Experimental investigation of rheological properties and thermal conductivity of SiO$_2$–P25 TiO$_2$ hybrid nanofluids

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Abstract

Over many years, great efforts have been made to develop new fluids for heat transfer applications. In this paper, the thermal conductivity (TC) and viscosity of SiO$_2$–P25 TiO$_2$ (SiO$_2$–P25) hybrid nanofluids were investigated for different nanoparticle volume concentrations (0.5, 1.0 and 1.5 vol%) at five various temperatures (20, 30, 40, 50 and 60 °C). The mixture ratio (SiO$_2$:P25) in all prepared hybrid nanofluids was 1:1. Besides, pure SiO$_2$, P25 nanofluids were prepared with the same concentrations for comparison with the hybrid nanofluids. The base fluid used for the preparation of nanofluids was a mixture of deionized water and ethylene glycol at a ratio of 5:1. Before preparing the nanofluids, the nanoparticles were analyzed with energy-dispersive X-ray analysis, scanning electron microscope, X-ray powder diffraction, and Fourier transform infrared spectroscopy. The zeta potentials of the prepared nanofluids except SiO$_2$ nanofluids were above 30 mV. These nanofluids were visually observed for stability in many days. The TC enhancement of the hybrid nanofluid was higher than the pure nanofluid. In particular, with 1.0 vol% concentration, the maximum enhancement of SiO$_2$, P25 and SiO$_2$–P25 nanofluids were 7.5%, 9.9% and 10.5%, respectively. The rheology of the nanofluids was Newtonian. The viscosity increment of SiO$_2$, P25 and hybrid nanofluids were 19%, 32% and 24% with 0.5 vol% concentration. A new correlation was developed for the TC and dynamic viscosity of SiO$_2$–P25 hybrid nanofluid.

Keywords Silicon dioxide · Titanium dioxide · Base fluid · Nanofluids · Thermal conductivity · Viscosity

Introduction

Masuda et al. [1] and Choi [2] started working with nanofluids as an effective heat transfer fluid. In recent years, the nanofluids have become more popular due to the improvement of their thermal characteristics compared to conventional fluids like EG, water and oil. There are a lot of engineering applications of nanofluids such as solar...
thermal, automobile and electronic cooling applications [3–8]. It is evidenced that the TC of nanofluids mostly depends on the property of nanoparticles [9].

Compared to the standard nanofluid, hybrid nanofluids (HNs) offer even more possibilities. The composite nanofluids or HNs are the colloidal dispersion of two or more kinds of nanoparticles with the BF [10]. According to Sundar et al. [11], there are three main types of HN: metal matrix, ceramic matrix and polymer matrix nanocomposites. The nanoparticles can be prepared by various techniques or by the combination of different techniques such as ball milling, chemical vapor deposition and plasma treatment [12–16]. There are two types of nanofluid preparations, including a one-step method and a two-step method. In the first one, the production of nanoparticles and dispersion of nanoparticles into BF are combined in one step. In the two-step method, the nanoparticles are prepared first and then dispersed into the BFs [17]. Because of new characteristics, HNs have been investigated with different nanoparticles, BFs, temperatures and concentrations. Nabil et al. [18] and Ganvir et al. [19] presented some reviews about their thermophysical properties. Hybrid nanofluid with carbon nanotubes grafted to alumina/iron oxide spheres dispersed in poly-alpha-olefin was studied by Han et al. [20]. A TC enhancement of 21% for a volume concentration of 0.2% was obtained. The carbon nanotubes play an important role in the augmentation of TC. The Al2O3–Cu/water HNs with volume concentrations from 0.1 to 2% were investigated by Suresh et al. [21]. A maximum TC enhancement of 12.11% compared to single Al2O3 was shown at a volume concentration of 2%. Madhesd et al. [22] investigated Cu–TiO2 HNs in the application of water-based coolant. The TC of the fluid increased by 48.4% compared to the BF of water up to 0.7 vol% of the hybrid nanocomposite. It was found that the functionalized surface and the high crystallinity of the nanocomposite improved the enhancement of TC. In recent years, further investigations on the viscosity of HNs have been performed [23–26]. A numerical study on hybrid nanocomposite of TiO2, Al2O3 and SiO2 nanoparticles dispersed in water was performed [27]. Al2O3 (25%) was mixed with TiO2 (75%) or SiO2 (75%) for preparing HNs at concentrations of 0.5, 1.0 and 1.5 vol%. An experimental investigation on the rheological behavior of Fe–CuO HNs was performed in water–EG at a proportion of 20:80 vol%. The concentration range of HNs was 0.04–1.5 vol%. They found that at low concentration, the rheology of HNs was Newtonian, whereas at high concentration, HN exhibited non-Newtonian behavior (shear-thinning) [28]. Sundar et al. and Zakaria et al. [29, 30] investigated the TC of nanofluids with the BF of DW and EG mixture. They found that the enhancement of TC was affected by volume concentration and temperature. Additionally, the particle size and stability of nanofluid contributed to the improvement of TC [31, 32]. It was found that the combination of nanofluids has higher TC and lower dynamic viscosity [33–35].

