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Effect of Various Surfactants on the Viscosity, Thermal and Electrical Conductivity of Graphene Nanoplatelets Nanofluid

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Abstract

The effects of surfactants on the stability and thermophysical properties of graphene nanoplatelets nanofluids are experimentally studied at different temperatures. Graphene nanoplatelets (GNP) nanofluids were prepared with various surfactants, including sodium dodecylbenzene sulfonate (SDBS), sodium dodecyl sulfate (SDS), Gum Arabic (GA), and Tween 80 at different GNP-surfactant ratios (2:1, 1:1, and 1:2). The best dispersion and stabilization over 2 weeks was found to be with a GNP-surfactant ratio of 2:1 for SDBS-based nanofluids and 1:1 for nanofluids with other surfactants. A comparative study of the effects of the different surfactants on the electrical conductivity, pH, thermal conductivity, and viscosity was carried out. The study observed that all nanofluids' electrical conductivity and thermal conductivity are augmented at elevated temperatures while the pH and viscosity deteriorate at higher temperatures. The electrical conductivity measurements of the GNP nanofluids show that SDBS addition contributes the highest enhancement of 154.33 % compared to water. This was followed by SDS, GA, and Tween 80-based nanofluid, which has an electrical conductivity enhancement of 153.25 %, 21.48 %, and 2.83 %, respectively. In comparison to water, the thermal conductivity results revealed that SDBS, GA, SDS, and Tween 80-based nanofluid has a maximum enhancement of 5.50 %,5.66 %, 6.45 %, and 8.96 %, respectively, at 45 °C. This shows that a higher thermal conductivity enhancement is achieved using Tween 80 as the dispersant. The experimental results further revealed that the viscosity of the nanofluids greatly increased with the use of GA compared to other surfactants. Compared to water, a maximum viscosity increase of 5.79 %, 17.54 %, 19.30 %, and 22.81 % was obtained for SDBS-GNP, GA-GNP, SDS-GNP, and Tween 80-GNP, respectively at 55 °C.

Keywords Electrical conductivity · Graphene nanoplatelets · Nanofluids · Stability · Surfactants · Thermal conductivity · Viscosity

1 Introduction

Nanofluid is an advanced thermo-fluid with the capability to improve heat transfer and energy efficiency of different industrial applications, which requires heating and cooling. Nanofluids are developed by loading highly conductive nanomaterials into conventional thermo-fluids such as water, oil, and glycols. This is usually achieved either by a single-step approach system, in which the nanomaterial is synthesized simultaneously into the base fluid, or a double-step approach, in which an already synthesized nanomaterial is loaded into the base fluid [1]. The latter approach is commonly used as it is more economical. However, one of the significant challenges associated with this approach is poor stability due to the clustering of nanomaterials [2].

Graphene, a nanostructured carbon material, is a promising nanomaterial for developing highly conductive nanofluids. This carbon nanomaterial has superb thermo-electrical and physical properties [3]. However, due to the hydrophobic nature of graphene, they tend to agglomerate when dispersed in conventional thermo-fluids. These agglomerates can block heat pipes, increase erosion-corrosion and elevate pressure drop. To improve the stability of nanofluids, surfactants are often added as a non-covalent modifier to enhance the dispersion and distribution of nanomaterials in the base fluids. However, these surfactants will likely influence the thermophysical properties of the nanofluids. Some studies reported that surfactants type impacts the transport mechanism of the nanofluids [4, 5]. Hence, it is pertinent to investigate the effects of the different surfactants on graphene-based nanofluids' stability and thermophysical properties.

Numerous studies on several surfactant-based stable dispersion of nanofluids have been conducted. Shanbedi et al. [6] evaluated the effects of SDS, CTAB, and GA on the dispersibility of MWCNT in an aqueous solution at different surfactant-MWCNT ratios. They reported that SDS-based nanofluid has the best stability, followed by that of CTAB and GA. Sadri et al. [7] assessed the effects of GA, SDS, and SDBS on the thermophysical properties of MWCNT. They noticed that the use of GA as a dispersant improves the thermal conductivity of CNT nanofluids better than SDS and SDBS. Kim et al. [8] compared the effects of different surfactants (SDS, SDBS, and DB) on the thermal conductivity of carbon nanomaterials. They found that Dodecyl Betaine is a better dispersant than SDS and SDBS. They further revealed that SDS stabilized the dispersion of graphene in an aqueous solution better than SDBS, while SDBS is better with CNT. Almanassra et al. [9] examined the effects of SDS, GA, and PVP on the thermophysical properties of CNT nanofluids. The study shows that the viscosity of nanofluids is higher with the use of SDS in comparison to GA and PVP. They further noticed that the addition of the different surfactants has no effect on the thermal conductivity of the nanofluids. This doesn't agree with a host of literature [7, 8, 10, 11], where the thermal conductivity is greatly influenced by the surfactant used.

