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Characterisation and molecular interaction studies of beryllium oxide- silicone oil nanofluids through ultrasonic measurements at various temperature

Merita T. Britto[1], Catherine J. Grace [2], Prakash Packiaraj[3], Kanchan Kumar[4], Rubila Sundararaj[5], and Solomon Jeevaraj A. Kingson[1,*]

[1]Department of Physics, Ananda College, Tamil Nadu, India
[2]Department of Mathematics, Karunya Institute of Technology and Sciences, Tamil Nadu, India
[3]Department of Physics, LRG Government Arts College, Tamil Nadu, India
[4]Department of Physics and Nanotechnology, FMED laboratory, SRM Institute of Science and Technology, Tamil Nadu, India
[5]Department of Food technology, Sri Shakthi Institute of Engineering and Technology, Tamil Nadu, India
[*]Corresponding author: drkingson@karunya.edu

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Abstract

The synthesis of the Beryllium oxide (BeO) nanoparticles was prepared via chemical precipitation. BeO nanoparticles were characterized by annealing them at 840°C. Its hexagonal shape was perfect. These results were confirmed using fourier transform infrared (FTIR) as well as Raman spectra. Raman as well as FTIR spectra demonstrate the Be-O-Be stretching connection between the beryllium and oxygen atoms. To make BeO nanofluids, the synthesized BeO nanoparticles were sonicated with a silicone oil base fluid. The silicone oil base fluid was infused with BeO using sonication at concentrations of 0.0005%, 0.001%, 0.0015%, 0.002%, 0.0025%, as well as 0.003% by volume. Ultrasonic velocity, viscosity and density were measured for the prepared silocone oil based BeO nanofluids. Silicone oil based BeO Nanofluids have a higher velocity value because of particle-fluid molecule interactions. The relationship between the concentration (ϕ) (0.0005, 0.001, 0.0015, 0.002, 0.0025, 0.003 vol. %) as well as temperature of nanofluids was also studied (313 Boltzmann's constant (K), 323 K as well as 333 K) using Kininogen Domain (KD2) thermal analyser. Silicone oil-based BeO nanofluid has a thermal conductivity increase of up to 30%, comparatively to the base fluid. As the temperature rises, particle and fluid's acoustic properties change almost linearly, suggesting weaker intermolecular interactions.

Keywords: Nanofluids, Molecular interaction studies, Thermal conductivity, Viscosity

1. Introduction

Latest developments in nanotechnology paved the way to the creation of new substances for transferring heat, known as nanofluids. These fluids exhibit more robust thermal characteristics than coolants. Nanoparticles' significantly have bigger relative surface area compared to ordinary particles not only dramatically improves temperature transfer capacity, but also increases the stability of the solution [1,2].

Numerous studies [3,4] have examined many aspects of nanofluids, such as their stability, the effect of sonication time, as well as the addition of surfactants. Various liquid mixtures' physicochemical features have been described by using ultrasonic velocity as well as its thermodynamical characteristics, such as molecular attachment as well as dissociation [5]. Ultrasonic velocity aids in the identification of the kinetics of chemical interactions in pure liquids as well as nanofluids by correlating the unique forces between atoms or molecules. Even while ultrasonic properties for micrometer-sized particles were published [6-8], there were only a few publications available on the acoustical features of nanofluids.

The limited thermal conductivity of common fluids fundamentally limits the ability to transfer temperature [9]. The biggest difficulty is while using such large particles will settle in fluids very quickly [10]. Nanofluids are a novel temperature transfer fluid that may significantly enhance the performance of more conventional fluids [11]. Beryllium oxide (BeO) is an oxide that is both unique among nanoparticles and exceptionally good at insulating electricity. In terms of heat transfer, it's efficient. It has a very high melting point. It's quite insulating as well as has a high intensity level. There is a high degree of chemical as well as thermal stability. It has a low dielectric constant. Additionally, its dielectric loss is low. It works quite well with today's technology. BeO, is widely used in microelectronics, nuclear technology, photoelectron technology, as well as vacuum electronics. Therefore, BeO, a ceramic oxide material with exceptionally high thermal conductivity, was chosen as the material for the nanofluids production in this investigation. Ceramic beryllium oxide has a high melting point as well as strong thermal conductivity, making it useful in high-temperature applications. BeO retains its structural integrity even when subjected to very high temperatures. Therefore, instead of using the other nanoparticles that are typically dispersed in a temperature transfer fluid, BeO nanoparticles are used. The significant increase in thermal efficiency observed in the experimental studies demonstrates the promise of employing nanofluids. Consequently, BeO nanofluids can be used as a temperature transfer fluid [12,13].

In addition to its uses as hydraulic oil in airplanes and a temperature bath in laboratories, silicone oil is also a temperature transfer fluid [14]. Changes in the fluid medium's structure may occur when a high thermal conductivity oxide material [15,16] like BeO is dispersed in a temperature transfer fluid like silicone oil; these changes can be probed with acoustic investigations [17,18]. The effects of concentration (0.0005, 0.001, 0.0015, 0.002, 0.003, vol.%) and temperature (313 K, 323 K, and 333 K) on acoustic parameters like adiabatic compressibility (β), free length (L_f), acoustic impedance (Z), Rao's constant (R), molar compressibility (W), relaxation time (τ), free volume (V_f), Gibbs free energy (G), and internal pressure (π_i). This work used ultrasonic measurements at different temperatures to probe structural characteristics as well as molecular interaction in silicone oil based BeO.

2. Materials and methods

BeO with an average crystalline size of 20-25 nm was prepared using ultrasonic-assisted chemical precipitation to make BeO/silicone oil nanofluids [19,20]. The production of nanofluids can be broken down into two categories: one-step methods as well as two-step methods. Silicone oil based BeO nanofluids were prepared using a two-stage method. To examine the fourier transform infrared (FTIR) spectra of BeO nanoparticles in the wavenumber range 600-1800 cm^{-1}, a BRUKER: RFS 27 FT (Model: Shimadzu Prestige-21) was utilized. The BRUKER RFS 27 FT-Raman spectrophotometer is a multi-RAM, st as well as -alone type. This spectrum spans from 4000 to 50 cm^{-1} with a resolution of 2 cm^{-1}. The Nd: YAG laser used for this has a wavelength of 1064 nm. Preparing nanofluids required a two-step process: first, nanoparticles were made on their own, as well as then, they were introduced to the working fluids. Produced independently, BeO nanoparticles were then dispersed in silicone oil [21].