From the results of Agresti et al. [36] and Turgut et al. [37], the TC of pure TiO2 nanofluid was higher than of pure SiO2 nanofluid; meanwhile, the viscosity of SiO2 nanofluid was lower than of TiO2 nanofluid. Producing hybrid or composite nanofluids from SiO2 and TiO2 nanoparticles is expected to enhance the useful characteristic of single nanofluids, such as higher TC of TiO2 nanofluid and lower viscosity of SiO2 nanofluid. Some works have been performed to evaluate the TC of SiO2–TiO2 HNs. Nabil et al. used TiO2 (50 nm) and SiO2 (22 nm) nanoparticles for investigating the heat transfer enhancement of HNs with different concentrations (0.5–3 vol%), temperatures (30–80 °C), BF ratios, nanoparticle ratios and forced convection mode [35, 38–40]. They found that the TC enhancement of HNs was 22.1% at 3.0 vol% and 70 °C compared to the BF. Meanwhile, 62.5% increment of relative viscosity was observed for 3.0% volume concentration.

Due to the instability in nanofluids, the aggregation of nanoparticles causes a decrease in the thermo-physical characteristics. This is a critical problem for nanofluids, which limits their engineering applications. The preparation of nanofluids with good stability is the priority challenge [41, 42]. Nanoparticles cause the TC and viscosity of nanofluids to be higher due to the motion of nanoparticles in suspension. The instability of nanofluids and higher viscosity result in decreasing the heat transfer. Therefore, the stability, viscosity and TC should be investigated in detail [17]. Besides, the results obtained in different research groups are not consistent. Also, studying the properties of the nanofluids is often not completely performed. The theoretical understanding of the mechanisms is the lack of improvement of properties [43].

To the best of authors’ knowledge, there are no reports on the TC enhancement and viscosity of these SiO2–P25 HNs. The purpose of this research is to prepare the stable SiO2–P25 HNs with SiO2 (10–20 nm) and P25 (21 nm) nanoparticles and investigate their rheological property and TC. The experimental study is conducted for 0.5, 1.0 and 1.5 volume concentrations with the nanoparticle mixture ratio (SiO2:P25) of 1:1. The temperatures during the experiments are from 20 to 60 °C. The properties of the nanoparticles are investigated with EDX, SEM, XRD and FT-IR. Lastly, the relevant correlations are proposed using the results of the present study.
Materials and methods

Materials

Silicon dioxide (SiO₂) nanopowder (99.5%, 10–20 nm, 637238-50G), P25 titanium dioxide (P25) nanopowder (≥ 99.5%, 21 nm, 718467-100G) and ethylene glycol (≥ 99%, 102466-1L) were purchased from Sigma-Aldrich, Hungary. The materials were analytical reagent grades and utilized as original, with no other change. DI and EG were used as BFs. DI was produced in the Department of Inorganic and Analytical Chemistry laboratory, Budapest University of Technology and Economics (Hungary). Tables 1 and 2 show the properties of P25, SiO₂ nanoparticles, ethylene glycol and water.

Preparation of nanofluid

SiO₂, P25 nanofluids and SiO₂–P25 HNs were prepared by dispersing different amounts of SiO₂, P25 nanoparticles and SiO₂–P25 mixture (1:1 volume ratio) in DI and EG mixture (5:1). SiO₂–P25 in amounts of 0.5 vol%, 1.0 vol% and 1.5 vol% was dispersed in an appropriate mass of DI and EG. Then, SiO₂–P25 HN colloidal solutions were sonicated at 130 W and 45 kHz using an ultrasonication instrument for 1 h. Table 3 shows pure SiO₂, P25 nanofluids and SiO₂–P25 HN sample specifications.

