In the present investigation, TiO$_2$ nanostructures were synthesised via a simple sol-gel technique and characterised with X-ray diffraction (XRD), scanning electron microscopy with energy-dispersive X-ray analysis (SEM-EDX), high-resolution transmission electron microscopy (HR-TEM) and ultraviolet-visible (UV-vis) spectroscopy. The temperature and concentration dependence of thermal conductivity enhancement (TCE) and ultrasonic velocity have been explored in ethylene glycol-based TiO$_2$ nanofluids. The obtained results showed 24% enhancement in thermal conductivity at higher temperature (80°C) of the base fluid ethylene glycol by adding 1.0 wt% of TiO$_2$ nanoparticles. The behaviour of TCE and ultrasonic velocity with temperature in prepared nanofluids has been explained with the help of existing phenomena. The increase in ultrasonic velocity in ethylene glycol with TiO$_2$ nanoparticles shows that a strong cohesive interaction force arises among the nanoparticles and base fluid. These results
1. Introduction

Nanoparticles are traditionally defined as particles with at least one of the characteristic dimensions being up to 100 nm. Nanoparticles have a large surface to volume ratio. This is the most important factor to explain the anomalous behaviour of nanoparticles as compared to their bulk counterparts (1–3). Metal oxide nanoparticles, predominantly transition metals, are much preferred for their wide and attractive choice of properties (4–6). The metals with their varying valences can form a vast range of oxide compounds when processed through suitable synthesis methodologies (7, 8). Metal oxides can display metallic, semiconducting or insulating character according to their electronic structure (9–11). Among the metal oxide nanoparticles, TiO$_2$ nanoparticles are attractive due to their high stability, commercial availability and comparatively low cost (12, 13). They are also free from health hazards (14). TiO$_2$ nanoparticles have also attracted considerable attention for their potential applications in technologies such as fabrication of microelectronic circuits, sensors, fuel cells, solar cells, electronics, piezoelectric devices, medicine, pharmaceuticals, cooling, heat transfer and power generation (15–17). The use of oxides in the semiconductor industry is the most active area and generally computer chips are made from oxide compounds.

