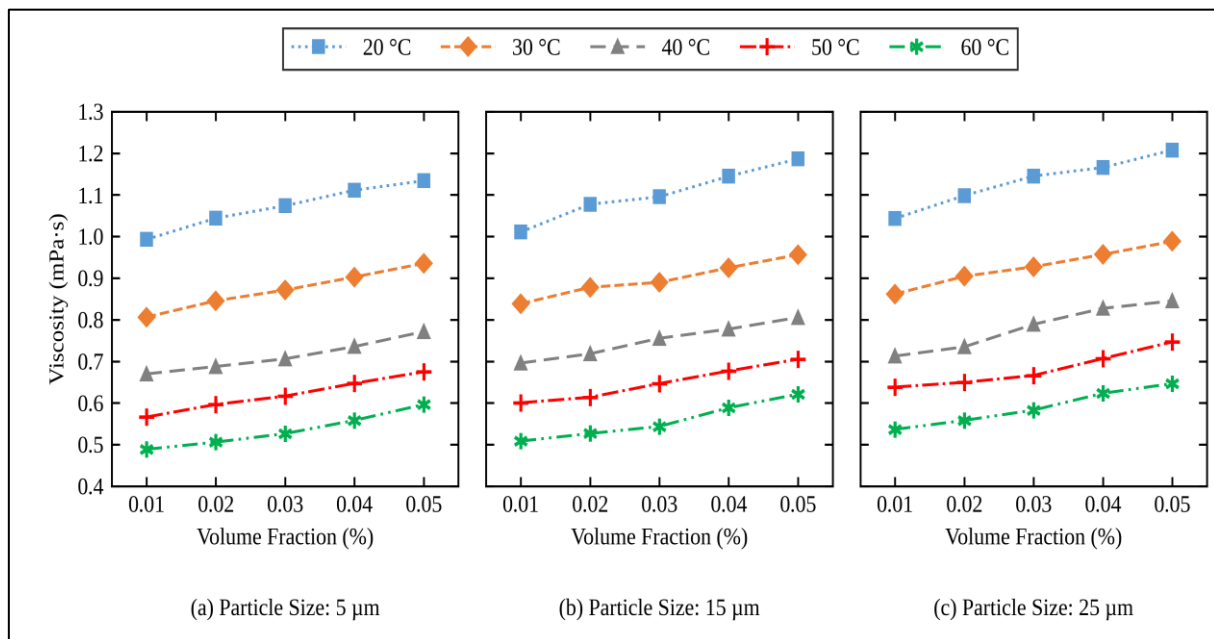


Fig 2 Variation of Viscosity with Volume Fraction for GnP Diameters of (a) 5 µm, (b) 15 µm and (c) 25 µm

➤ Effect of Volume Fraction

The variation of GnP nanofluid viscosity with volume fraction is shown in Fig. 2. For all particle sizes and temperatures, the viscosity increased with volume fraction. At 20 °C, increasing the volume fraction from 0.01 to 0.05 vol.% raised the viscosity by 14.20%, 17.38% and 15.77% for the 5, 15 and 25 µm GnP, respectively. Relative to distilled water, the 0.05 vol.% nanofluids were 16.98–24.58% more viscous at 20 °C and 31.45–42.53% more viscous at 60 °C, with the largest increase of 42.53% obtained for the 25 µm GnP at 60 °C.

This increase agrees with earlier studies on water-based GnP nanofluids [9–11] and is commonly attributed to stronger particle–particle and particle–fluid interactions and to particle agglomeration at higher loadings, which increase the resistance to flow [9,10]. For comparison, Sarsam et al. [11] observed an increase of about 12% when the concentration of triethanolamine-treated GnP increased from 0.025 to 0.1 wt% at 20 °C, which is of similar magnitude to the present results.

➤ Effect of Temperature

Fig. 3 shows that the viscosity of all GnP nanofluids decreased as the temperature increased. For 0.05 vol.%, raising the temperature from 20 to 60 °C reduced the viscosity by 47.41%, 47.64% and 46.46% for the 5, 15 and 25 µm GnP, respectively. Within the ranges studied, temperature therefore produced the largest change in viscosity of the three parameters. Over the same range, the viscosity of distilled water decreased by 53.20%, so the nanofluid viscosity decreased proportionally less than that of the base fluid, and the relative viscosity was higher at 60 °C than at 20 °C.