Characterization methods

The crystal structure of SiO₂ and P25 was investigated by using PANalytical X’PERT PRO MPD XRD with Cu Kα irradiation. Data were collected for the 2θ range of 5° to 65° at a resolution of 3 degrees/min. Morphological characterization of SiO₂ and P25 was done by LEO 1440 XB SEM at 5 kV in a high vacuum mode with a secondary electron detector. The chemical composition of SiO₂ and P25 was studied by using EDX analysis with JEOL JSM-5500LV electron microscope. Infrared spectra of nanopowders were studied by Excalibur FTS 3000 Bio-Rad FT-IR in the 400–4000 cm⁻¹ domain in transmittance mode, the sensitivity of measurements was 4 cm⁻¹, and the number of scans was 64.

A Brookhaven ZETAPALS device was used for ZP measurement of SiO₂–P25 HNs. The ZP (ζ) was obtained from electrophoretic mobility (EM) of particles thanks to the Henry equation by applying the Smoluchowski approximation [46]. Each sample was tested three times, and the average value was reported.

The rheological behavior of SiO₂–P25 HN was measured using a rotation viscometer (Anton Paar Physica MCR 301) at different shear rates and temperatures. The number of data points per measurement was 15. The amplitude was 5%, and the angular frequencies were between 0.6 and 3600 s⁻¹.

The TC of SiO₂–P25 HN samples was measured based on the modified transient plane source technique using a TCi Thermal conductivity analyzer. The TC of all samples was measured at five different temperatures of 20, 30, 40, 50 and 60 °C. A temperature-controlled oven was used to maintain the temperature at the desired set point. All samples were kept in the oven for 30 min to reach that temperature. Three TC measurements were taken for each sample, and an average value was reported.

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**Table 1** Properties of P25 and SiO₂ nanoparticles [44]

| Properties                  | SiO₂ | P25 |
|-----------------------------|------|-----|
| Color                       | White| White|
| Molecular mass/g mol⁻¹      | 60.08| 79.87|
| Average particle diameter/nm| 10–20| 21   |
| Density/kg m⁻³              | 2220 | 4260 |
| Melting point/°C            | 2230 | 1850 |

**Table 2** Properties of ethylene glycol and water [45]

| Properties                  | Ethylene glycol | Water |
|-----------------------------|-----------------|-------|
| Formula                     | C₂H₆O₂          | H₂O   |
| Molecular mass/g mol⁻¹      | 62.07           | 18.02 |
| Freezing point/°C           | −12.7           | 0     |
| Boiling point, at 101.3 kPa/°C | 198             | 100   |
| Viscosity at 20 °C/mPas     | 20.9            | 1     |
| Density/kg m⁻³              | 1113            | 997   |
| Thermal conductivity/W mK⁻¹ | 0.258           | 0.609 |
| Specific heat at 20 °C/J kg⁻¹ K⁻¹ | 2347         | 4186  |

**Table 3** Specification of SiO₂, P25 nanofluids and SiO₂–P25 hybrid nanofluid samples

| Sample names | SiO₂/vol% | P25/vol% | DI and EG mixture (5:1)/vol% |
|--------------|-----------|----------|-------------------------------|
| SiO₂-0.5     | 0.50      | 0.00     | 99.50                         |
| SiO₂-1.0     | 1.00      | 0.00     | 99.00                         |
| SiO₂-1.5     | 1.50      | 0.00     | 98.50                         |
| P25-0.5      | 0.00      | 0.50     | 99.50                         |
| P25-1.0      | 0.00      | 1.00     | 99.00                         |
| P25-1.5      | 0.00      | 1.50     | 98.50                         |
| SiO₂–P25-0.5 | 0.25      | 0.25     | 99.50                         |
| SiO₂–P25-1.0 | 0.50      | 0.50     | 99.00                         |
| SiO₂–P25-1.5 | 0.75      | 0.75     | 98.50                         |
Results and discussion

SiO₂ and P25 structure

Figure 1 shows the XRD pattern of SiO₂ and P25. For the XRD pattern of SiO₂ (Fig. 1a), the amorphous nature of the used nano-SiO₂ could be seen from the diffractogram [47]. The broad diffraction peak confirmed a completely amorphous structure. Except for a broad band centered at 2θ = 22.5°, there is no diffraction peak observed. This peak is the characteristic peak for amorphous SiO₂. It also reveals no impurity peaks for SiO₂ nanoparticles. Based on the XRD patterns of P25 (Fig. 1b), P25 consists of rutile and anatase phases. The anatase form is the main component with peaks at 2θ values of 25.4°, 37.9°, 48.1°, 54°, 55.1° and 62.8°. The rutile phase is an adjunct at 2θ values of 27.6°, 36.2°, 41.4° and 54.4° [48]. There are not any lines corresponding to any impurity phases, so the high purity of the P25 sample is indicated.