Intrinsically small thermal conductivity of conventional heat transfer fluids is a primary limitation to developing energy efficient heat transfer fluids for cooling applications. One innovative approach is to suspend low dimensional particles in base fluids to enhance their heat transfer performance (18–20). But micrometre or millimetre sized particles cannot be used in microsystems because they can block microchannels, damage or wear out pumps, pipes or bearings and these particles tend to precipitate. Yu and Choi (21) in 1995 first coined the term ‘nanofluids’: a nanoparticle-liquid dispersion consisting of particles with 1–100 nm size offers new potential for heat transfer fluids. Stable nanofluids are prepared mainly by two techniques: (a) single step technique; and (b) two step technique. In the single step technique, nanoparticles are made and dispersed simultaneously into the base fluids. In the two step technique, nanoparticles are prepared first and then dispersed into base fluids. Most nanofluids containing oxide nanoparticles and carbon nanotubes are produced by the two step method. The nanoparticles are dispersed into liquid using an ultrasonic bath or high power tip ultrasonicator with different sonication time while controlling overheating of the nanofluids. In the present investigation, the two step method of nanofluids synthesis has been used to prepare TiO$_2$-ethylene glycol nanofluids (22, 23). Sound transmission through a medium, such as colloidal suspensions, porous materials, magneto-rheological medium and nanofluids, has also been a subject of great interest in recent years (24). The anomalous behaviour of the ultrasonic velocity in sintered TiO$_2$ nanofluids provides information about the pore size and shape of nanoparticles (25). The most significant application of nanofluids is their use as heat transfer fluids. The main goal of nanofluids is to attain the highest possible value for thermal conductivity at the smallest possible concentrations of nanoparticles (26). There exists a new class of nanofluids having very low heat transfer rate which are used for cooling to maintain the desired performance and reliability of machines, microelectronic devices and optical instruments in the microelectronics and transportation industries (27–29). Nanofluids have been extensively explored for use in many applications. These include cooling a new class of super powerful and small computers and other electronic devices for use in military systems, aeroplanes or spacecraft as well as for large-scale cooling. Al$_2$O$_3$–water nanofluids have been used to maintain a high temperature gradient in thermoelectrics that convert waste heat to useful electrical energy (30). Metal oxide nanoparticle-based nanofluids have been investigated to enhance energy efficiency in a heating, ventilation and air conditioning (HVAC) system to give major environmental benefits (29). Recent development suggests that these nanofluids can be utilised to enhance heat transfer from solar collectors to storage tanks and to increase energy density, making them potential candidates in the renewable energy industry. Other projected applications of nanofluids include sensors and diagnostics that instantly detect chemical warfare agents in water or water- or foodborne contamination. Iron oxide based nanofluids have shown great promise in biomedical applications such as cooling medical devices, cancer treatment and drug delivery (31). One very important application of nanofluids is in heat transfer systems. Assorted studies have been carried out on the heat transfer enhancement of...
nanofluids and an appreciable enhancement has been found in the thermal conductivity correlated to the base fluid. Murshed et al. (13) measured the TCE of nanofluids by dispersing TiO$_2$ nanoparticles in the matrix of ethylene glycol. They observed 18% TCE at 5 vol%. Duangthongsuk et al. (14) have done a similar study in water-based nanofluid by dispersion of TiO$_2$ nanoparticles at 2 vol% and reported 7% TCE. Khedkar et al. (32) measured the TCE in TiO$_2$ nanoparticles with ethylene glycol as base fluid. They reported 19.52% TCE at 7.0 vol% concentration of nanoparticles. Angayarkanni et al. (33) measured the TCE in TiO$_2$ nanoparticles with water as base fluid. They reported 15.1% TCE at 4.0 vol% concentration of nanoparticles. Other metallic oxide nanoparticles have also been used for preparation of nanofluids. Beck et al. (30) determined the thermal conductivity of Al$_2$O$_3$/ethylene glycol nanofluids and reported a maximum TCE of up to 16.3% for 3.0 vol% concentration. Khedkar et al. (34) measured the temperature-dependent enhancement of thermal conductivity in CuO + water with different concentrations. They reported 32.3% TCE at 7.5 wt% concentration. Esfe et al. (35) measured the TCE in MgO nanoparticles with ethylene glycol + water (40:60 wt%) as base fluid. They reported 34.43% TCE at 3.0 vol% concentration of nanoparticles. Li et al. (36) determined the thermal conductivity of ZnO-ethylene glycol nanofluids and they reported the maximum TCE of nanofluid up to 13.0% for 2.4 vol% concentration. Murshed et al. (13) measured the TCE of nanofluids by dispersing CuO nanoparticles in the matrix of ethylene glycol. They observed 21% TCE at 2 vol%. All these measurements have been reported at higher temperature and higher volume fraction.

In the present work, we synthesised TiO$_2$ nanoparticles through the chemical route and characterised by XRD, TEM, SEM-EDX and UV-vis spectroscopy techniques. After synthesis, the TiO$_2$ nanoparticles were suspended in ethylene glycol as carrier fluid with the help of an ultrasonicator with different sonication times and nanoparticle concentrations to prepare TiO$_2$-ethylene glycol nanofluids. The thermal conductivity measurements were performed for 0.2 wt%, 0.5 wt% and 1.0 wt% nanoparticle loaded nanofluids using a TPS-500 S Thermal Constants Analyser (Hot Disk, Sweden). Ultrasonic velocity and particle size distribution (PSD) measurements were done for the ultrasonic characterisation of the prepared nanofluids. The possible mechanisms of enhancement in thermal conductivity, ultrasonic velocity and PSD of nanoparticles in nanofluids are discussed. The reported data and their analysis suggest potential applications in industries associated with heat transfer management.

2. Experimental Details

2.1 Synthesis of Titania Nanoparticles

TiO$_2$ nanoparticles were successfully synthesised by a simple sol-gel method (37) using Ti[(OCH(CH$_3$)$_2$)$_4$, generally referred to as titanium tetra-isopropoxide (TTIP), as a precursor purchased from Sigma-Aldrich Company (USA) with purity of 97%. Titanium(IV) isopropoxide was dropped slowly into the mixed solution of distilled water and ethanol in the ratios of 1:4:1 (TTIP: water: ethanol). The solution was stirred continuously for 1 h at room temperature to obtain a white slurry. HNO$_3$ was used to adjust pH value in the range 2–3. The white slurry mixture was dried at 120°C for 3 h on a hot plate; the dried powder was sintered at 450°C for 3 h. Finally, we obtained the required TiO$_2$ nanoparticles. The flow chart of synthesis of TiO$_2$ nanoparticles is given in Figure 1. The synthesised sample of TiO$_2$ nanoparticles were analysed with XRD pattern using a SmartLab® X-ray diffractometer (Rigaku Corporation, Japan).