This decrease is consistent with the literature [7,10] and is commonly attributed to the increased thermal motion of the particles and fluid molecules and the weakening of inter-particle and inter-molecular forces at higher temperatures

[9,10]. The present reduction is similar to the decrease of about 46% observed by Sadeghinezhad et al. [10] for 0.1 wt% GnP over the same temperature range, and Selvam et al. [7] and Vallejo et al. [8] likewise reported that the viscosity of GnP nanofluids decreases less with temperature than that of the base fluid, so that the viscosity ratio increases with temperature.

➤ Effect of Particle Size

The variation of viscosity with particle diameter at 0.05 vol.% and 20 °C is shown in Fig. 4. The viscosity increased with particle diameter, from 1.134 mPa·s for 5 µm GnP to 1.186 mPa·s for 15 µm and 1.208 mPa·s for 25 µm, i.e. increases of 4.62% and 6.50% relative to the 5 µm nanofluid. The same trend was observed at the other volume fractions and temperatures (Figs. 2 and 3).

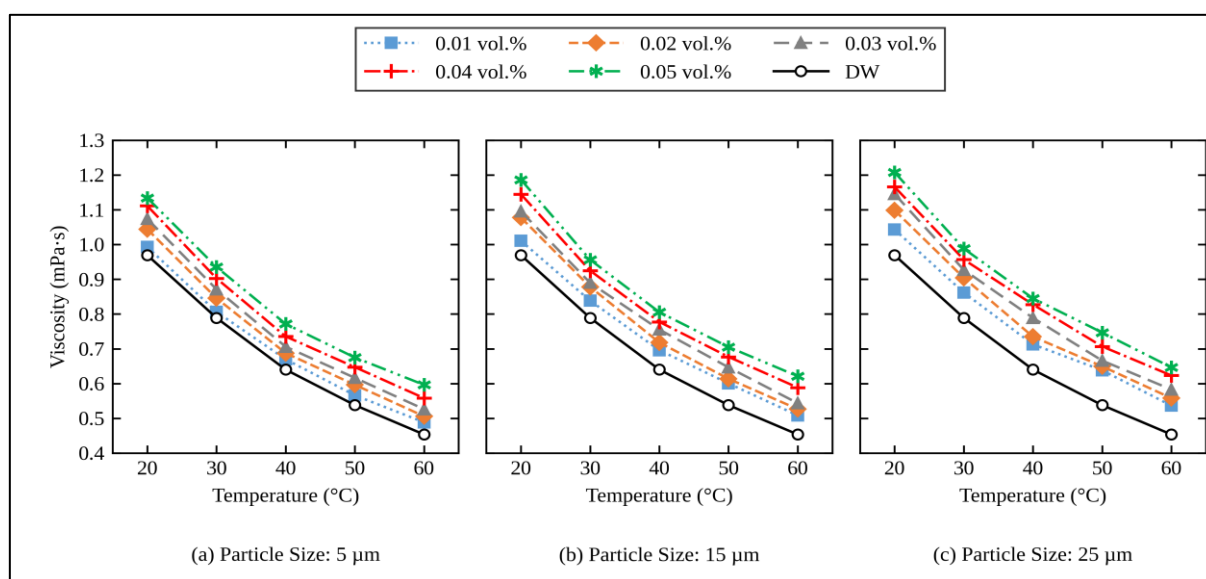


Fig 3 Variation of Viscosity with Temperature for GnP Diameters of (a) 5 µm, (b) 15 µm and (c) 25 µm