Nanofluids were not produced with stabilizing agents. Instead, ultrasonic pulses generated by the UP400S ultrasonic Processor [22] were used to improve particle dispersion in the fluid. The UP400S ultrasonic processor is used to sonicate samples with sonotrodes whose diameters range from 3 mm to 40 mm, as well as whose volumes are from 5 ml to 4000 ml (400W, 20 kHz). Using flow cells flange connections, it is possible to sonicate liquids in ideal conditions in terms of temperature and pressure. This is commonly used in the processing of samples with higher volumes. A soundproof enclosure is recommended because to the high power as well as severe cavitation that will produce noise. The 20 kHz AC line voltage is converted into the electrical energy used to run the acoustic dismembrator. A longitudinal mechanical vibration will develop in a converter that uses a lead zirconate titanate electrostrictive element that contracts in response to alternating voltage.

Although individual nanoparticles are not destroyed by sonication, the cluster of nanoparticles does break down into smaller clusters, resulting in a lower total number of clusters. Concentrations of beryllium oxide nanoparticles in the base fluid were varied by volume from 0.0005% to 0.003% in 0.0005 increments. Law of mixing formula [23] was used to calculate the number of BeO nanoparticles required to create nanofluids. BeO nanoparticles are weighed to within 0.01mg using a sensitive scale (Model: Shimadzu ELB 300). Using a specific gravity bottle as well as a thermometer, we were able to determine the density by employing a relative measurement technique. All the prepared nanofluids with different volume fractions having their density, viscosity, as well as ultrasonic velocity were measured as a function of temperature at T = 313 K, 323 K, as well as 333 K. The rheological behavior of the fluids can be studied with the use of specialized rheometers as well as the Kininogen Domain (KD2) pro thermal analyzer [24-26]. The nanofluids' viscosity was measured using a Brookfield DV-III ultra-programmable rheometers [24-26]. To operate, the DV-III ultra-rheometers pulls a spindle through a calibrated spring while it is immersed in the test fluid. The measurement's accuracy is based on the spindle's rotation speed, which varies across the measurement's range (in centipoise). The range of possible viscosities is inversely proportional to the spindle size and rotational speed. An ultrasonic pulse-echo velocity meter (VCT 70A) was used to measure velocities at a constant frequency of 2 MHz A temperature sensor is integrated into the sample holder to monitor the temperature of the test sample while just 9 mL of sample volume is required. Accurate temperature regulation is essential for any rheological study to be successful. In this case, a temperature-controlled water bath is connected to the sample holder for optimum temperature maintenance. For both Newtonian as well as non-Newtonian fluids, it is possible to record and store data on a computer. A Newtonian fluid's viscosity is insensitive to shear stresses.

The KD2 pro thermal analyser is a portable device with characteristics including a wide temperature range, data storage and retrieval, and memory storage. The single-needle thermal conductivity sensor (KS-1) for liquids, measuring 60 mm in length and 1.3 mm in diameter, measures the thermal conductivity of fluid samples. The 0.1 to 2.0 W/mK thermal conductivity of fluids can be measured with +5% accuracy using this stainless-steel sensor needle, which features a temperature element, a thermistor. The sensor is connected to the controller module (which includes a battery, a 16-bit microcontroller, an analog/digital (A/D) converter, as well as power management circuitry) through a platinum wire that also acts as a thermometer to measure the line temperature. The temperature of the liquid mixture was maintained by continuously recirculating water from a water bath with a thermostatically controlled temperature to within 0.1 K.

3. Results and discussion

3.1 FTIR analysis of BeO nanoparticle

Numerous BeO-containing minerals have at around 742 cm^{-1} in their infrared spectra is shown as in Figure 1. Oxygen-bridging vibrations between beryllium and oxygen may account for the 742 cm^{-1} absorption peaks. The infrared maximum for BeO has been determined to be at 742 cm^{-1} [27]. This is caused by the vibration of a single beryllium atom as it passes through a tetrahedron of stationary oxygen atoms. The frequency of this vibration is triply degenerated for a perfect tetrahedron. The degeneracy is broken only by minor tetrahedron deformation. Absorption at 1581 cm^{-1} [28] are caused by the BeO stretching vibrations. Changes in vibrational frequencies can be attributed to factors such as the size effect, dipolar interactions, interfacial effects, quantum confinement effect, and high internal stress in nanoparticles as compared to bulk BeO. The Be-O-Be stretching link between beryllium and oxygen has been detected by FTIR.

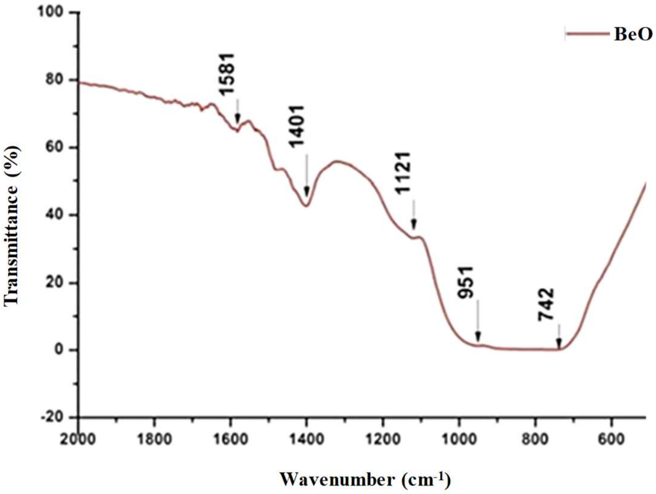

Figure 1 FTIR spectra of the BeO nanoparticle.

3.2 Raman analysis of BeO nanoparticle

Figure 2 depicts the vibrational Raman spectrum of a BeO nanoparticle that has been annealed at 840 degrees Celsius. The 684 cm^{-1} Raman mode found is similar to the 725 cm^{-1} Raman mode reported for bulk BeO in [29]. BeO can be identified by its diagnostic peak at 684 cm^{-1} [25]. Given the magnitude of the frequency change, we can infer that the particle has shrunk from macroscopic to nanometric proportions. BeO's significant Raman shift is associated with hard phonon modes, which may lead to enhanced thermal conductivity. Because BeO nanoparticles have a high thermal conductivity, the heat energy generated by the motion of the channel carrier can be quickly dissipated. Two unique Raman modes are located at 630 cm^{-1} and 998 cm^{-1}, and they are caused by the Be-O-Be [30], Be = O stretching vibrations. RAMAN active modes at 630 cm^{-1} and 394 cm^{-1} have been described by similarly few researchers [31-33]. The Be-O-Be stretching bond between beryllium and oxygen is observed using Raman spectroscopy.