Further, it is pertinent to state that the stability of nanofluids has been evaluated using numerous techniques, including electron microscopy, UV–Vis spectroscopy, zeta potential analysis, etc. [1]. Zeta potential is one of the most widely used techniques. Zeta potential is an indicator of the surface charge of nanomaterials, which provides information on the nanofluids' stability [12]. This technique has been used by numerous authors [10, 13] in studying stability.

Based on the literature review and to the best of our knowledge, it was observed that studies on the effects of different surfactants on the thermophysical properties of graphene nanoplatelets (GNP) nanofluids are limited. Hence, this study will focus on the influence of non-ionic surfactants and anionic surfactants on the electrical conductivity, pH, viscosity, and thermal conductivity of water-based GNP nanofluids. This study focused on using water as the base fluid for nanofluid due to its higher specific heat, low viscosity and higher thermal conductivity compared to other conventional base fluids [14]. Water, the most commonly used base fluid, is non-toxic and cheaper than other conventional fluids such as glycol. The surfactants that will be explored include SDS, SDBS, GA, and Tween 80. The stability of the nanofluids will be evaluated using zeta potential measurement. All the aforementioned thermoelectric and physical properties will be measured at different temperatures.

2 Materials and Methods

Graphene nanoplatelets and different surfactants, including SDBS, SDS, GA, and Tween 80, were used in this study. All of these materials were acquired from Sigma-Aldrich, Germany. The GNP has a surface area of 50–80 $m^2 \cdot g^{-1}$, a particle size of 5 μm, and an average thickness of 15 nm.

All the nanofluid samples were prepared using two-step preparation techniques. The surfactant was first added to distilled water and stirred for at least 5 min before adding 0.25 wt% (~ 0.1 vol%) of GNP, further stirred for 10 min. The samples were then further sonicated using OMNI Ruptor Homogenizer for an optimized period of 30 min. Radwag AS 220.R2 digital weighing balance (± 0.01 g accuracy, Radom, Poland) was used to take all weight measurements in this study. The nanofluids were prepared at different GNP-surfactant ratios of 2:1, 1:1, and 1:2. The effects of the GNP-surfactant ratios on the stability of the nanofluids were evaluated using zeta potential measurement and photographic visual observation. The zeta potential measurement was done using Malvern Zetasizer Nano ZS.

The effects of the different surfactant addition were investigated by measuring the thermophysical properties of the nanofluid samples. EUTECH CON700 electrical conductivity meter (± 1 % accuracy), Jenway 3510 pH meter (± 0.003 accuracy), SV-10 Vibro-viscometer (A&D, Japan), and KD2 Pro thermal properties analyzer (Decagon Devices Inc., USA) were used to measure the electrical conductivity, pH, viscosity, and thermal conductivity of the nanofluid samples, respectively. All these properties were measured at different temperature ranges of 15–55 °C except for thermal conductivity measured at 15–45 °C. The temperature of the samples was controlled using LAUDA programmable water bath (± 0.01 °C resolution).

The uncertainty for measuring electrical conductivity, thermal conductivity, and viscosity is ± 2.50 %, ± 5.52 %, and ± 3.78 %, respectively.

3 Results and Discussion

3.1 Nanofluid Stability

The stability of nanofluid is essential for its heat transfer application. The stability of GNP nanofluids stabilized using SDBS, SDS, GA, and Tween 80 with different GNP-surfactant ratios (1:2, 1:1, and 2:1) was evaluated using zeta potential measurement and visual observation techniques. In order to measure the zeta potential, all the nanofluid samples were diluted at a ratio of 1:30. This is done to enable transmission of light when taking the zeta potential measurement using the dynamic light scattering system. This technique have also been used by a host of authors for dark graphene nanofluid samples [15, 16]. The absolute zeta potential values of the nanofluid samples are presented in Fig. 1. SDBS-GNP nanofluids can be found to have the highest absolute zeta potential value at all the GNP-surfactant ratios. This was followed by SDS-GNP, GA-GNP, and Tween 80-GNP nanofluids. This result clearly shows that all the nanofluid samples exhibit moderate to good stability with minor sediments. Further, the zeta potential of the different surfactant-based nanofluids can be found to increase with an increase in the concentration of surfactants from the GNP-surfactant ratio of 2:1 to 1:1. However, there was a slight reduction in zeta potential with a further increase to the GNP-surfactant ratio of 1:2.