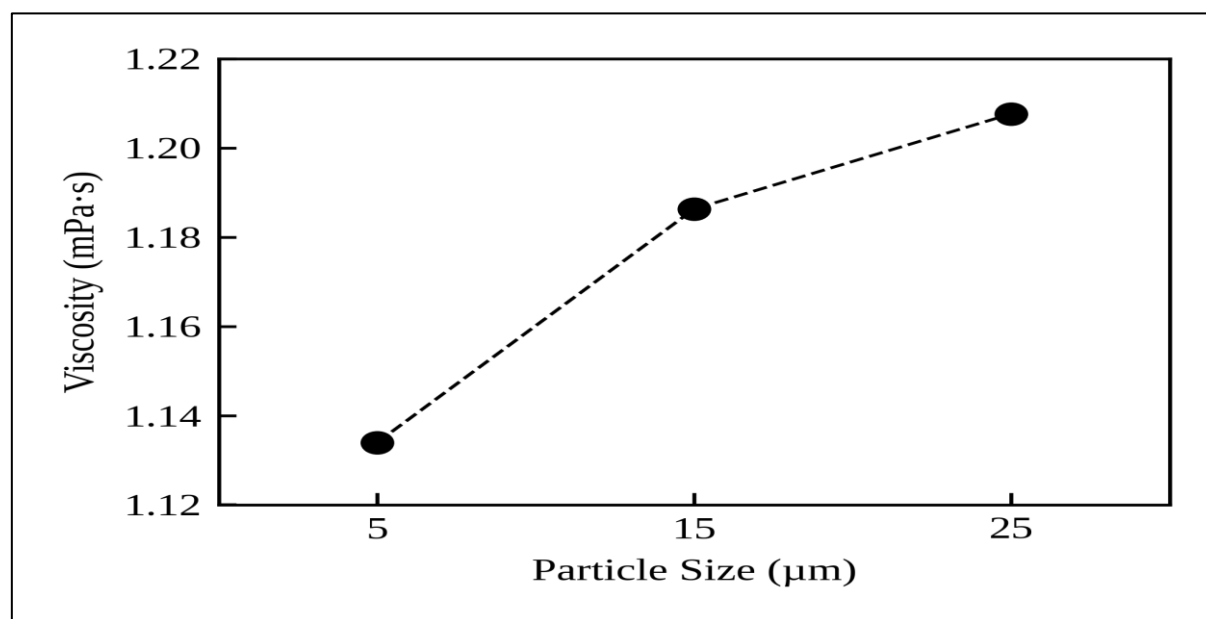


Fig 4 Variation of Viscosity with Particle Diameter at 0.05 vol.% and 20 °C

Increases of viscosity with particle size have also been reported for water-based TiO₂ nanofluids [33] and, at higher concentrations, Al₂O₃ nanofluids [34], although these involved spherical nanoparticles much smaller than the present platelets. One possible explanation is that, for platelets of fixed thickness, a larger diameter corresponds to a larger axis ratio β , for which the intrinsic viscosity σ in the Brenner and Condiff [27] formulation is higher ($\sigma = 36.54, 88.86$ and 136.59 for $5, 15$ and $25 \mu\text{m}$ with $t_p = 8 \text{ nm}$). Studies on GnP of similar diameter have also reported that viscosity depends on specific surface area [9,11], so platelet thickness and surface area should be considered alongside diameter; the present data are not sufficient to separate these effects.

➤ Comparison with Existing Viscosity Correlations

The measured viscosities at 50°C are compared with the predictions of the ten correlations in Fig. 5. For the $5 \mu\text{m}$ GnP, the Sarsam et al. [11] and Toh and Ting [23] models agreed well with the experimental data, with average deviations of 2.69% and 1.04%, respectively. The Einstein [19], Batchelor [21], Brinkman [20], Brenner and Condiff [27], Buongiorno [29], Maiga et al. [30] and Corcione [28] models underpredicted the measured viscosity at all particle sizes, whereas the Bahaya et al. [22] model overpredicted it. For the 15 and $25 \mu\text{m}$ GnP, the Sarsam et al. [11] model again gave the closest agreement, with average deviations of 1.80–6.54%, whereas the Toh and Ting [23] model increasingly overpredicted the data as particle size increased.