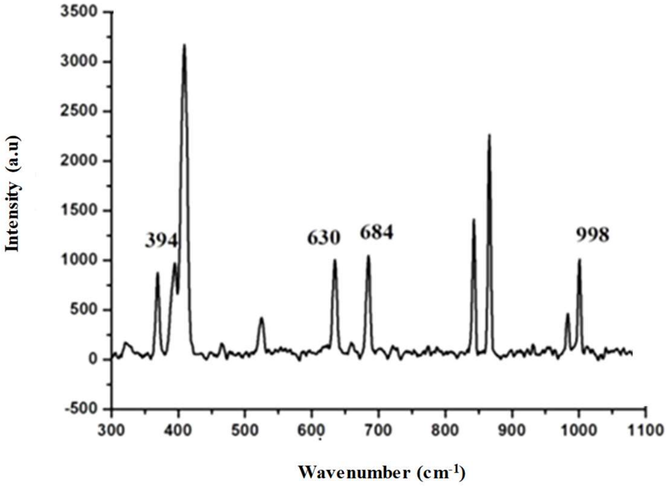

Figure 2 Raman spectra of the BeO nanoparticle.

Nanoparticles of BeO with a high thermal conductivity were synthesized with the help of ultra-sonication and chemical precipitation method. Annealing at 840 degrees Celsius results in a perfectly hexagonal structure, as predicted by the calculated structural parameters for the BeO data. This was verified with the help of FTIR as well as Raman spectroscopy. Both Raman and FTIR elucidate the Be-O-Be stretching relationship between beryllium as well as oxygen atoms.

3.3 The theory of molecular interactions

Subtracting the unknown parameter from the measured values at different temperatures applying some relationships [22,34,35] can help make sense of the molecular interaction studies conducted in silicone oil-based Beryllium oxide nanofluids. The density was obtained using the formula [22,35].

$$\rho_2 = \left(\frac{W\_2}{W\_1}\right) \rho_1 \tag{1}$$

where, W_1 = weight of distilled water, W_2 = Weight of experimental liquid, ρ_1 = Density of water, and ρ_2 = Density of Experimental liquid.

$$\beta = \frac{1}{U^2} \rho \tag{2}$$

$$L_f = KT\beta^{\frac{1}{2}} \tag{3}$$

$$\tau = \frac{4\eta}{3} (\beta) \tag{4}$$

$$\Delta G = kT \ln\left(\frac{kT}{h}\right) \tag{5}$$

$$\pi_i = bRT \left(\frac{k\eta}{U}\right)^{\frac{1}{2}} \left(\frac{\rho^{\frac{2}{3}}}{M_{eff}^{\frac{7}{6}}}\right) \tag{6}$$

$$V_f = \left(\frac{M_{eff} U}{K\eta}\right)^{\frac{3}{2}} \tag{7}$$

$$Z = U.\rho \tag{8}$$

where 'U'- ultrasonic velocity, 'KT'- Jacobson's constant, 'k'- Boltzmann's constant, 'h'- Planck's constant, 'b'- cubic packing ('2' for all liquids), 'R'- gas constant, 'T'- absolute temperature, 'M_{eff}' - liquid mixture effective mass, 'K' - 4.281×10^9.

The acoustical characteristics were calculated using density as well as ultrasonic velocity measurements of the pure as well as silicone oil-based BeO nanofluids at three different temperatures (313 K, 323 K, as well as 333 K). In the previous work, the effect of BeO concentration on acoustical characteristics in a silicone oil-based BeO nanofluids system at 303 K was examined [19].

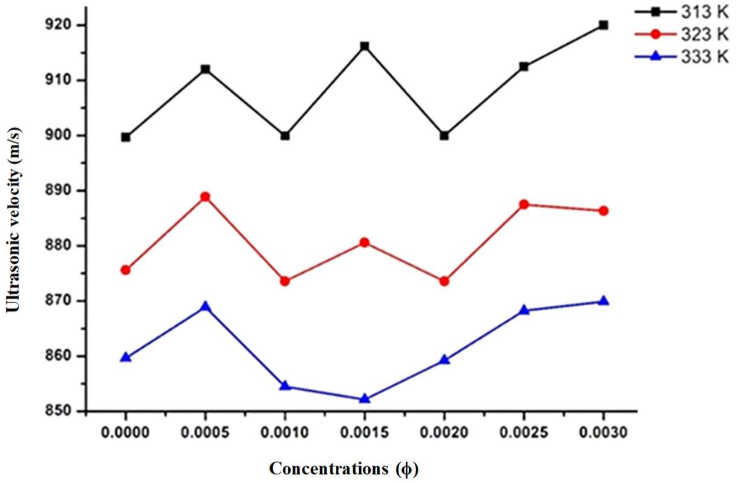

Figure 3 Variation of ultrasonic velocity with different concentrations (ϕ) of BeO nanoparticle in Silicone oil based BeO nanofluids at various temperatures.

Increases in the velocity value of silicone oil-based nanofluids are the result of interactions between particles and molecules of the base fluid. This is because of the attractive force that holds things together [36]. One possible explanation for the increase with increasing concentration is that hydrogen bonds form between the OH molecules of silicon as well as the -O- of BeO nanoparticles, leading to contact forces. Ultrasonic velocity changes non-linearly, suggesting a weak intermolecular force in the nanofluids system as well as a rise in thermal energy. The surface effect, caused by the oxidized sites of BeO nanoparticles interacting with base fluid molecules, may be responsible for the observed acceleration in the BeO nanofluids system. We find that the application of heat energy enhances the motion of molecules in nanofluids. Molecular mobility in the fluid medium is increased by heat agitation, competing with the BeO-base fluid molecule interaction that tends to break the molecule apart.

As can be seen in Figure 3, the increased velocity of BeO-Silicone oil nanofluids is the result of particle fluid interactions within the nanofluids. The cohesive force of the attraction is responsible for this [37,38]. Ultrasonic velocity in BeO nanofluids decreases as temperature rises because the intermolecular link between the constituent molecules breaks. When a solid object collides with a liquid, the ultrasonic waves in the fluid are distorted. Brownian motion, and mobility of molecules, causes intermolecular forces to decrease, explaining this phenomenon. When the fluid holding the BeO nanofluids in suspension is heated as well as agitated, the molecules spread out. Poor particle-fluid interaction is a hallmark of this process at elevated temperatures.