Figure 2 shows the SEM image of the morphological structure of nano-SiO₂. It can be observed from the SEM image that nano-SiO₂ has a nanosize of ca. 15 nm in accordance with the manufacturer’s specifications. The SEM image of nano-P25 is shown in Fig. 3. It can be found that the particle size is 10–20 nm. The P25 and SiO₂ nanoparticles tend to stick together into the larger particles. The aggregation size of SiO₂ is larger than of P25.

The functional groups support the achievement of a proper dispersion. The FT-IR spectrum of P25 nanoparticles is shown in Fig. 4. The broadband centered at around 600 cm⁻¹ is assigned to the bending vibration (Ti–O-Ti) bonds in the TiO₂ lattice. The broadband centered at around 3420 cm⁻¹ is attributed to the intermolecular interaction of the hydroxyl group (–OH) with H₂O molecule on TiO₂.
surface. The peak at around 1650 cm\(^{-1}\) confirms the typi-
cal bending vibration of –OH group [49]. Figure 5 shows
the FT-IR spectrum of SiO\(_2\) nanoparticles. The peaks at
around 3420 cm\(^{-1}\) and 1630 cm\(^{-1}\) can be ascribed to the
–OH stretching and bending vibrations of absorbed water
molecules on the SiO\(_2\) nanoparticles, respectively. The
peaks at 1101 and 475 cm\(^{-1}\) refer to the Si–O-Si asymmetric
stretching and bending vibrations. The Si–O bond stretching
vibration appears at 1384 cm\(^{-1}\). The peaks at 961 cm\(^{-1}\) and
801 cm\(^{-1}\) are attributed to the Si–O-(H-H\(_2\)O) bending vibra-
tions and in-plane bending vibrations of geminol groups,
respectively.

Fig. 3  SEM images of P25
nanoparticles

Fig. 4  FT-IR spectrum of P25
nanoparticles

Fig. 5  FT-IR spectrum of SiO\(_2\)
nanoparticles
Table 4 contains the EDX results of P25 and SiO₂ nanoparticles. The results are the average values of different measurement points in the atomic percentage. These results confirm the chemical composition of the used nanoparticles.

### Zeta potential measurement

Table 5 shows the ZP of 0.5 vol% SiO₂–P25 nanofluids with different surfactants. For improving the stability of SiO₂–P25 HN, different surfactants are used such as CTAB (cetyl trimethylammonium bromide), SDBS (sodium dodecylbenzenesulfonate), SCMC (sodium carboxymethylcellulose) and TX (Triton X-100). Among the used surfactants, the CTAB gives the best result with − 19.09 mV. According to the ZP values, the SiO₂–P25 HNs have the best stability without any surfactants. However, by visual observation, it can be seen that the role of surfactant is not much important in improving the stability of the HNs. Further studies can focus on the stability of nanofluid by changing surfactant concentration, other types of surfactants and solvents.

Table 5 ZP of 0.5 vol% SiO₂–P25 nanofluids with different surfactants

| Surfactant | ZP of 0.5 vol% SiO₂–P₂5 hybrid nanofluid/mV |
|------------|-----------------------------------------------|
| N/A        | −30.42                                        |
| CTAB       | −19.09                                        |
| SDBS       | −10.46                                        |
| SCMC       | −10.09                                        |
| TX         | −17.34                                        |

Colloidal solutions with ZPs lower − 30 mV have acceptable stability [50, 51]. Table 6 shows ZP values of SiO₂, P25 pure nanofluids and SiO₂–P₂5 hybrid nanofluids with different concentrations. The ZP of 0.5, 1.0 and 1.5 vol% SiO₂–P₂5 HN was −30.42 mV, −33.03 mV and −43.33 mV, respectively. This shows the stability of nanofluids. These ZP values indicate the slower aggregation behavior of SiO₂–P₂5 nanoparticles by increasing the concentration. It means that by increasing the concentrations of nanofluids, the negative electrical surface charge of SiO₂–P₂5 increased; thus, the -OH groups were ionized. P₂5 nanofluids provide good stability with high ZP. ZP results showed that SiO₂ nanofluids have moderate stability.