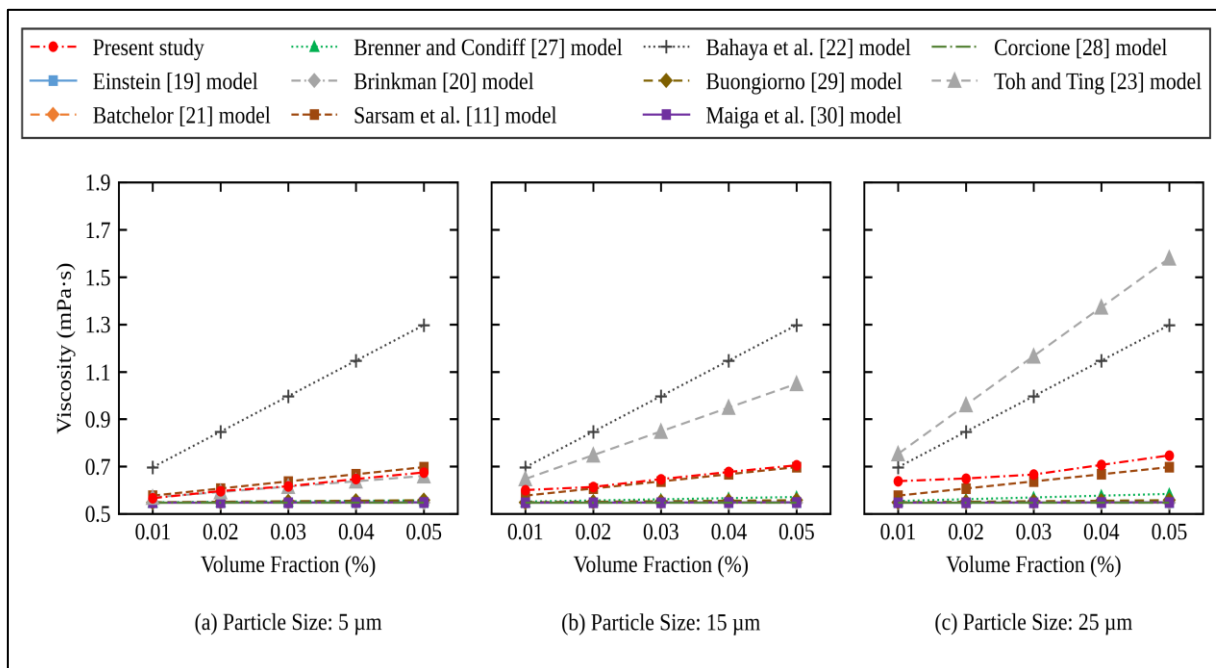


Fig 5 Comparison of the Present Experimental Viscosity with Correlation Predictions at 50°C for GnP Diameters of (a) $5 \mu\text{m}$, (b) $15 \mu\text{m}$ and (c) $25 \mu\text{m}$

These comparisons show that models developed for spherical particles, or those that depend only on volume fraction with small coefficients, substantially underpredict the viscosity of the present GnP nanofluids. This is consistent with Vallejo et al. [8], who found that classical models underestimated the viscosity of functionalised GnP nanofluids, and with Ebrahim et al. [35], who reported that the classical Einstein, Batchelor, Brinkman and Wang models did not reliably predict the viscosity of their dilute water-based GnP nanofluids. Recent reviews have summarised the available viscosity data and prediction models for graphene-based nanofluids [36] and the thermophysical properties of aqueous GnP nanofluids [37]. Among the models considered, the empirical Sarsam et al. [11] correlation gave the best overall agreement with the present data, whereas the geometry-dependent Toh and Ting [23] correlation agreed well only for the $5 \mu\text{m}$ GnP; the accuracy of such empirical models depends on the conditions under which they were fitted.

➤ Proposed Viscosity Correlation

Although the Sarsam et al. [11] model approximates the present data, it is a function of volume fraction only and does not account for particle size, and its deviation was largest for the $25 \mu\text{m}$ GnP. A correlation that accounts for particle geometry was therefore developed by modifying the Brenner and Condiff [27] model, which includes a particle axis ratio through the intrinsic viscosity σ . The exponent of the intrinsic viscosity term was adjusted iteratively to match published viscosity data for GnP nanofluids and was changed from 1 to 1.6, giving (3):

$$C_\mu = 1 + \sigma^{1.6}\phi \quad (3)$$

Where $\sigma = 0.312\beta/(\ln 2\beta - 1.5) + 2 - 0.5/(\ln 2\beta - 1.5) - 1.872/\beta$ and $\beta = d_p/t_p$. As an example, for $\phi = 0.01 \text{ vol.}\%$, $d_p = 5 \mu\text{m}$ and $t_p = 8 \text{ nm}$, $\sigma = 36.54$ and (3) gives $C_\mu = 1.03165$.