It has been found that L_f for Silicone oil-based nanofluids drop at 333 K then show a fluctuation with increasing BeO nanoparticle concentration in the base fluid according to Table 1. The improved molecular connections are evidenced by the decrease in adiabatic compressibility. The molecular bonding between the newly generated entities makes them more compact as well as less prone to compression. Interactions between particles and base fluids at the molecular level can alter the structure of the molecules, which in turn modifies their compressibility. With an increase in particle concentration, the intermolecular interaction rises, forcing the molecules into closer packing reducing L_f [39]. As the temperature of a liquid mixture rises, the adiabatic compressibility rises along with it, signifying the presence of a distinct molecular interaction between the molecules. Increases in temperature cause the nanofluid's molecules to disperse because of thermal expansion and the intermolecular repulsive interactions between them. The intermolecular force provides an explanation for the compressibility of the nanofluids system, where a reduction in repulsive force results in increased compressibility. Therefore, the molecules in the particle fluid system are compressed when the pressure is raised. Because of this, the acoustic velocity and compressibility both rise as a result of the increased intermolecular repulsive force. An increase in adiabatic compressibility with increasing temperature results from the increased molecular motion that occurs at higher temperatures [40]. This motion is conducive to the stable suspension of nanoparticles in a base fluid medium. Ultrasonic wave propagation in a nano suspension will be affected by the temperature, as both the stiffness of the nanofluids and the possibility of particle agglomeration increase with increasing temperature. The free length of the particles is reduced as a result of the weak force of interaction between the particles and the molecules of the base fluid as the concentration of the particles increases.

When adiabatic compressibility drops, it means there are more intermolecular bonds. The molecular bond makes the new entities tight and resistant to compression. In the presence of a solvent, solutes having a strong dipole-dipole interaction may become more mobile, having a greater probability of coming into contact with solvent molecules. It is possible that BeO molecules will cluster visibly around the +ve ions in the solutions. Higher concentrations cause BeO to agglomerate, decreasing the contact force between the solid and the solvent.

Table 1 Variation of adiabatic β as well as L_f with ϕ of BeO nanoparticles in Silicone oil-based nanofluids at various temperatures.

Concentration (ϕ)	β x 10^{-10} [m^2/N]	β x 10^{-10} [m^2/N]	β x 10^{-10} [m^2/N]	L_f x10^{-11} [m]	L_f x10^{-11} [m]	L_f x10^{-11} [m]
	313 K	323 K	333 K	313 K	323 K	333 K
0	1.2751	1.3578	1.4136	7.2473	7.6100	7.8987
0.0005	1.2434	1.3174	1.3818	7.1567	7.4959	7.8095
0.0010	1.2844	1.3720	1.4376	7.2736	7.6496	7.9654
0.0015	1.2315	1.3363	1.4286	7.1222	7.5495	7.9406
0.0020	1.2821	1.3728	1.4227	7.2671	7.6518	7.9241
0.0025	1.2472	1.3238	1.3891	7.1675	7.5139	7.8299
0.0030	1.2268	1.3325	1.3871	7.1087	7.5386	7.8243

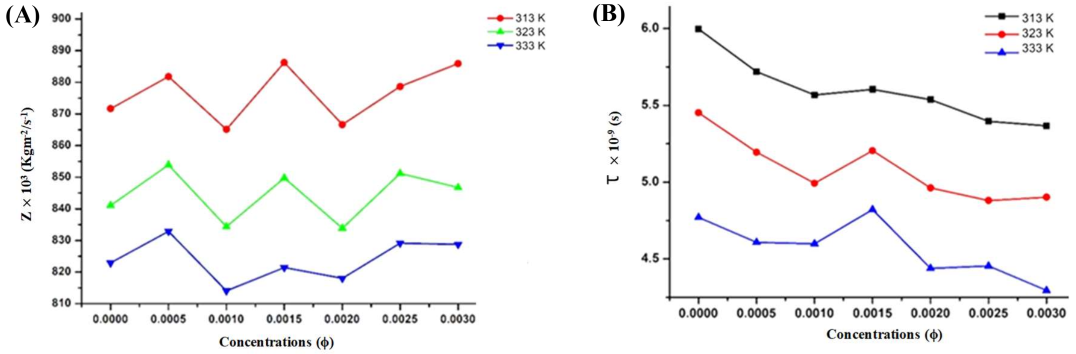

Figure 4 Variation of (A) Z and (B) τ with ϕ of BeO nanoparticle in Silicone oil based BeO nanofluids at various temperatures.

At greater concentrations, the rise in acoustic impedance implies a substantial interaction between the particle and the base fluid molecules, which affects the structural arrangement, as seen in Figure 4 [41]. In the nanofluid medium at a greater concentration, molecular interaction occurs between dissimilar molecules [42], resulting in a high impedance.

Figure 4 displays the values of Z and τ for silicone oil based BeO nanofluids at varying concentrations as well as temperatures. Increased intermolecular distance results from ultrasonic waves' propagation-induced impedance [43]. It is possible to track the modes of sound wave transmission and reflection in nanoparticles and molecules of the base fluid by measuring their particular acoustic impedance. The fluids' and particles' molecular packing structures play a role. The absence of compound formation or strong molecular connection is shown by the non-linear fluctuation in particular acoustic impedance. As its name implies, it is the inverse of adiabatic compressibility. There is some behavioural similarity between the acoustic impedance values and the velocity. The relationship between adiabatic compressibility and acoustic impedance is inverse. Increases in acoustic impedance point to structural changes brought on by interactions between particles and molecules of the base fluid. In a nanofluids medium with a high concentration, unlike molecules interact [39], resulting in a high impedance. The acoustic impedance value drops as the temperature rises. The creation of a charge transfer complex between solute molecules as well as the non-linear behaviour of acoustic impedance [44] both lend credence to the notion of molecular interaction. The period of time that passes before the kinetic energy of an excitation can be measured as a translational energy is known as the relaxation time. Results show that concentration and temperature both rises, so does the relaxing time. In addition, viscous forces are crucial to this procedure. The tendency toward lessening may be attributable to a shift in the molecular interaction's fundamental character. The structural effect of particles in base fluid molecules is reflected in the acoustic impedance and relaxation duration of BeO nanofluid systems.

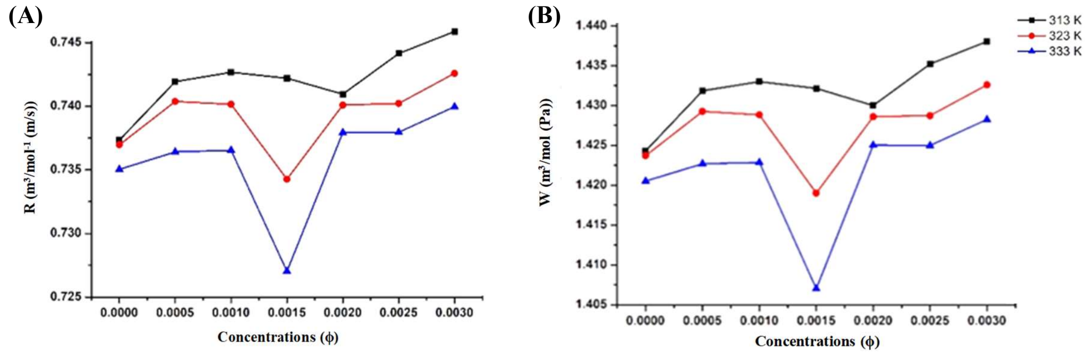

Figure 5 Variation of (A) R as well as (B) W with ϕ of BeO nanoparticle in Silicone oil based BeO nanofluids at various temperatures.