![Flow chart showing the synthesis of TiO$_2$ nanoparticles](https://example.com/flowchart.png)
(with $\lambda = 1.5406$ Å Cu$K_\alpha$ radiation) operating at 40 kV, 30 mA and at room temperature. The XRD patterns were used to determine the crystallite size, lattice parameter and phase identification. The structural and morphological analysis of TiO$_2$ nanoparticles were done by HR-TEM and the selected area electron diffraction (SAED) pattern using the model Tecnai$^\text{TM}G^\text{2}$ F30 field emission gun transmission electron microscope (FEI Company, USA) operating at 200 kV accelerating voltage with resolution point: 0.17 Angstrom line: 1.24 Å and magnification 1500 LM to 520 kx. Tescan MAIA3 field emission scanning electron microscope (Tescan, Czech Republic) operating at 12.0 kV and magnification 21.4 Kx was used for SEM-EDX analysis of the morphology and average particle size of the TiO$_2$ nanoparticles. The UV-vis absorption spectrum was recorded using Shimadzu UV-2330 spectrometer (Shimadzu Corporation, Japan) in the range 200–700 nm. The UV-vis spectrum was used to determine direct energy band gap of the TiO$_2$ nanoparticles.

2.2 Preparation of Titania-Ethylene Glycol Nanofluids

TiO$_2$-ethylene glycol nanofluids were prepared at different concentrations, 0.2 wt%, 0.5 wt% and 1.0 wt% of TiO$_2$ nanoparticles. When TiO$_2$ nanoparticles are added to the ethylene glycol base fluid, the nanoparticles produce a sediment within a few minutes because they remain in clusters without being dispersed. For the uniform dispersion of nanoparticles in the base fluid, we used an ultrasonic homogeniser VC 505 (Sonics & Materials Inc, USA) working at 20–40 kHz, 500 W.

3. Results and Discussion

3.1 Structural Analysis

The crystal phases of the synthesised TiO$_2$ nanoparticles were determined by XRD patterns as shown in Figure 2. The obtained peaks in the diffraction pattern are identified with the JCPDS Card No. 88-1175. The interplanar spacing has been calculated using Equation (i):

$$d = \frac{n\lambda}{2\sin\theta}$$

where $\lambda$ represents the wavelength of Cu$K_\alpha$ (1.5406 Å) radiation, $\theta$ is the angle between incident beam and the reflection lattice planes and $n = 1$ is the order of the XRD spectra. The highest peak is observed at $2\theta = 25.4^\circ$ which was indicated to plane (101) and $d$ spacing corresponding to this peak is 3.12 Å. The other peaks in XRD pattern are observed at $2\theta = 27.6^\circ, 37.9^\circ, 48.2^\circ, 54.1^\circ, 55.1^\circ, 62.8^\circ, 69^\circ, 70.4^\circ, 75.1^\circ$ and $82.8^\circ$ correspond to the (110), (004), (200), (105), (211), (002), (116), (112), (215) and (312) planes of TiO$_2$ nanoparticles and $d$ spacing are calculated as 2.83 Å, 2.43 Å, 1.88 Å, 1.69 Å, 1.66 Å, 1.47 Å, 1.35 Å, 1.33 Å, 1.26 Å and 1.16 Å, respectively. The intensity of the obtained peaks indicates the well-formed crystalline nature of the sample. The average crystallite size has been computed with Scherrer’s equation (Equation (ii)) (38):

$$D = \frac{K\lambda}{\beta_{20} \cos\theta}$$

where $\beta_{20}$ represents the full width at half maxima (FWHM) and $K$ is the Scherrer constant. From this formula, the calculated average crystallite size of the given sample is approximately ~23 nm.