➤ Comparison of the Proposed Correlation with Viscosity Data

The proposed correlation was compared with published viscosity data for GnP nanofluids (Figs. 6 and 7) and with the present data (Fig. 8). Because the exponent of 1.6 was determined empirically, these comparisons should not be regarded as an independent validation. The published concentrations, reported in wt%, were converted to vol.% using a GnP density of 2.2 g/cm³. Where a study reported only relative viscosity [16], it was converted to dynamic viscosity using the reference viscosity of water [26]. The deviations are given as the average absolute deviation for each data set, calculated as the mean of $|\mu_{\text{model}} - \mu_{\text{exp}}| / \mu_{\text{exp}} \times 100\%$ over the nanofluid points, excluding the base-fluid

point. Deviations of a few percent are comparable to the difference between the measured and reference water viscosities (about 2%) and to the uncertainty of values read from published figures.

For low volume fractions (Fig. 6), the model agreed with the water-based GnP data of Mehrali et al. [9], Sadeghinezhad et al. [10] and Iranmanesh et al. [16] for specific surface areas of 300 and 500 m²/g, and with the data of Sarsam et al. [11] for triethanolamine-treated GnP with a specific surface area of 750 m²/g, with average deviations of 1.16–5.57%. For GnP with a specific surface area of 750 m²/g [9,16,17], the model underpredicted the data, with average deviations of 5.75–13.19%.

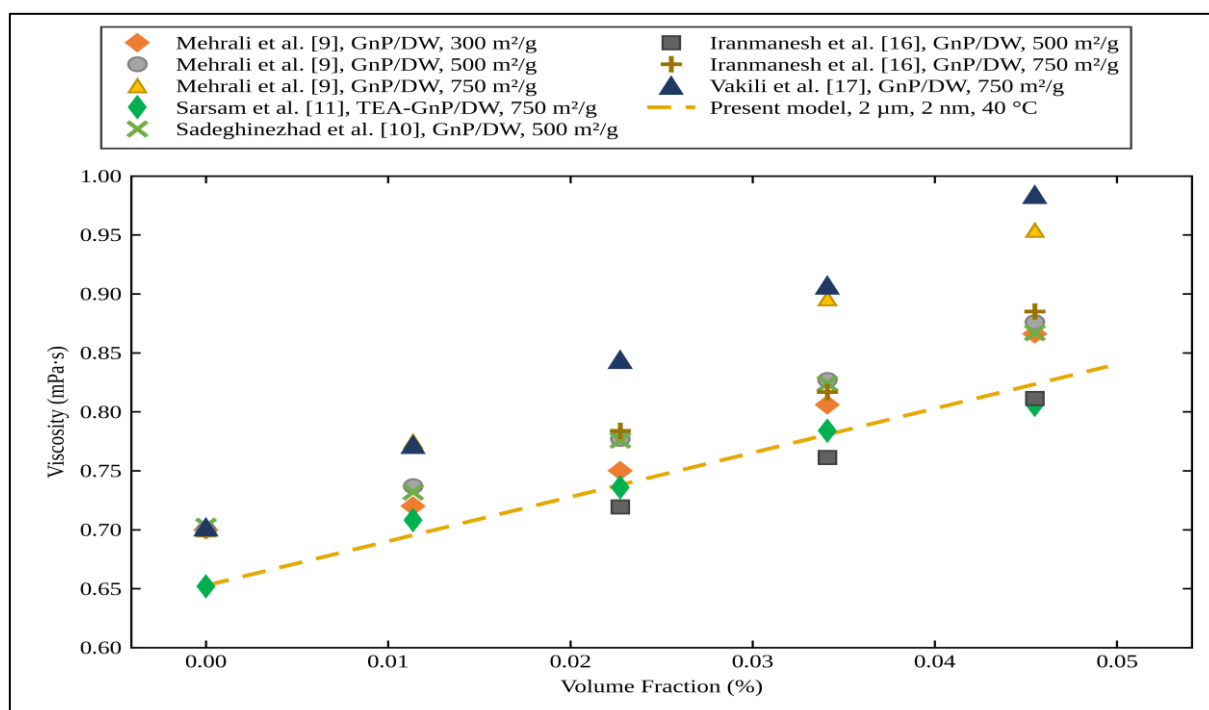


Fig 6 Comparison of the Proposed Correlation with Published Viscosity Data at 40 °C