In order to investigate the long-term stability of the nanofluid samples, images of the samples were taken immediately after preparation and 2 weeks after preparation. The photographic images are presented in Fig. 2. After 2 weeks, all the nanofluids except for SDBS-based nanofluids with GNP-surfactant ratios of 1:1

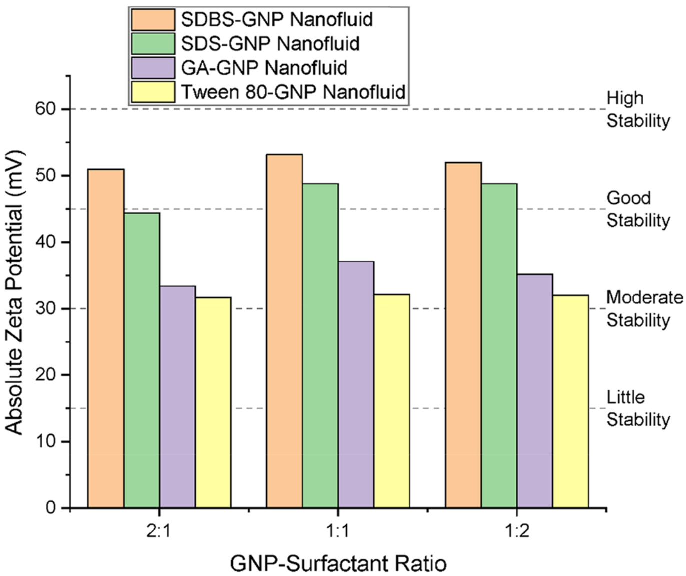

Fig. 1 Absolute zeta potential of GNP nanofluids with various surfactants at different GNP-surfactant ratios

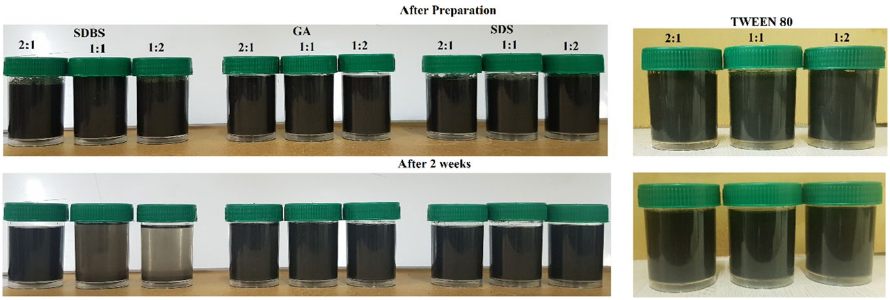

Fig. 2 Photographic images of the nanofluids after preparation and after 2 weeks of preparation

and 1:2 were stable without any visible sedimentation. This indicates that despite the higher zeta potential value of SDBS-based GNP nanofluids, the nanofluids tend to agglomerate at a surfactant concentration, which is more than half the concentration of GNP. Given the results of stability, further studies on the thermophysical properties of GNP nanofluids will be conducted on GNP nanofluids with a GNP-surfactant ratio of 2:1 for SDBS and 1:1 for other surfactants. Also, the stability of SDS-GNP and Tween 80-GNP nanofluids were further verified by monitoring the viscosity of the nanofluids for 1440 min after preparation at a temperature of 20 °C. The viscosity of the examined nanofluids were found to be relatively stable with minor changes in viscosity as shown in Fig. 3. The morphology of a stable GNP nanofluid was done using Transmission electron microscope