3.2 TEM, SEM and EDS/EDX Analysis

The TEM image of a crystalline sample is shown in Figure 3(a). The average particle size of the TiO$_2$ nanoparticles ranged from 20–26 nm as shown in the histogram (Figure 3(b)). The SAED pattern in Figure 3(c) shows principally 10 rings which are ascribed to (101), (110), (103), (004), (111), (200), (105), (211), (002) and (116) planes, respectively. These planes are consistent with the XRD results. The $d$ spacings are in agreement
with the tetragonal structure of TiO$_2$ nanoparticles (JCPDS Card No. 88-1175). For the structural analysis TiO$_2$ nanoparticles were also examined by HR-TEM as shown in Figure 3(d). The crystalline nature of the nanoparticles is visible in the HR-TEM micrograph. The lattice spacing 0.31 nm and 0.28 nm corresponds to (101) and (110) planes respectively. The size and morphology of the TiO$_2$ nanoparticles were also determined using SEM. Figure 4 shows typical SEM images of TiO$_2$ nanoparticles. The SEM image shows random distribution of TiO$_2$ nanoparticles having sizes in the range 18–26 nm. In Figure 4, there is a soft agglomeration of the nanoparticles: isolated particles are connected to each other by attractive physical interactions like Van der Waals force. The agglomeration of nanoparticles in the base fluid probably affects the thermal conductivity performance of the nanofluids. Agglomeration of nanoparticles affects the Brownian motion of the nanoparticles resulting in a decrease in thermal performance of the nanofluids. To remove agglomerations of nanoparticles in the base fluid, a sonication process has been used to break the intermolecular interactions. The EDX spectrum (Figure 5) of the TiO$_2$ nanoparticles provides information about the constituent components of our sample, which contains titanium and oxygen. The high intensity peaks for titanium and oxygen justifies that the sample contains mainly TiO$_2$.

### 3.3 UV-Vis Spectra Analysis

The UV-vis absorption spectrum at room temperature of TiO$_2$ nanoparticles has been recorded in the wavelength range 200–700 nm and is shown in Figure 6(a). It is obvious from the UV-vis absorption spectrum that the peak observed at 315 nm represents a blue shift compared with its bulk counterpart. This indicates that the particle size of the TiO$_2$ nanoparticles has been reduced (38–40). The optical absorption of the TiO$_2$ nanoparticles is analysed by Equation (iii):

$$\alpha \nu = B (\nu - E_g)^m$$  

where $E_g$ represents the optical band gap of nanoparticles, $B$ is a constant, $\alpha$ is the optical absorption coefficient of the nanoparticles. The exponent $m$ depends on the nature of the transition,
\[ m = \frac{1}{2}, 2, \frac{3}{2}, 3 \] for allowed direct, allowed indirect, forbidden direct and forbidden indirect transitions respectively. Figure 6(b) shows the Tauc plot of TiO\(_2\) nanoparticles, a satisfactory fit is obtained for \((\alpha h\nu)^2\) vs. \(h\nu\) indicating the presence of a direct band gap. The optical energy gap of the TiO\(_2\) nanoparticles has been determined as 3.28 eV by extrapolating the linear portion of this plot at \((\alpha h\nu)^2 = 0\).

### 3.4 Thermal Conductivity Measurement

The thermal conductivity of the nanofluids was measured by using a Hot Disk TPS-500 S thermal constant analyser. The Hot Disk TPS-500 S is the newest transient plane source (TPS) thermal constants analyser. The TPS technique has been used to determine the thermal conductivity of a nanofluid. The temperature dependent thermal conductivity of the TiO\(_2\)-ethylene glycol nanofluids is plotted in Figure 7(a) at 0.2 wt%, 0.5 wt% and 1.0 wt%. The results show that the thermal conductivity of TiO\(_2\)-ethylene glycol nanofluids increases with concentration of TiO\(_2\) nanoparticles. The thermal conductivity exhibits a slow increase for 0.2 wt% nanofluids while it shows relatively fast increase for 0.5 wt% and 1.0 wt% nanofluid in the temperature range...
20–80°C. At 20°C, the value of thermal conductivity of pure ethylene glycol is 0.285 W mK⁻¹ and it has been increased to 0.314 W mK⁻¹ for 1.0 wt% concentration of TiO₂ nanoparticles in ethylene glycol base fluid. The expression of TCE is given by Equation (iv) (41):

\[
\text{TCE\%} = \left[ \frac{\text{TC}_{nf} - \text{TC}_{bf}}{\text{TC}_{bf}} \right] \times 100
\]

where \( \text{TC}_{nf} \) and \( \text{TC}_{bf} \) are the thermal conductivity of nanofluid and base fluid respectively.

A number of investigators have developed models for determining the thermal conductivity of nanofluids containing spherical particles. They only consider the effect of volume fraction of the particles. However the thermal conductivity of nanofluids depends on various factors such as size, shape, volume fraction of the suspended particles as well as temperature of suspensions. A few models also propose that the TCE is due to the ordered layering of liquid molecules near the solid particles (42, 43).