The correlation was also compared with data not included in Fig. 6: the water–ethylene glycol (70:30 by volume) nanofluids of Selvam et al. [15] at 0.1–0.5 vol.%, which contained 15 μm GnP with a reported thickness of 5–10 nm. The correlation substantially overpredicted their viscosity: at 50 °C, their dynamic viscosity, calculated from the reported kinematic viscosity and density, was 18–44% higher than that of the base fluid, whereas the correlation predicts viscosity ratios of about 2.0–5.9 for a thickness of 10 nm, corresponding to an average deviation of about 195%; thinner platelets within the reported range would give larger deviations. Although these nanofluids also differed in base fluid and contained a surfactant, this overprediction is consistent with the behaviour observed for the present 15 and 25 μm GnP.

Fig. 7 compares the model with published data over a range of temperatures. The calculations for Figs. 6 and 7 used a platelet diameter of 2 μm and thickness of 2 nm. For the Amiri et al. [12] comparison, these were adopted as representative assumed values within the reported

dimensional ranges for the pristine GnP. For Vakili et al. [17], who report a diameter of less than 2 μm, 2 μm was adopted as an upper value. For 0.0455 vol.% GnP, the average deviations from the data of Mehrali et al. [9], Amiri et al. [12], Sadeghinezhad et al. [10] and Iranmanesh et al. [16] ranged from 4.37% to 7.84%. For GnP with a specific surface area of 750 m²/g, the average deviations ranged from 3.67% to 14.49%. For most datasets, the correlation tended to underpredict viscosity at higher temperatures; because the correlation assumes a temperature-independent ratio to the base-fluid viscosity, it cannot capture the slower decrease of nanofluid viscosity with temperature. The Sarsam et al. [11] dataset was an exception: the correlation overpredicted viscosity throughout 20–40 °C, with the largest deviation occurring at 20 °C.

Fig. 8 compares the model with the present data for different particle sizes at 0.01 vol.% and 50 °C. The model reproduced the increase of viscosity with particle diameter from 5 to 25 μm, with an average deviation of about 3.8%. However, when the model was applied to the present data at

higher volume fractions (50 °C, using the same reference water viscosity as in Fig. 5), the agreement deteriorated with increasing particle size. At 0.05 vol.%, the model underpredicted the viscosity of the 5 μm nanofluid by 6.1% but overpredicted that of the 15 μm and 25 μm nanofluids by 28.4% and 68.8%, respectively. The average deviations over

0.01–0.05 vol.% were 3.3%, 17.0% and 41.9% for 5, 15 and 25 μm , respectively. This overprediction arises because $\sigma^{1.6}$ increases rapidly with the axis ratio, making the predicted viscosity increasingly sensitive to volume fraction for larger platelets.