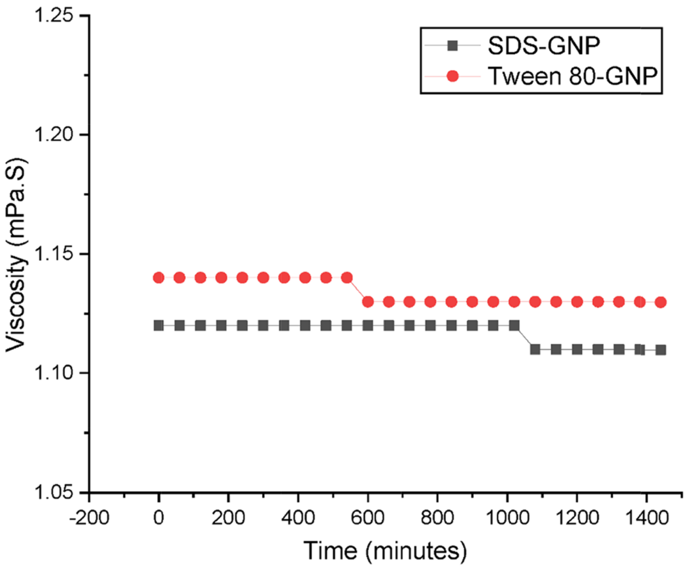

Fig. 3 Viscosity measurement of the nanofluids for 24 h

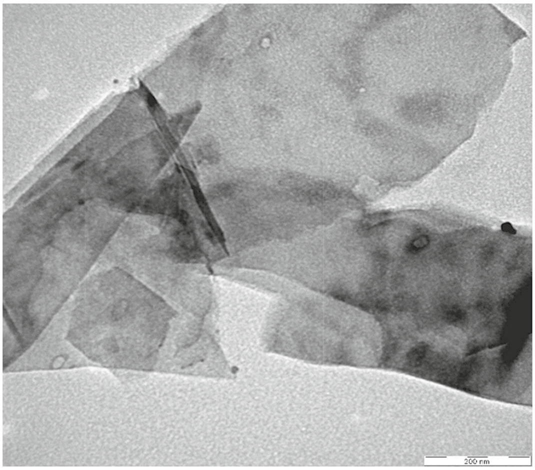

Fig. 4 TEM morphology of a stably dispersed GNP nanofluid

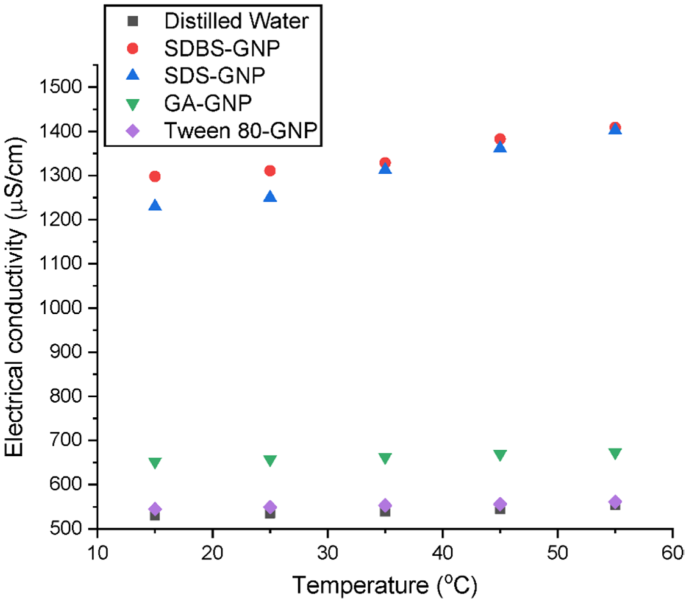

Fig. 5 Electrical conductivity of GNP nanofluids at different temperatures

(TEM). The TEM image is presented in Fig. 4. The GNP sheets with straight line and sharp edges can be clearly seen in the image.

3.2 Electrical Conductivity

The effects of different surfactants on the electrical conductivity ($\sigma_{\mathrm{nanofluid}}$) was investigated. Figure 5 shows the $\sigma_{\mathrm{nanofluid}}$ as a function of temperature. The result shows that the $\sigma_{nanofluid}$ is influenced by temperature and the surfactant type. The σ value of all the samples can be found to increase with an increase in temperature. This could be ascribed to the brisk movement of molecules at elevated temperatures. This causes particles to collide with each other often, thus improving the electrical conductivity of the nanofluids. The $\sigma_{nanofluid}$ of all the nanofluids can be found to be higher than σ_{water}. This shows that the addition of GNP and surfactants brings about the formation of an electrical double layer effect, which increases σ. This electric double layer effect occurs when the particles' surface attracts ions of opposite charges when suspended in distilled water.

The electrical conductivity enhancement ($\sigma_{enhancement}$) of the GNP nanofluids are presented in Fig. 6. The $\sigma_{enhancement}$ were determined using Eq. 1 [17].

$$\sigma_{enhancement} = \left(\frac{\sigma_{nanofluid} - \sigma_{water}}{\sigma_{water}} \right) \times 100 \tag{1}$$

where $\sigma_{nanofluid}$ is the viscosity of GNP nanofluids while σ_{water} is the electrical conductivity of water. The results reveal that there is an almost linear relationship between $\sigma_{enhancement}$ and temperature. SDBS-GNP can be found to have the highest $\sigma_{enhancement}$ at all temperatures. This was followed by SDS-GNP and GA-GNP, with Tween 80-GNP nanofluid having the least enhancement. In comparison to distilled water, a maximum enhancement of 154.33 %, 153.25 %, 23.1 %, and 2.83 % was estimated for SDBS-GNP, SDS-GNP, GA-GNP, and Tween 80-GNP nanofluids. This indicates that the addition of anionic surfactants significantly enhanced