In addition to describing the TCE in nanofluids, we consider the effect of three possible mechanisms for heat transfer in nanofluids: (a) translational Brownian motion, (b) the existence of an interparticle potential and (c) convection in the liquid due to the Brownian movement. In the low temperature region, the mean free path due to the collision of nanoparticles increases and leads to TCE due to Brownian particle (\( K_{\text{Brownian}} \)) as given as Equation (v):

\[
K_{\text{Brownian}} = \frac{\phi C_N V_N l}{3}
\]

where \( \phi \) is the volume fraction, \( C_N \) is the heat capacity per unit volume of the nanoparticles, \( l \) is the mean free path and \( V_N \) is root mean square velocity of the particles.

This model explains the individual effect of temperature on the TCE in nanofluids with the help of Brownian motion but does not consider the effect of surface functionality and particle loading of nanoparticles. To overcome the shortcomings of this model, Prasher et al. (44) presents an order-of-magnitude justification to show a local convection effect caused by the Brownian movement of the nanoparticles. Based on the Brownian motion induced convection effect from multiple nanoparticles, the model of Prasher et al. for the TCE ratio of a nanofluid is given in Equation (vi):

\[
\frac{K}{K_r} = \left[ 1 + AR_p^{0.333} \phi \right] \left[ (1 + 2\alpha) + 2\phi (1 - \alpha) \right] (1 + 2\alpha) - \phi (1 - \alpha) \]

where \( K \) is the thermal conductivity of nanofluids, \( K_r \) is the thermal conductivity of fluids, \( A \) and \( m \) are the best fit constants, and should be same for different experimental data for a particular fluid. \( R_p \) and \( P \) are Reynolds and Prandtl numbers respectively (Equation (vii)):

\[
\alpha = 2R_p K_r / d_N
\]

where \( d_N \) is the particle diameter, \( R_p \) is the interfacial resistance (Equation (viii)):

\[
R_p = \frac{1}{V_N} \sqrt{\frac{18k_b T}{\pi \rho_N d_N}}
\]

The Reynolds number \( (R_p) \) is based on the root-mean-square velocity \( (V_N) \) of a Brownian particle defined as Equation (ix) (45, 46):

\[
V_N = \frac{1}{d_N} \sqrt{\frac{18k_b T}{\pi \rho_N d_N}}
\]

where \( \rho_N \) is the density of the particles, \( k_b \) is the Boltzmann constant and \( T \) is the temperature in Kelvin scale.

**Figure 7(b)** shows the variation of the TCE with temperature ranging from 20–80°C. It is clear from **Figure 7(b)** that the enhancement in thermal conductivity of TiO₂-ethylene glycol nanofluids is achieved with increasing concentrations of nanoparticles and temperatures. At 20°C, we observed 3.3% to 6.5% and 11.2% TCE on 0.2 wt%, 0.5 wt% and 1.0 wt%, and at 80°C, the TCE becomes 9.9%, 18.3% and 23.8% for 0.2 wt%, 0.5 wt% and 1.0 wt% respectively for TiO₂-ethylene glycol nanofluids. This enhancement
is due to better uniformity and stability of suspensions. It has been found that ultrasonication increases the stability and uniformity of the nanofluids. The achieved values of TCE are higher than any of the results reported previously for TiO$_2$-ethylene glycol or TiO$_2$-water based nanofluids (13, 14, 30, 31) at such small concentrations. In preparation of the nanofluids, we used very small amounts of nanoparticles, so the fluidic properties of the liquid are almost unaffected, allowing for the easy flow of liquids and better transfer of heat. As the temperature increases, the TCE in the TiO$_2$-ethylene glycol nanofluids may be attributed to Brownian motion of nanoparticles. It is obvious from Equation (ix) that the root-mean-square velocity ($v_N$) of a Brownian particle depends upon particle diameter. If the particle diameter is small, root-mean-square velocity of a Brownian particle is large. Since the synthesised nanoparticles are small in diameter (approximately 22 nm) this results in the increase of Brownian motion, causing convection which in turn increases the thermal conductivity of the nanofluids. The high TCEs are probably due to the small size of nanoparticles because as the particle size decreases, the surface-to-volume ratio of particles increases, which can lead to enhanced thermal conductivity of nanofluids.