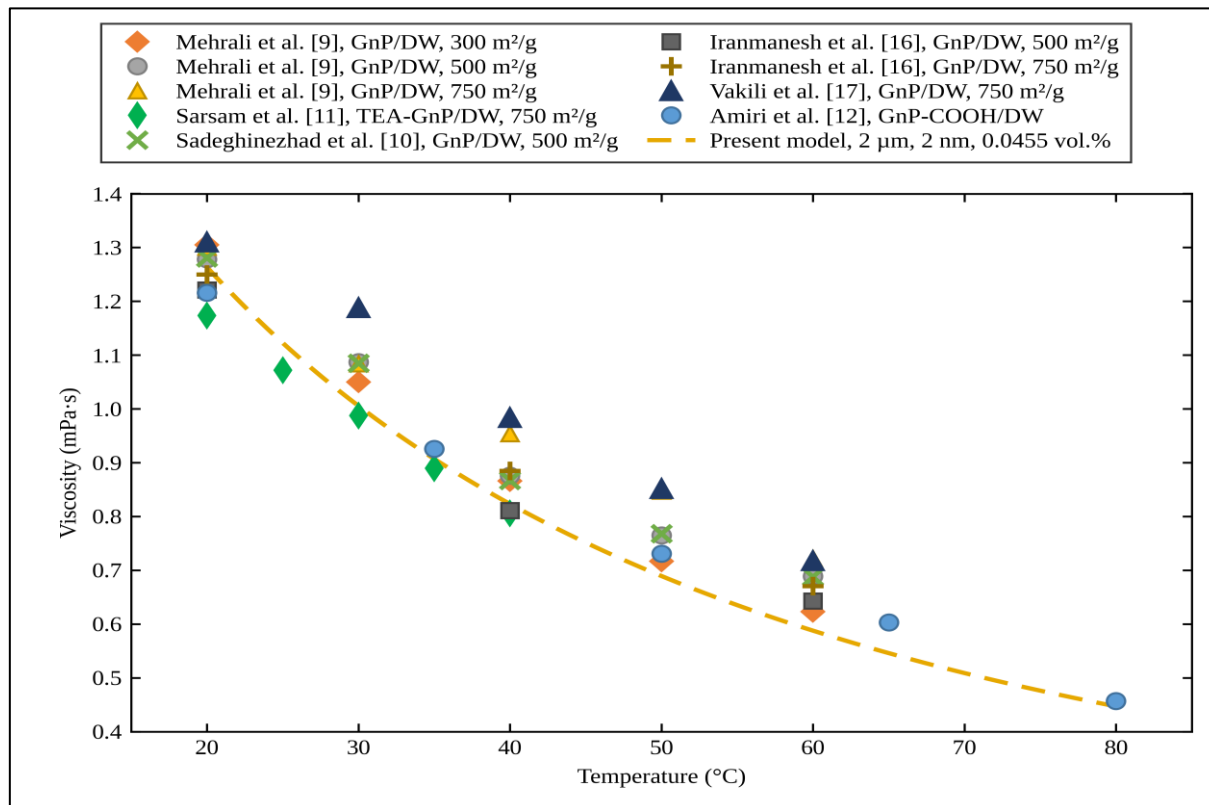


Fig 7 Comparison of the Proposed Correlation with Published Viscosity Data at 0.0455 vol.% (0.1 wt%)