Table 6 ZP of SiO₂, P25 nanofluids and SiO₂–P₂5 hybrid nanofluids with different concentrations

| Nanofluids   | Zeta potential/mV |
|--------------|-------------------|
| SiO₂-0.5     | −23.04            |
| SiO₂-1.0     | −24.17            |
| SiO₂-1.5     | −25.23            |
| P₂5-0.5      | −34.49            |
| P₂5-1.0      | −33.28            |
| P₂5-1.5      | −30.94            |

Rheological properties of SiO₂–P₂5 hybrid nanofluid

The viscosity of the BF was measured, and the results are compared to the literature in order to verify the measurement. The results are compared to the BF in the ASHRAE standard [45] as shown in Fig. 6. The maximum error is less than 1.0%, and the measurements are trustable.

For determining the rheological behaviors of SiO₂–P₂5 HNs, the shear stress at different shear rates is investigated for three volume concentrations of 0.5, 1.0 and 1.5 at five temperatures: 20, 30, 40, 50 and 60 °C as shown in Fig. 7. Shear stress of all SiO₂–P₂5 HN samples decreases with increasing temperature and increases with increasing fraction of nanofluids.
This reduction behavior of viscosity may be caused because higher temperature increases the Brownian and thermal motion of molecules and their average velocity, leading to weakened intermolecular interaction and adhesion forces between molecules [25, 52]. For low shear rates (less than 5 s⁻¹), the nanofluid behaves as a non-Newtonian fluid or shear-thinning fluid. It means the viscosity of all HNs decreases with the increase in the shear rate. In a case of high shear rates, the viscosity of SiO₂–P25 HNs is almost independent of the applied shear rate. This means the HN is Newtonian as shown in Fig. 7. Bahrami et al. [28] and Nabil et al. [38] found the Fe–CuO nanofluids and TiO₂–SiO₂ nanofluids owned Newtonian rheological behavior for different temperatures and concentrations. These results indicate that the properties of nanoparticles and temperature are important factors in the rheological properties of nanofluids. The rheological behavior generally depends on particle size and morphology, nanoparticle fraction, BF, electro-viscous
effects and solution chemistry-related surface layer [53]. Mehrali et al. showed that at low shear rates, the structure of fluid changes temporarily when the spindle rotates in the fluid, and molecules are gradually arranged in the direction of increasing shear, causing less reduction in viscosity.

Nevertheless, the maximum amount of possible shear ordering was attained as the shear rate was high enough. The larger aggregate molecules were broken down into smaller sizes, causing less viscosity [54]. With the presence of
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nanoparticles in HNs, it can be explained that the viscosity of SiO$_2$–P25 HNs is higher than the BF.

Figure 8 shows the relative viscosity of SiO$_2$–P25 HNs. The relative viscosity increases with the increase in the volume concentration, while temperature does not play an important role. The lowest relative viscosity of 24% increase was obtained for 0.5% volume fraction, while the highest enhancement of relative viscosity was 58% for 1.5 vol%. The relative viscosity increased from 24 to 58% compared to the BF.
Figure 9 shows a comparison of the relative viscosity between the present work (0.5 vol%) with the data from Nabil et al. [38]. The results from the present research show little higher relative viscosity than the literature between 20 and 60 °C. The SiO2 nanofluids still have the smallest relative viscosity, while the P25 nanofluids have the highest viscosity. The viscosity strongly depends on nanoparticles, BFs and concentrations.

**Thermal conductivity of SiO2–P25 hybrid nanofluid**

The TC of all SiO2–P25 HNs at various temperatures is shown in Fig. 10. The calibration tests for distilled water are verified before the measurement of samples, and the results are obtained within 0.5% error. All SiO2–P25 HNs show higher TC compared to DI/EG mixture at all temperatures. SiO2–P25 HNs at 0.5 vol%, 1.0 vol% and 1.5 vol% showed 4.72%, 7.19% and 9.03% TC enhancement compared to the EG/DI mixture at 20 °C, respectively. The TC of SiO2–P25 HNs is enhanced by increasing the temperature. Nevertheless, the effect of temperature and concentration on the enhancement of TC is different. On the one hand, the temperature causes the TC of nanofluids to be higher because of the reduction in viscosity and the augmentation in Brownian motion of nanoparticles [55]. On the other hand, the relationship between TC enhancement and concentration of SiO2–P25 nanoparticles is not completely linear. This is understandable; as the number of nanoparticles in the solution increases, the TC of the solution also increases. In addition to the concentration and temperature, the extent of TC enhancement of nanofluids depends on the type of used nanomaterials, pH, surfactants and the type of BF, which influence the motion of particles in suspension.