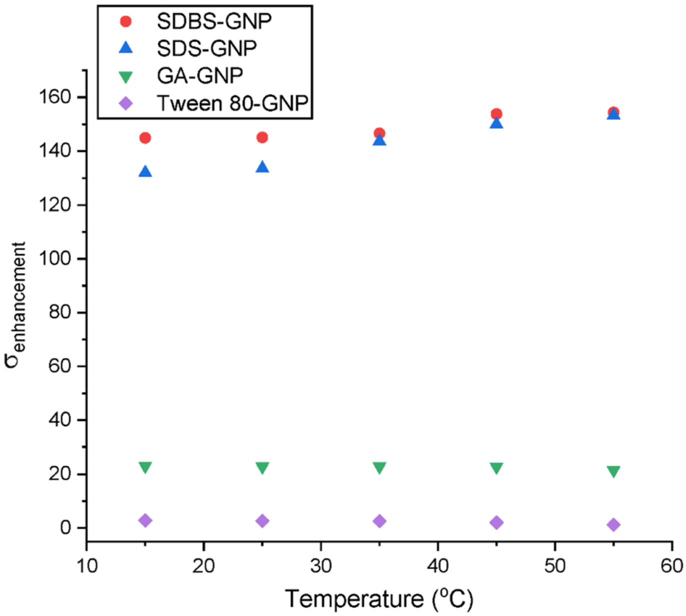

Fig. 6 Electrical conductivity enhancement of GNP nanofluids at different temperatures

$\sigma_{nanofluid}$ more than non-ionic surfactants. These enhancement attributes of anionic surfactants agree with previous studies [18–20].

The pH of the different nanofluids was measured at different temperatures. The study reveals that the pH value of all the nanofluids reduces when the temperature is increased. A decreasing pH range from 7.692–7.455, 8.320–7.979, 8.437–7.740, 8.505–7.921, and 7.877–6.973 was obtained for distilled water, SDBS-GNP, SDS-GNP, GA-GNP, and Tween 80-GNP, respectively at a temperature of 15–55 °C.

3.3 Viscosity

The effects of surfactants on the viscosity of nanofluids were studied. Figure 7 shows the viscosity of the GNP nanofluids with different surfactants as a function of temperature. According to the results, the viscosity of all the examined nanofluids can be found to reduce as temperature increases. This result conforms with the study by numerous authors [7, 21–23]. The viscosity diminution at elevated temperature could be ascribed to enhanced mobility of molecules and volume expansion, which reduces the density of fluids. The result shows that GA-GNP nanofluid has the highest viscosity, followed by Tween 80-GNP, SDS-GNP, and SDBS-GNP, while distilled water has the lowest viscosity. This shows that the type of surfactants has a significant effect on the nanofluid viscosity. The viscosity results between GA and SDS-based nanofluids are not in agreement with the study by Almanassra et al. [9] and Wang et al. [24], as they found SDS-based

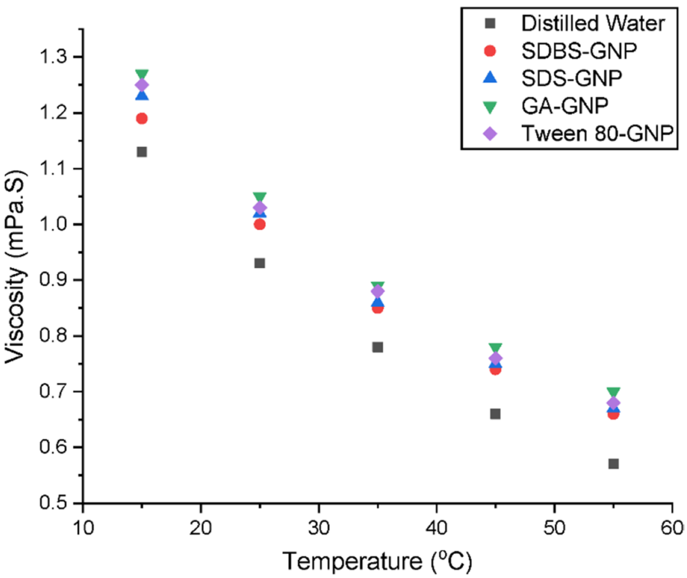

Fig. 7 Viscosity of GNP nanofluids at different temperature

nanofluids to possess a remarkably higher viscosity than that of GA. However, the result is consistent with the study by Sarsam et al. [15]. They observed that GA-based nanofluid has a higher viscosity than other surfactant-based nanofluids, despite using a lower GA concentration.