Figure 5 shows the variation of W as well as R with respect to the concentration of BeO dispersed in the base fluids of Silicone oil. From the data, it can be shown that the molar compressibility (also known as Wada's constant) as well as the molar sound velocity (also known as Rao's constant) both change in a concentration-dependent manner. The presence of molecular interaction in the nanofluids system is revealed by the nonlinear shift. Values are shown to decrease as temperature rises, indicating that thermal agitation disrupts molecule connection. Despite sharing a similar dependence on concentration as well as temperature, the molar compressibility and molar sound velocity also have different values. Both Rao's and Wada's constants remain constant regardless of temperature. Wada's constant and Rao's constant both decrease with increasing temperature because the ultrasonic velocity within the nanofluid medium varies with regard to temperature.

The magnitude of the forces between molecules can be inferred from the internal pressure. Cohesive energy density is a measurement of the overall molecular cohesion per unit volume, represents the physical contribution to that density. One of the qualities of internal pressure is solubility. Under the influence of the medium's internal pressure, the dispersed solutes interact with the solvent. The formation of these bonds and interactions is the result of the Coulombic or Van der Waal’s interaction, and hydrogen bonding. Cohesive or internal pressure is the van der Waal's equation term for the attracting force of the molecule (a/v^2). The interactions between the solvent, the solute, and the solvent cause a shift in this one variable.

BeO: silicon oil nanofluids' solubility features are easily explained by their volume concentration since the internal pressure gradually lowers as the free volume increases. The molecular interactions between molecules of the same type and those of different types are affected by the molecules' structural arrangements, shape, and size. Since the molecules of a liquid are not closely packed. There is free space between the molecules for the movement, this space is called free volume, and the average potential between the molecules is said to be zero V_f. If the free volume is decreasing, this indicates that the particles or fluid molecules are interacting weakly with one another. So, the fact that the free volume has grown suggests that the particles and fluid molecules are interacting strongly. Figure 6 shows that as temperature rises, free volume expands [45], while Figure 6 shows that as temperature rises, internal pressure collapses [46].

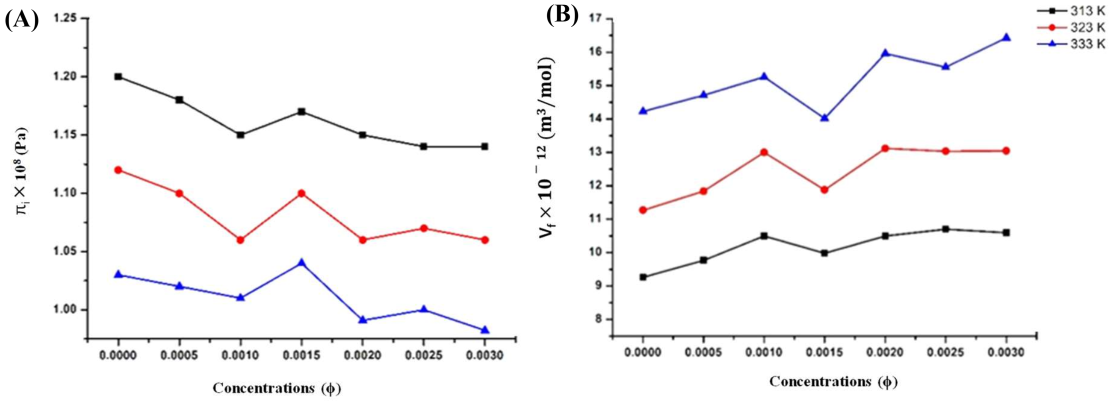

Figure 6 Variation of (A) π_i as well as (B) V_f with a ϕ of BeO nanoparticle in Silicone oil based BeO nanofluids at various temperatures.

Because of the surface tension of the contact, a free energy barrier will increase, allowing the system to transition from one phase to the next. The rearrangement of molecules in the mixture will take longer since the Gibbs free energy has reduced, as illustrated in Figure 7. Between the base fluid and the particle, an intermediate complex is formed, resulting in the production of reaction products. This demonstrates that hydrogen bonds can form in BeO nanofluids.

The intermolecular force of repulsion occurs between particles and Silicone oil molecules, allowing molecules to freely move with regard to one another in the fluid flow. As the distance between the particles grows the fluid flow becomes more mobilised, and the flow around one particle is affected by the flow around other particles.

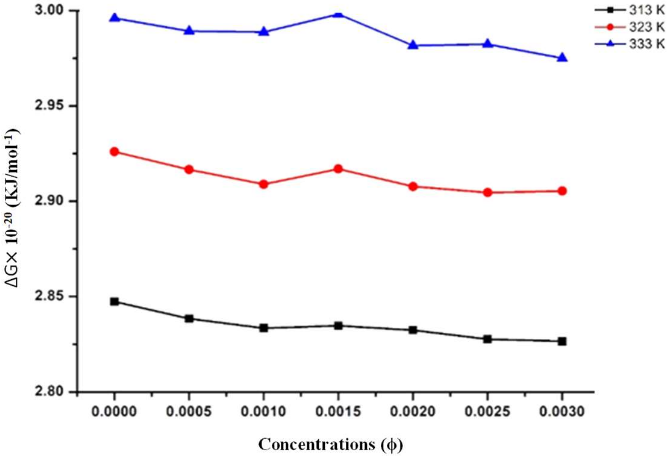

Figure 7 Variation of ΔG with ϕ of BeO nanoparticle in Silicone oil based nanofluids at various temperatures.

When it comes to rheological behaviour, nanofluids exhibit a transition from Newtonian to non-Newtonian behaviour [47,48]. The non-Newtonian rheological behaviour of nanofluids strengthens with increasing concentration. The features of a particle suspension will alter when thermal circulation is applied above a specific temperature. For nanofluids, the Newtonian viscosity of the base fluid is turned into non-Newtonian [49] when the temperature increases [50,51] because of the interaction between the BeO nanoparticles and the molecules of the base fluid. As the binding energy between molecules drops, the cohesive force between them weakens [52]. The mobility of the molecules is also responsible for the bond breakage. As the BeO nanofluids concentration increases to 0.0015, the viscosity of the underlying silicone oil increases as well. This is because the fluid flow becomes more resistive as a result of nanoparticle entrapment [53]. Figure 8 shows that when the temperature increases, the viscosity decreases.