3.5 Determination of Ultrasonic Velocity using Interferometric Technique

The ultrasonic velocity in nanofluids was measured using an ultrasonic interferometer (model nanofluid-10X, Mittal Enterprises, India) at 3 MHz frequency in temperature range 20–80°C. The measured ultrasonic velocity in ethylene glycol matrix and three nanofluids samples containing 0.2 wt%, 0.5 wt% and 1.0 wt% of TiO$_2$ in temperature range 20–80°C are shown in Figure 8. It is obvious from Figure 8 that the ultrasonic velocity in the nanofluids increases with the temperature. The plot also indicates that the ultrasonic velocity in the nanofluids is larger than that of pure ethylene glycol matrix (1410 m s$^{-1}$) at 20°C and the velocity increases with the particle concentration (1430 m s$^{-1}$) for 1.0 wt% loading at the same temperature of 20°C.
If we consider \( (\rho_m, \mu) \) and \( (k_m, k) \) are the density and the compressibility of fluid and suspended particles respectively, \( B \) and \( \phi \) are the bulk modulus and the particle volume fraction; then the effective density \( (\rho_{\text{eff}}) \) and compressibility \( (k_{\text{eff}}) \) of the suspension becomes as Equation (x) (47–49):

\[
\rho_{\text{eff}} = \rho_m \phi + \rho_m (1 - \phi) \quad (x)
\]

where \( B, \rho \) and \( k \) represent the bulk modulus, density and compressibility of the medium respectively. \( \lambda \) and \( \mu \) are the material dependent quantities known as Lamé moduli or Lamé coefficients. The compressibility and density of a fluid medium are changed by the dispersion of nanoparticles and are the function of the particle volume fraction.

From Equation (x), it is clear that the evaluation of the effective bulk modulus and compressibility of the suspension is performed with calculation of effective Lamé moduli, which depends on particle volume fraction of suspended particles.

It is obvious from Equations (x) and (xi) that the bulk modulus and change in density of the nanoparticles suspension as a function of volume fraction causes an enhancement in the ultrasonic velocity. An increase in the wave velocity with increase in the particle concentration of given nanofluids indicates that there is positive change in the bulk modulus and density of the nanofluids.

It may be predicted that the comparative change in the density with respect to bulk modulus is small. As the particle concentration in nanofluids increases, the compressibility of the given matrix decreases. A strong cohesive interaction occurs among the molecules after dispersion of TiO\(_2\) nanoparticles in the ethylene glycol matrix. Thus for the TiO\(_2\) nanofluids, the ultrasonic velocities are larger in comparison to the ethylene glycol matrix and increase with the nanoparticle concentration.

In the low frequency region, the velocity in nanofluids is independent of particle size (49, 50). Here all the nanofluids have been prepared with nanoparticles fabricated at low evaporation rate and velocity of the ultrasonic wave is measured at different temperatures and low frequency (3 MHz). Thus it was concluded that the temperature dependent velocity at low frequency in the nanofluids depends only on the particle concentration. At low frequency, the ultrasonic velocity in a nanofluid is a quadratic function of temperature (Equation (xii) (51)):

\[
V = V_0 + V_1 T - V_2 T^2 \quad (xii)
\]

where \( V_0 \) is the ultrasonic velocity at 0°C, \( V_1 \) and \( V_2 \) are the absolute temperature coefficients of velocity and \( T \) is the temperature difference between experimental and initial temperature (0°C). The first and second terms in Equation (xii) are in good agreement for a simple liquid system, but the third nonlinear term is caused by non-linear change in bulk modulus and density of the nanofluid system with temperature.