The relative viscosity ($\mu_{relative}$) and viscosity increment ($\mu_{increment}$) of the GNP nanofluids are presented in Figs. 8 and 9. The $\mu_{relative}$ and $\mu_{increment}$ were determined using Eqs. 2 and 3.

$$\mu_{relative} = \mu_{nanofluid}/\mu_{water} \tag{2}$$

$$\mu_{increment} = (\mu_{relative} - 1) \times 100 \tag{3}$$

where $\mu_{nanofluid}$ is the viscosity of GNP nanofluids while μ_{water} is the viscosity of water. The results reveal that a rise in temperature brings about an increase in $\mu_{relative}$ and $\mu_{increment}$. GA-GNP can be found to have the highest $\mu_{enhancement}$ at all temperatures. This was followed by Tween 80-GNP and SDS-GNP, with SDBS-GNP nanofluid having the least increment. In comparison to distilled water, a maximum increment of 15.79 %, 17.54 %, 22.81 %, and 19.30 % was estimated for SDBS-GNP, SDS-GNP, GA-GNP, and Tween 80-GNP nanofluids, respectively at 55 °C.

3.4 Thermal Conductivity

The thermal conductivity ($\lambda_{nanofluid}$) of the GNP nanofluids with different surfactants as a function of temperature was investigated, and the results are presented in Fig. 10. The result reveals an increase in the $\lambda_{nanofluid}$ as the nanofluid temperature