Figure 11 shows the enhancement of TC obtained from the present work and previous studies. It can be seen that the TC of the HNs in the present research is higher than the TC of SiO2 pure nanofluid, P25 nanofluid and even SiO2–P25 HNs. This can be explained that P25 contributes greatly to increasing the TC of the HNs.

**Regression correlations**

The following correlation is proposed based on experimental data:

\[
\text{Relative viscosity} = \frac{\mu_{nf}}{\mu_{bf}} = 1.1036 \left(1 + \frac{T}{70}\right)^{0.03667} \left(1 + \frac{\phi}{100}\right)^{22.4472},
\]

where \(\mu_{nf}\) and \(\mu_{bf}\) represent the viscosity of nanofluid and viscosity of BF, while \(\phi\) and \(T\) are volume concentration and temperature. This correlation is valid for a range of concentrations \(0 \leq \Phi \leq 1.5\%\) and range of temperatures \(30 ^\circ C \leq T \leq 70 ^\circ C\). The average and standard deviations are 1.1% and 1.2%. The maximum deviation is found to be 2.4%. Figure 12 shows the tabulation of viscosity from the experiment and Eq. 1.

Meanwhile, Eq. 2 is proposed based on experimental data where \(k_{nf}\) and \(k_{bf}\) represent the TC of nanofluid and TC of BF.
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Fig. 10 TC and enhancement of TC of pure SiO₂, P25 and SiO₂–P25 hybrid nanofluids at different temperatures
The average deviation and standard deviations are 0.30% and 0.36%. The maximum deviation is found to be 0.79%. The tabulation of TC from the experiment and Eq. 2 is shown in Fig. 13. From these results, it can be seen that the experimental data are inappropriate agreement with the correlation proposed.

\[
k_{nf} = k_{bf} \times 1.0156 \left(1 + \frac{T}{70}\right)^{0.0848} \left(1 + \frac{\phi}{100}\right)^{3.474}, \tag{2}
\]

Conclusions

Pure SiO₂, P25 nanofluids and SiO₂–P25 HNs were prepared using SiO₂ and P25 nanoparticles for characterizing the properties of nanoparticles and HNs by different techniques. The volume concentrations of nanofluid were 0.5, 1.0 and 1.5 vol%. The mixture of DI and EG at a ratio of 5:1 was used as the BF of nanofluids. The viscosity and TC of HNs were studied from 20 to 60 °C. The SEM showed that
the particle sizes of SiO₂ and P25 nanoparticles were ca. 15 nm and 10–20 nm, respectively. From XRD, the property of SiO₂ was amorphous, while P25 consisted of rutile and anatase phases. The infrared spectroscopy and elemental analysis have stated the chemical properties of nanoparticles and also the presence of functional groups on the surface of the particle. The stability of HNs was confirmed by ZP results. These nanofluids were visually observed in many days. The effective TC of HNs was improved up to 12.24% as compared to the mixture of BFs for 1.5 vol% concentration. The TC enhancement of the hybrid nanofluid was higher than the pure nanofluid. In particular, with 1.0 vol% concentration, the maximum enhancement of SiO₂ was higher than the pure nanofluid. In particular, with 1.0 vol% concentration, the maximum enhancement of SiO₂, P25 and SiO₂–P25 nanofluids are 7.5%, 9.9% and 10.5%, respectively. Rheological properties were studied, and it is seen that the rheology of HNs was Newtonian behavior. The viscosity increment of SiO₂, P25 and hybrid nanofluids were 19%, 32% and 24% with 0.5 vol% concentration. Compared to the SiO₂, P25 and hybrid SiO₂–P25 nanofluids, it could be a good heat transfer fluid. The correlations of TC and viscosity for this type of nanofluid were developed. The results confirmed good accuracy.

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Author contributions IMS and TLB were involved in conceptualization; TLB, ZIV, IEL, JM and IAB took part in methodology; ZIV and TLB carried out investigation; IMS performed funding acquisition; IMS collected the resources and supervised the study; TLB wrote the original draft; TLB, JM, SW and IMS wrote, reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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