When the BeO concentration is increased, the viscosity decreases at 333 K. It is the attraction forces between the molecules, not the particles' amount, size, or shape that determine the viscosity. When BeO nanoparticles are mixed with the base fluid, the contact between the particles is diminished because of the increased repulsive forces caused by the denser solid surface. Because of less friction during fluid motion, viscosity values fall. Increasing the sonicating time spent on the nanoparticle suspension causes the viscosity to decrease [54]. According to [55], nanofluids viscosity is affected by the kinetic energy of the fluid molecules. High-viscosity silicone oil flows more smoothly than low-viscosity base fluids. The viscous shear stresses are modified by the increase in concentration of the base fluids. Particle shape will affect nanofluids viscosity for the same concentration as observed in [56]. According to [57], when the particle fraction increases, the importance of the viscosity in determining the particle dispersion size increases.

The experimental results show that a higher concentration of nanoparticles dispersed across a material will increase its thermal conductivity because of Brownian motion and inter-particle diffusion effects. As temperatures increase, so does the thermal conductivity of a substance. The higher kinetic energy of the fluid's molecules could be the reason for this. An increased rate of rotation and vibrational motion within the molecule leads to greater collisions between particles [58].

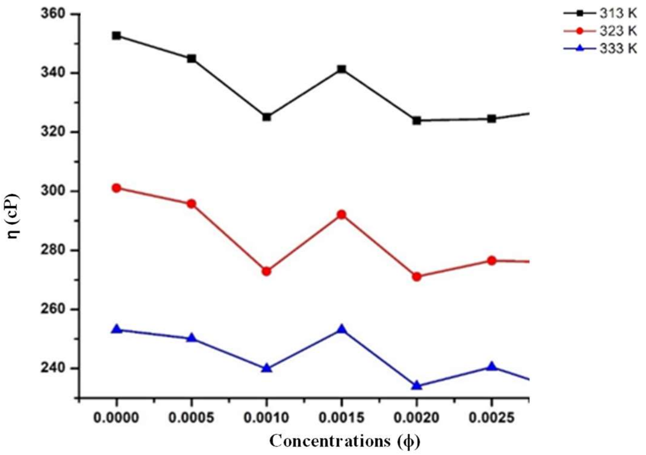

Figure 8 Variation of viscosity (η) with different concentrations (ϕ) of BeO nanoparticle in Silicone oil based nanofluids at various temperatures.

A high thermal conductivity is provided by the nanofluids medium because of the dense packing of the BeO nanoparticles, which is achieved by increasing the fraction of BeO nanoparticles. The experimental studies clearly show that the rise in thermal conductivity is strongly influenced by the temperature. Increasing the BeO concentration in all three systems brings the particles closer together, resulting in better thermal conductivity. Nanoparticles dispersed in base fluids produce large surface per unit volume, enhancing thermal performance [59].

A nano scale particle increases Brownian motion velocity aids in thermal transmission because it provides an additional pathway for heat to dissipate through the medium. When the concentration of BeO nanoparticles is high enough, they form a conducting path. This effect, as discovered by [60], may result in a rise in the frequency of lattice vibration. At room temperature, the energy stored in the bonds between the base fluids is transferred to neighbouring molecules, increasing the thermal conductivity of the base fluids [61].

Figure 9 graphically displays the linear relationship between Beryllium oxide nanoparticle concentration and thermal conductivity. Increases in temperature are accompanied by a corresponding increase in thermal conductivity. One possible explanation is that the kinetic energy of the fluid's molecules has increased. Increased particle impact occurs as the rotational and vibrational rates of molecules increase [62,63].

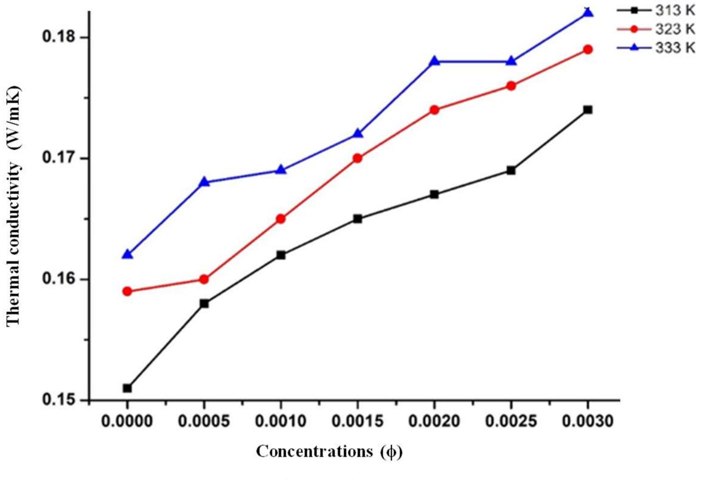

Figure 9 Variation of thermal conductivity with ϕ of Silicone oil based BeO nanofluids at various temperatures.

4. Conclusion

Raman and FTIR both show that the link between the beryllium and oxygen atoms is a Be-O-Be stretching bond. The ultrasonic velocity of BeO Nanofluids decreases as the temperature rises because the intermolecular bond between the component molecules breaks. This is because intermolecular forces are less as a result of the

Brownian motion of molecules. This phenomenon, especially noticeable at elevated temperatures, is a sign of insufficient interaction between particles and the surrounding fluid.

Ultrasonic wave speed changes as it travels through a fluid owing to molecular interactions were analyzed at different concentrations and temperatures to determine the acoustical properties of Silicone oil-based BeO nanofluids. In a nanofluid environment, molecules can join forces to create complexes. Internal pressure, Gibbs free energy, Rao's constant and Wada's constant, the degree of molecular interaction term, all reveal that complex formation is absent from Nanofluids, with molecule association instead resulting from hydrogen bonding, dipole-dipole, hyper conjugation, and charge transfer.

Temperature increases are accompanied by a decrease in density and viscosity in silicone oil based BeO nanofluid. An increase in BeO nanoparticle concentration correlates with a rise in thermal conductivity. Increases in temperature are accompanied by a corresponding increase in thermal conductivity. The increased high thermal efficiency seen in the trials demonstrates the potential future utility of employing BeO: silicon oil nanofluids. Silicone oil-based BeO nanofluids have a thermal conductivity increase of up to 30%, comparatively to the base fluid. As the temperature rises, the particle and fluid's acoustic properties change almost linearly, suggesting weaker intermolecular interactions.