### 3.6. Particle Size Distribution in Titania+Ethylene Glycol Nanofluid by Acoustical Particle Sizer

The acoustic particle sizer APS-100 (Matec Applied Sciences, USA) was used to examine the PSD in the nanofluids. The APS-100 works on Epstein and Carhart theory (52) and is mainly based on the ultrasonic spectroscopic method. The APS-100 computes the sound attenuation (dB) per unit length (cm) over the 1–100 MHz frequency range in particle-liquid suspensions with high precision. This attenuation spectrum can be converted to PSD data. According to Epstein and Carhart theory (52), the attenuation of the ultrasonic wave in a nanofluid can be understood with the understanding of the thermal wave length \( (\lambda_T = \sqrt{2K_s / (\rho_s C_s \omega)}) \); \( K_s \), \( \rho_s \) and \( C_s \): thermal conductivity, density and specific heat of the dispersed particle; \( \omega \): frequency of the wave) and the viscous wave length \( (\lambda_v = \sqrt{\eta / (\rho_v \omega)}) \); \( \eta \): viscosity of the matrix. When the viscous wave length is comparable to particle radius \( (r) \), the viscous loss is a prominent cause behind the ultrasonic attenuation; while the viscous drag, scattering and thermal losses are effective when the thermal wave length \( \lambda_T \approx r \). The expressions for the ordinary viscous dissipation \( (\alpha_v) \), the viscous drag loss \( (\alpha_{v0}) \) (47, 50) of the sound waves are given as Equation (xiii) and Equation (xiv):

\[
\alpha_v = \frac{\omega^2}{2 \rho_m V} \left( \frac{4}{3} \eta_d + \eta_v \right) \quad (xiii)
\]

\[
\alpha_{v0} = 18 \bar{\kappa} \phi (1 - \delta)^2 \left[ \frac{y^2 (1 + y)}{(2y^2 + 6 + 9y\delta)^2} \right] \quad (xiv)
\]

where \( \eta_d \) and \( \eta_v \) represent the dynamic and the volume viscosities of the nanofluid, \( \bar{\kappa} \) is the
wave number, \( \delta = \rho_{m}/\rho_{s} \), \( \gamma = \omega \sqrt{\eta/2n_{d}} \). Biwa (53) calculated the change in the ultrasonic attenuation with respect to volume fraction caused by scattering at microscale in low frequency limit. The expression to compute the ultrasonic attenuation is given as Equation (xv) (53):

\[
\frac{d\alpha}{d\phi} = -\alpha + \frac{\gamma_{sca}}{(8/3)\pi r^2}
\]

where \( \gamma_{sca} \) represents the scattering cross-section which depends on the frequency of the ultrasonic wave, particle size, bulk modulus and density of the base/carrier fluid and suspended particles. The thermal attenuation is caused by temperature variation produced by propagation of the sound waves in different components of suspension. The thermal loss mainly depends on the frequency and particle size. The particle size has been obtained by APS-100 in range of 19 nm to 24 nm as visualised in Figure 9. It has been confirmed from Figures 3(a) and 9 that the PSD obtained by APS-100 is in good agreement with that obtained by the TEM micrograph. Ultrasonic spectroscopy is sensitive to particles with radius between about 10 nm to 1000 nm. The maximum particle concentration which can be analysed varies between about 1 wt% to 50 wt% depending on the nature of the system. On the other hand, the technique is unsuitable for analysing dilute suspensions i.e., particle concentrations below about 1 wt%. In the present study (Figure 9) the weight percentage of TiO\(_2\) is 1 wt%. Systems with different weight percentages of TiO\(_2\) show the same PSD because nanoparticles are dispersed in base fluid with the same technique and the same ultrasonication time.

4. Conclusions

In this investigation, we have successfully synthesised TiO\(_2\) nanoparticles by a simple sol-gel method. The structural and morphological characterisation of synthesised TiO\(_2\) nanoparticles was performed by XRD and HR-TEM. The average crystal size was found to be \( \sim 23 \) nm using Scherrer’s formula. The average particle size was observed by TEM micrograph and found to be in the range 20–26 nm. The optical energy gap of the TiO\(_2\) nanoparticles was determined using Tauc plot and found to be 3.28 eV. Ultrasonic spectroscopy was used to determine the size of the nanoparticles and their distribution in the matrix was established. The results were in good agreement with the more costly TEM method. TPS was used to measure the thermal conductivity of the TiO\(_2\)+ethylene glycol nanofluids. The thermal conductivity of nanofluids increases with increase in temperature as well as particle loading. TCE of 24% was observed for 1.0 wt% loading of TiO\(_2\) nanoparticles at 80°C. Thermal conductivity data are very important for advanced heat transfer management systems in many industrial applications. The temperature and concentration dependence of the ultrasonic velocity in nanofluids was also measured. The ultrasonic velocity in nanofluids mainly depends on the particle loadings.

Thus, the anomalous enhancement of the thermal conductivity of nanofluids can be used in coolant technology and in heat transfer management systems. Ultrasonic techniques are an efficient tool to characterise nanofluids, providing useful information about the emerging properties of exotic materials like nanofluids along with their microstructural features.

References

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