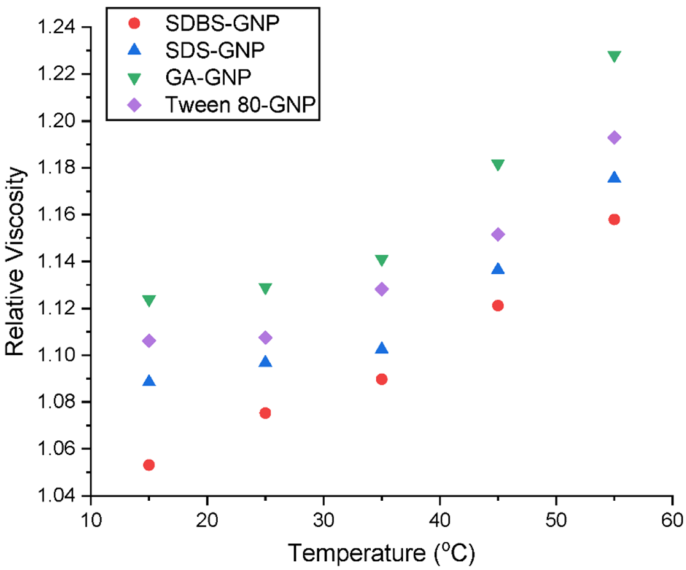

Fig. 8 Relative viscosity of GNP nanofluids at different temperature

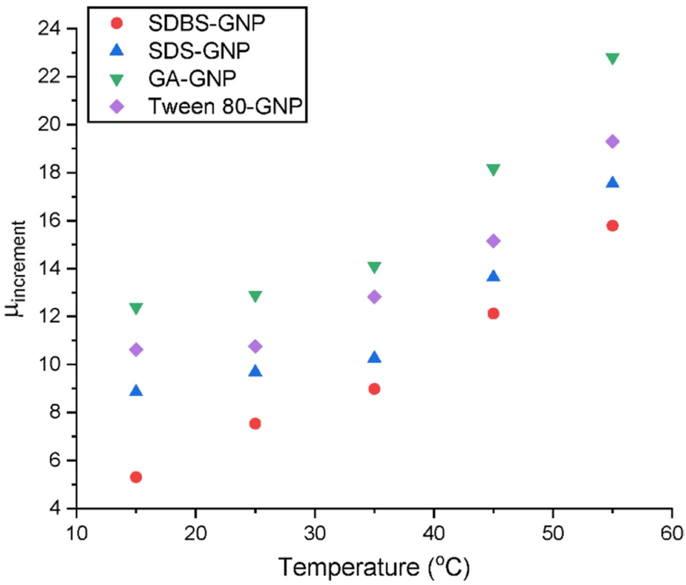

Fig. 9 Viscosity increment of GNP nanofluids at different temperature

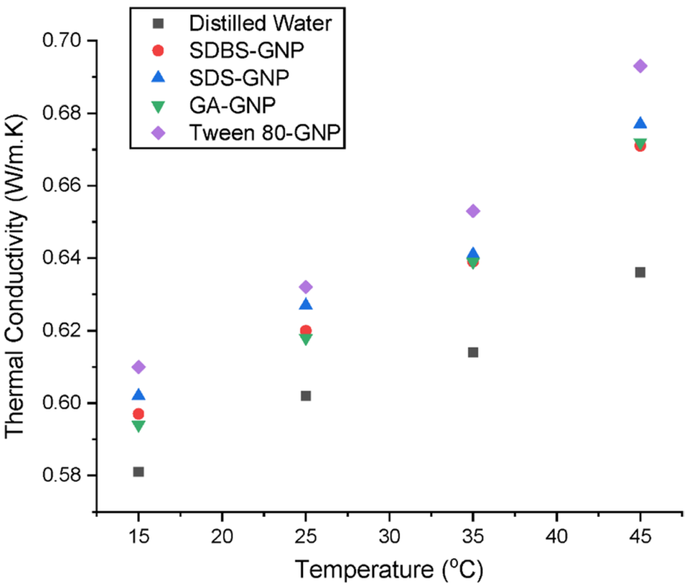

Fig. 10 Thermal conductivity of GNP nanofluids at different temperature

is elevated. This conforms with numerous studies on nanofluids [7, 21, 22, 25]. The temperature-induced enhancement could be attributed to a different mechanism, including Brownian motion, clustering, or interfacial layer [26]. It can also be seen that the $\lambda_{nanofluid}$ of all the nanofluids can be found to be higher than that of water.

However, unlike the study by Almanassra et al. [9], the type of surfactants affects the $\lambda_{nanofluid}$. Tween 80-GNP nanofluid can be found to have the highest $\lambda_{nanofluid}$, followed by SDS-GNP and GA-GNP, with SDBS-GNP nanofluid having the lowest $\lambda_{nanofluid}$. This experimental result conflicts with the study by Sadri et al. [7] and Sarsam et al. [15], as they found the thermal conductivity of GA-based nanofluid to be higher than that of SDS and SDBS. However, the lower thermal conductivity attributes of SDBS-based nanofluids in the study by Sadri et al. [7] agree with this study's experimental results. In contrast to this result, some authors [8, 27, 28] observed a superior increase in thermal conductivity of SDBS-based nanofluid than that of SDS. This indicates that the effects of surfactants on the nanofluid's transport mechanism are dependent on the nanomaterial used.

The relative thermal conductivity ($\lambda_{relative}$) and thermal conductivity ($\lambda_{enhancement}$) of the GNP nanofluids are presented in Figs. 11 and 12. The $\lambda_{relative}$ and $\lambda_{enhancement}$ were determined using Eqs. 4 and 5.

$$\lambda_{relative} = \lambda_{nanofluid}/\lambda_{water} \tag{4}$$

$$\lambda_{enhancement} = (\lambda_{relative} - 1) \times 100 \tag{5}$$

where $\lambda_{nanofluid}$ is the thermal conductivity of GNP nanofluids while λ_{water} is the thermal conductivity of water. The results reveal that a rise in temperature brings about an increase in $\lambda_{relative}$ and $\lambda_{enhancement}$. Tween 80-GNP can be found to have the highest $\lambda_{enhancement}$ at all temperatures. This was followed by SDS-GNP and GA-GNP, while SDBS-GNP nanofluid has the lowest $\lambda_{enhancement}$. In comparison to distilled water, a maximum enhancement of 5.50 %, 6.45 %, 5.66 %, and 8.96 % was