5. Acknowledgements

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6. References

[1] Cakmak NK, Said Z, Sundar LS, Ali ZM, Tiwari AK. Preparation, characterization, stability, and thermal conductivity of rGO-Fe3O4-TiO2 hybrid nanofluid: an experimental study. Powder Technol. 2020;372:235-245.

[2] Yang L, Ji W, Mao M, Huang JN. An updated review on the properties, fabrication and application of hybrid-nanofluids along with their environmental effects. J Clean Prod. 2020;257:120408.

[3] Philip J, Shima PD. Thermal properties of nanofluids. Adv Colloid Interface Sci. 2012;183:30-45.

[4] Nath R, Roy R, Mandal A, Ghosh R, Chatterjee W, Pramanik R. Establishment of Innovative Approaches of Nanofluids. 2021.

[5] Bakhtazma F, Alavi F. Second-order thermodynamic derivative properties of ionic liquids from ePC-SAFT: the effect of partial ionic dissociation. Ind Eng Chem Res. 2019;58:22408-22417.

[6] Dheyab MA, Aziz AA, Jameel MS, Khaniabadi PM, Mehrdel B. Mechanisms of effective gold shell on Fe3O4 core nanoparticles formation using sonochemistry method. Ultrason Sonochem. 2020;64:104865.

[7] Ma Z, Collins DJ, Ai Y. Detachable acoustofluidic system for particle separation via a traveling surface acoustic wave. Anal Chem. 2016;88:5316-5323.

[8] Doinikov AA, Gerlt MS, Pavlic A, Dual J. Acoustic streaming produced by sharp-edge structures in microfluidic devices. Microfluid Nanofluidics. 2020;24:1-3.

[9] Pourpasha H, Heris SZ, Mahian O, Wongwises S. The effect of multi-wall carbon nanotubes/turbine meter oil nanofluid concentration on the thermophysical properties of lubricants. Powder Technol. 2020;367:133-142.

[10] Pourpasha H, Zeinali Heris S, Asadi A. Experimental investigation of nano-TiO2/turbine meter oil nanofluid. J Therm Anal Calorim. 2019;138;57-67.

[11] Pourpasha H, Zeinali HS, Mohammadfam Y. Comparison between multi-walled carbon nanotubes and titanium dioxide nanoparticles as additives on performance of turbine meter oil nano lubricant. Sci Rep. 2021;11:1-19.

[12] Kanti P, Sharma KV, CG R, Azmi WH. Experimental determination of thermophysical properties of Indonesian fly-ash nanofluid for heat transfer applications. Part Sci Technol. 2021;39:597-606.

[13] Kanti P, Sharma KV, Ramachandra, CG, Minea AA. Effect of ball milling on the thermal conductivity and viscosity of Indian coal fly ash nanofluid. J Heat Transfer. 2020;49:4475-4490.

[14] Aziz T, Fan H, Khan FU, Haroon M, Cheng L. Modified silicone oil types, mechanical properties and applications. Polym. Bull. 2019;76:2129-2145.

[15] Kanti P, Sharma KV, Yashawantha KM, Jamei M, Said Z. Properties of water-based fly ash-copper hybrid nanofluid for solar energy applications: application of RBF model. Sol Energy Mater Sol Cells. 2022;234:111423.

[16] Kanti P, Sharma KV, Khedkar RS, Rehman TU. Synthesis, characterization, stability, and thermal properties of graphene oxide based hybrid nanofluids for thermal applications: Experimental approach. Diam Relat Mater. 2022;128:109265.

[17] Han Z, Fina A. Thermal conductivity of carbon nanotubes and their polymer nanocomposites: a review Prog Polym Sci. 2011;36:914-944.

[18] Idumah CI, Hassan A. Recently emerging trends in thermal conductivity of polymer nanocomposites. Rev Chem Eng. 2016;32:413-457.

[19] Britto T, Jeevaraj A. Effect of annealing temperature and ultrasonication on the structural properties of beryllium oxide nanoparticles synthesized via chemical precipitation method. J Bionanosci. 2018;12:266-270.

[20] Britto T, Jeevaraj A. Acoustical studies on beryllium oxide/silicone oil nanofluids. Sensor Letters. 2020;18:69-73.

[21] Sundharam E, Jeevaraj A, Chinnusamy C. Effect of ultrasonication on the synthesis of barium oxide nanoparticles. J Bionanosci. 2017;11:310-314.

[22] Prakash P, John C, Kingson SJA, Asfaw BT. An investigation of the dielectric properties of barium oxide: therm500 nanofluids at different temperatures. J Eng. 2022;4274436:1-8.

[23] Walrafen GE, Samanta SR. Raman and Infrared Spectra of Amorphous BeO and Be (OH) 2• 2H 2 O. Appl Spectrosc. 1979;33:524-525.

[24] Kiruba R, Gopalakrishnan M, Mahalingam T, Jeevaraj A. The effect of temperature on the ultrasonic properties of carbon nanotubes incorporated in zinc oxide nanofluids. J Nanofluids. 2013;2:50-54.

[25] Prakash P, Catherine Grace John J, Merita Anto Britto T, Rubila S, Kingson Solomon Jeevaraj A. Synthesis and characterization of zinc doped beryllium oxide: Ethylene glycol nanofluids. Songklanakarin J Sci Technol. 2022;44:979-986.

[26] Shah SN, Shahabuddin S, Khalid M, Mohd Sabri MF, Mohd Salleh MF, Muhamad Sarih N, Rahman S. rheological and thermal conductivity study of two-dimensional molybdenum disulfide-based ethylene glycol nanofluids for heat transfer applications. Nanomater. 2022;12(6):1021.

[27] Thompson CA, Andrews L. Noble gas complexes with BeO: infrared spectra of NG-BeO (NG= Ar, Kr, Xe). J Am Chem Soc. 1994;116:423-424.

[28] Loh E. Optical phonons in BeO crystals. Phys Rev. 1968;166:673.

[29] Kourouklis GA, Sood AK, Hochheimer HD, Jayaraman A. High-pressure Raman study of the optic-phonon modes in BeO. Phys. Rev B Condens Matter. 1985;31:8332.

[30] Morell G, Katiyar RS, Weisz SZ, Walter T, Schock HW, Balberg I. Crystalline phases at the p-ton-type transition in Cu-ternary semiconducting films. Appl Phys Lett. 1996;69:987-989.

[31] Pardanaud C, Rusu MI, Martin C, Giacometti G, Roubin P, Ferro Y, Allouche A, Oberkofler M, Köppen M, Dittmar T, Linsmeier C. Hydrogen retention in beryllium: concentration effect and nanocrystalline growth. J Condens Matter Phys. 2015;27:475401.