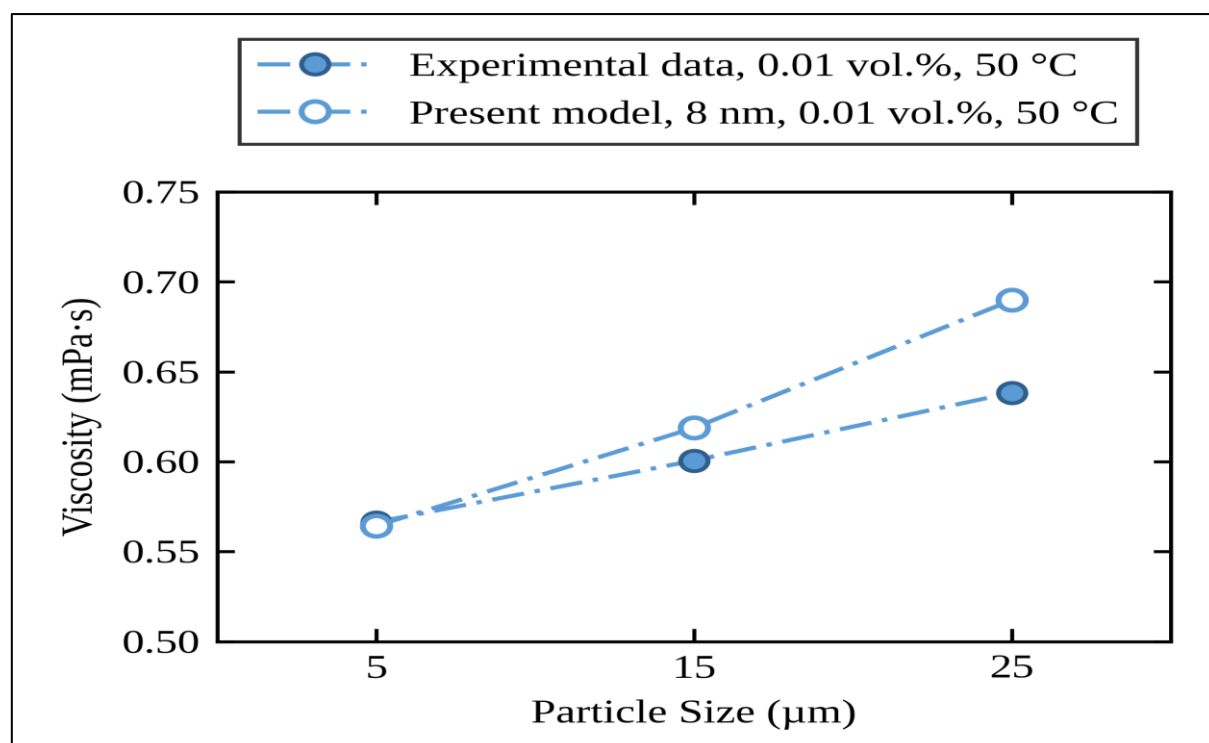


Fig 8 Comparison of the Proposed Correlation with the Present Viscosity Data for Different Particle Sizes at 0.01 vol.% and 50 °C

Overall, the proposed correlation performs best for water-based GnP nanofluids with specific surface areas of 300–500 m²/g. Its larger deviations for water–ethylene glycol base fluids and high-surface-area GnP suggest that these factors are not captured by a correlation based only on platelet geometry and volume fraction. The overprediction of the present data for the 15 and 25 µm GnP shows that the exponent of 1.6, which agrees with the published data for platelets of about 2 µm, does not extrapolate to larger platelets. For the present data, the proposed correlation was also less accurate than the simpler Sarsam et al. [11] correlation at all three particle sizes. The proposed correlation therefore shows agreement with the selected water-based GnP data for diameters of about 2–5 µm, but its general range of applicability has not been established, and a correlation that covers larger platelets requires further work.

IV. CONCLUSION

The viscosity of water-based GnP nanofluids was investigated experimentally for volume fractions of 0.01–0.05 vol.%, temperatures of 20–60 °C and particle diameters of 5–25 µm, and the results were compared with existing and newly proposed correlations. The main conclusions are as follows. First, viscosity increased with volume fraction; at 20 °C, increasing the volume fraction from 0.01 to 0.05 vol.% raised the viscosity by 14.20–17.38%. Second, viscosity decreased with temperature, by 46.46–47.64% between 20 and 60 °C at 0.05 vol.%, making temperature the most influential parameter within the ranges studied. Third, viscosity increased with particle diameter, by 6.50% from 5 to 25 µm at 0.05 vol.% and 20 °C, and the same trend was observed at all other volume fractions and temperatures. Fourth, at 50 °C, most existing correlations underpredicted the measured viscosity.

A modified Brenner and Condiff [27] correlation, $C_\mu = 1 + \sigma^{1.6}\phi$, was proposed. It agreed with published data for water-based GnP nanofluids with platelet diameters of about 2 µm and specific surface areas of 300–500 m²/g within average deviations of about 2–8%, but deviated by up to about 14% for 750 m²/g GnP, and also agreed with the present data at 0.01 vol.%. However, it overpredicted the viscosity of the present 15 and 25 µm nanofluids at higher volume fractions, by up to 68.8% at 0.05 vol.%, and for the present data it was less accurate than the Sarsam et al. [11] correlation, so its applicability is currently limited to smaller platelets. Future work should extend the measurements to include surfactants, other pH values, base fluids, particle shapes, sonication times and hybrid nanoparticles, use probe sonication, which is generally more effective than an ultrasonic bath [31], to improve dispersion, and refine the correlation over a wider and more systematic range of volume fraction, temperature, particle size and base fluid.

ACKNOWLEDGMENT

This research was funded by the University Research Grant from University of Technology Sarawak (UTS/RESEARCH/4/2024/03).

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