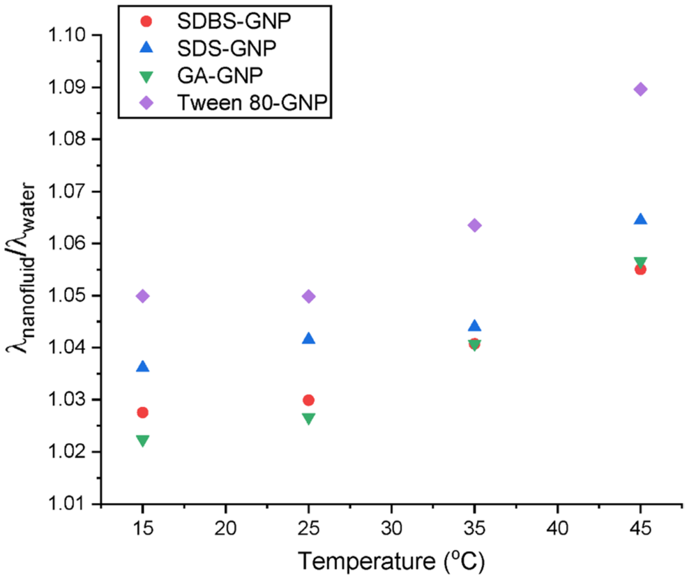

Fig. 11 Thermal conductivity ratio of GNP nanofluids at different temperature

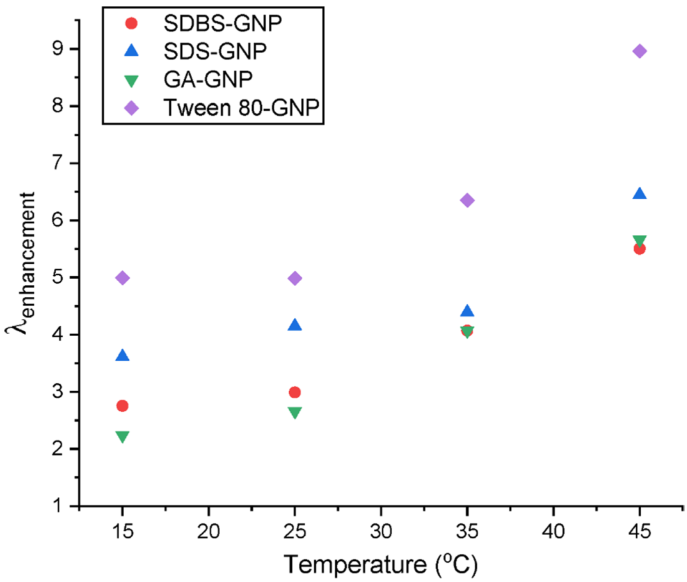

Fig. 12 Thermal conductivity enhancement of GNP nanofluids at different temperature

estimated for SDBS-GNP, SDS-GNP, GA-GNP, and Tween 80-GNP nanofluids, respectively at 45 °C .

4 Conclusion

The stable suspension of nanomaterials in base fluids is commonly achieved with the aid of surfactants. This study focused on the influence of different surfactants (SDBS, SDS, GA, and Tween 80) on the stability, electrical conductivity, thermal conductivity, and viscosity of GNP nanofluids. The major conclusions are as followed.

1. The zeta potential measurements show all the surfactants improved the stability of GNP nanofluids. However, the best stabilization and homogenous dispersion are achieved with SDBS as a surfactant at the different GNP-surfactant ratios. This was followed by SDS, GA, and, lastly, Tween 80.
2. The zeta potential of all the nanofluids increased with an increase in the surfactant concentration from the GNP-surfactant ratio of 2:1 to 1:1, after which it remains relatively unchanged or slightly reduces when increased to 1:2. However, over 2 weeks, there was visible agglomeration in SDBS-GNP nanofluids with GNP-surfactants ratios of 1:1 and 1:2.
3. The electrical conductivity and thermal conductivity of all the nanofluids increases with an increase in temperature, while the viscosity is reduced at elevated temperatures. All the nanofluids have higher electrical conductivity, thermal conductivity, and viscosity than water.

4. SDBS-GNP nanofluid has the highest electrical conductivity, followed by SDS-GNP, GA-GNP, and Tween 80-GNP nanofluids. SDBS-GNP, SDS-GNP, GA-GNP, and Tween 80-GNP nanofluid has a maximum electrical conductivity enhancement of 154.33 %, 153.25 %, 23.1 %, and 2.83 %, respectively.
5. Tween 80-GNP nanofluid has the highest thermal conductivity, followed by SDS-GNP, GA-GNP, and SDBS-GNP nanofluids. SDBS-GNP, GA-GNP, SDS-GNP, and Tween 80-GNP nanofluid has a maximum thermal conductivity enhancement of 5.50 %,5.66 %, 6.45 %, and 8.96 %, respectively, at 45 °C.
6. Finally, the highest viscosity was achieved using GA as a surfactant, followed by Tween-80 and SDS, with SDBS addition contributing the lowest increase in viscosity. SDBS-GNP, GA-GNP, SDS-GNP, and Tween 80-GNP nanofluid has a maximum viscosity increment of 15.79 %, 17.54 %, 19.30 %, and 22.81 %, respectively, at 55 °C.
7. The higher thermal conductivity enhancement of Tween 80-based GNP nanofluid shows its potential for higher heat transfer performance. Also, its lower electrical conductivity indicates its tendency to either inhibit or have little effect on the corrosion behavior of metals in heat exchangers.

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Data Availability The authors can confirm that all relevant data are included in the article. However, any supplementary information will be made available on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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