[32] Al-Nasrawy DK. Preparation and Characterization of BeO-Supported Feldspar Porcelain. Iraqi J Sci. 2016;57:404-413.

[33] Mansour RB, Galanis N, Nguyen CT. Developing laminar mixed convection of nanofluids in an inclined tube with uniform wall heat flux. Int J numer method h. 2009.

[34] Ravichandran S, Pushpanathan K, Sagadevan S, Marlinda AR, Mohammad F, Al-Lohedan HA, Johan MR. Influence of graphene concentration towards the thermo-acoustic and vibrational properties of graphene: polyvinyl alcohol composites. J Mater Sci Mater Electron. 2021;32:10359-10367.

[35] Priya CS, Nithya S, Velraj G, Kanappan AN. Molecular interactions studies in liquid mixture using ultrasonic technique. J Adv Sci Technol. 2010;18:59-74.

[36] Saravanan MR, Sivakumar S. Characterization of doped polyaniline by linear mode of MALDI-TOF MS method. 2011.

[37] Premalatha M, Jeevaraj KS. Effect of Concentration and Temperature on the Ultrasonic Parameters of Carbon Nanotube Nanofluids. J. Nanofluids. 2013;2:133-139.

[38] Jegadheeswaran S, Sundaramahalingam A, Pohekar SD. High-conductivity nanomaterials for enhancing thermal performance of latent heat thermal energy storage systems. J Therm Anal Calorim. 2019;138:1137-1166.

[39] Awasthi A, Shukla JP. Ultrasonic and IR study of intermolecular association through hydrogen bonding in ternary liquid mixtures. Ultrasonics. 2003;41(6):477-486.

[40] Kannappan V, Santhi BS, Jonathan DR. Ultrasonic investigation on segmental motion of some polymers in solution. Indian J Chem. 2014;53A:688-694.

[41] Naddaf A, Zeinali Heris S. Density and rheological properties of different nanofluids based on diesel oil at different mass concentrations. J Therm Anal Calorim. 2019;135:1229-1242.

[42] Rashin MN, Hemalatha J, Nalini RP, Ramya AV. Ultrasonic studies and microchannel flow behavior of copper oxide nanofluid. AIP Conf. Proc. 2011;1349(1):335-336.

[43] Rawat MK, Sangeeta A. Ultrasonic study of molecular interactions and compressibility behaviour of strontium soaps in chloroform-propylene glycol mixture. Indian J Pure Appl Phys. 2008;46(3):187-192.

[44] Paddison SJ, Elliott JA. Molecular modeling of the short-side-chain perfluorosulfonic acid membrane. J Phys Chem A. 2005;109:7583-7593.

[45] Pandey JD, Sanguri V, Yadav MK, Singh A. Intermolecular free length and free volume of pure liquids at varying temperatures and pressures. Indian J Chem. 2008;47A(7):1020-1025..

[46] Agrawal RC, Pandey GP. Solid polymer electrolytes: materials designing and all-solid-state battery applications: an overview. J Phys D. 2008;41:223001.

[47] Choi U, Tran T. Experimental studies of the effects of non-Newtonian surfactant solutions on the performance of a shell-and-tube heat exchanger. Recent developments in non-Newtonian flows and industrial applications. 1991;124:47-52.

[48] Zhou D. Heat transfer enhancement of copper nanofluid with acoustic cavitation. Int J.Heat Mass Transf. 2004;47(14-16):3109-3117.

[49] Mohammadfam Y, Heris SZ, Khazini L. Experimental Investigation of Fe3O4/hydraulic oil magnetic nanofluids rheological properties and performance in the presence of magnetic field. Tribol Int. 2020;142:105995.

[50] Prakash P, Kingson SJA, Mahmoud MH, Akhtar MS, Altinawi A. Ultrasonic Velocity, Viscosity and Thermal Conductivity Studies on Barium Oxide: Silicone Oil Nanofluids. Sci Adv Mater. 2023;15(6):818-823.

[51] Selvaraj V, Krishnan H. Graphene-silver alloyed quantum dots nanofluid: Synthesis and application in the cooling of a simulated electronic system. Appl Therm Eng. 2021;187:116580.

[52] Alizadeh H, Pourpasha H, Heris SZ, Estellé P. Experimental investigation on thermal performance of covalently functionalized hydroxylated and non-covalently functionalized multi-walled carbon nanotubes/transformer oil nanofluid. Case Stud Therm Eng. 2022;31:101713.

[53] Salimi-Yasar H, Heris SZ, Shanbedi M, Amiri A, Kameli A. Experimental investigation of thermal properties of cutting fluid using soluble oil-based TiO2 nanofluid. Powder Technol. 2017;310:213-220.

[54] Yang Y, Grulke EA, Zhang ZG, Wu G. Thermal and rheological properties of carbon nanotube-in-oil dispersions. J Appl Phys. 2006;99(11):114307.

[55] Yang Y, Zhang ZG, Grulke EA, Anderson WB, Wu G. Heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in laminar flow. Int J Heat Mass Transf. 2005;48(6):1107-1116.

[56] Timofeeva EV, Moravek MR, Singh D. Improving the heat transfer efficiency of synthetic oil with silica nanoparticles. J Colloid Interface Sci.2011;364(1):71-79.

[57] Nguyen CT, Desgranges F, Galanis N, Roy G, Maré T, Boucher S, Mintsa HA. Viscosity data for Al2O3–water nanofluid-hysteresis: is heat transfer enhancement using nanofluids reliable? Int J Therm Sci. 2008;47(2):103-111.

[58] Al-Amayreh M. Experimental study of termal conductivity of ethylene glycol water mixtures. Eur J Res. 2010;44(2):300-313.

[59] Liu MS, Lin MC, Tsai CY, Wang CC. Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method. Int J Heat Mass Transf. 2006;49(17-18):3028-3033.

[60] Shalkevich N, Shalkevich A, Bürgi T. Thermal conductivity of concentrated colloids in different states. J Phys Chem C. 2010;114(21):9568-9572.

[61] Tadjarodi A, Zabihi F, Afshar S. Experimental investigation of thermo-physical properties of platelet mesoporous SBA-15 silica particles dispersed in ethylene glycol and water mixture. Ceram Int. 2013;39(7):7649-7655.

[62] Sundaram D, Yang V, Yetter RA. Metal-based nanoenergetic materials: synthesis, properties, and applications. Prog Energy Combust Sci. 2017;61:293-365.

[63] Deng C, Zhang K. Thermal Conductivity of 1, 2-Ethanediol and 1, 2-propanediol binary aqueous solutions at temperature from 253 K to 373 K. Int J Thermophys. 2021;42:1-12.