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ORIGINAL ARTICLE

Effect of dispersion behavior on the heat transfer characteristics of alumina nanofluid: an experimental investigation and development of a new correlation function

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Abstract

Present work aims to study the dispersion characteristics of Al_2O_3 nano-dispersoid in water following different periods of ultrasonication and its impact on the thermal conductivity and viscosity of the nanofluid. Nanofluids with 0.5–2 vol% of Al_2O_3 nanoparticles have been prepared by ultrasonication for varying period. Al_2O_3 nanofluids reported a maximum thermal conductivity enhancement of 16.1% for 2 vol% of nanoparticle concentration, after an optimum ultrasonication of 2 h beyond which the thermal conductivity decreases with further ultrasonication. The optimum ultrasonication time required for uniform dispersion of nanoparticles increases with the increase in the Al_2O_3 volume fraction. For 1.5 vol% Al_2O_3 nanoparticle loading, the viscosity of nanofluid decreased by 33% with an increase in the sonication time from 30 to 90 min. Further increase in sonication time by 30 min resulted in 13% increase in the viscosity of Al_2O_3 nanofluid. This decrease in the thermal conductivity enhancement and increase in the viscosity beyond the optimum ultrasonication period have been attributed to the re-agglomeration of nanoparticles which are confirmed by TEM, and DLS results carried out after different instants of ultrasonication. The occurrence of re-agglomeration is explained in terms of the convective flow associated with the ultrasonication process. Various theoretical models like Maxwell or Hamilton–Crosser models which when used to predict the thermal conductivity of nanofluid, underestimate the thermal conductivity. A new correlation is, therefore, developed on the basis of experimental results. With an R^2 value of 0.9924, the correlation showed a good agreement with the present thermal conductivity data.

Keywords Nanofluids · Agglomeration · Thermal conductivity · Ultrasonication · Alumina nanoparticles · Viscosity

List of symbols

a	Thermal diffusivity, m^2/s
C	Euler's constant
c	Slope of the linear section of the plot ΔT (r, t) vs ln (t)
k	Thermal conductivity, W/m K
n	No. of readings
q	Constant heat produced per unit time and per unit length, J/m s
r	Diameter of platinum wire, m
s	Standard deviation
t	Time, s
u	Uncertainty
W	Mass, kg
ΔT	Temperature rise over the platinum wire, K

Greek letters

ρ	Density, kg/m^3
ϕ	Volume fraction, %
λ	Wavelength, Å

Subscripts

bf	Base fluid
nf	Nanofluid

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Introduction

There is an ever-increasing demand for faster heat dissipation in modern equipments such as computers, power electronics, high powered lasers, X-rays, etc., to maintain the desired level of performance. Hence, the idea of enhancement of heat transfer in industrial applications has led the researchers to look for an alternative cooling fluid or an alternative means of faster heat dissipation. While working at Argonne National Laboratory in 1995, Choi et al. [1] came up with a different fluid called nanofluid. It is a suspension of nanoparticles of a few nanometer (< 100 nm) in the base fluid (e.g. ethylene glycol, water, etc.). Following the pioneer work of Choi et al. [1], many researchers around the world have explored the field of nanofluid for different applications. Several types of nanoparticles have been reported in the literature to prepare nanofluids, which include metallic nanoparticles (Cu [2], Ag [3], and Au [4]), nonmetallic particles (Al_2O_3 [5], TiO_2 [6], SiC [7], Fe_3O_4 [8], and AlN [9], BN [10]), and different particle morphologies such as carbon nanotubes [11], nanorods [12], etc. Alumina (Al_2O_3) comes under the commonly used nanoparticles in different experimental research works for dispersion in already available conventional base fluids. On the theoretical front, significant research has been carried out to understand the dispersion behavior of the nanoparticles in the base fluids such as the instantaneous interactions taking place amid nanoparticles and base fluid molecules [13, 14], the effects of local nanoparticle concentration and particle velocity [15–19]

Having a stable nanofluid with uniform dispersion is of utmost priority for all industrial applications. Different methods such as adding surfactants, applying ultrasonic vibration, etc. are implemented to achieve the maximum stability of nanofluids. The use of both the methods are observed in many works. Several researchers have studied the effect of sonication by varying its different parameters for attaining better dispersion of nanoparticles in the nanofluid [20–26]. The thermo-physical properties and stability were found to be dependent on parameters like sonication time, sonication energy, etc., to which the nanofluids have been subjected to during synthesis. Garg et al. [27] reported a twofold effect of ultrasonication time on the MWCNT nanofluids. Here, ultrasonication for 40 min was found to be optimum for achieving a better dispersion. However, ultrasonication beyond this period led to the breakage of the nanotubes thereby reducing the aspect ratio of CNTs. Also, ultrasonication beyond the optimum duration resulted in a negative influence on the maximum enhancement in thermal conductivity. Nguyen et al. [28] after studying the effect of ultrasonication time on the dispersion stability of alumina nanofluids suggested that prolonged ultrasonication does not lead to a significant reduction in particle rather it manifested a tendency of re-agglomeration. EG-based MWCNT nanofluids were investigated by Ruan et al. [29]. They reported an increase in thermal conductivity with increase in sonication time. The breakage of agglomerates with increasing sonication time was considered to be the main reason for the thermal conductivity improvement. Also, an initial increase in the viscosity is observed which later decreases with further sonication time approaching the viscosity of base fluid. Yet another study by Sonawane et al. [30] showed the optimum sonication period of 60 min was able to attain maximum thermal conductivity enhancement for TiO_2-based nanofluids, but it started decreasing with further ultrasonication. It was proposed that beyond the optimum ultrasonication time a decrease in the effective surface area to volume ratio took place, which caused a reduction in the effective heat transfer area of nanoparticles. Asadi et al. [31] used $Mg(OH)_2$ nanofluids to study the effects of sonication time on its thermal conductivity. They observed a fall in the relative thermal conductivity with increasing sonication time, which was more prominent at higher nanoparticle loading. A further detailed study on finding the optimal sonication period for nanofluids was recommended. Li et al. [32], found in their work on Cu nanofluids, that higher sonication time and temperature tend to increase the Brownian motion causing the larger clusters to collapse. Eventually, it led to a decrease in the viscosity of nanofluids. Buonomo et al. [33] pointed out that sonication time and energy are important factors in determining the maximum limit of thermal conductivity increase of alumina nanofluids. A simple method was also proposed to estimate the minimum required sonication time to yield a stable nanofluid. Chen et al. [34] examined the thermal conductivity of paraffin based Al_2O_3 nanofluids at different time intervals of stirring and sonication. They concluded that prolonging the sonication time initially increased then decreased the thermal conductivity. An optimum sonication and stirring time were determined on the basis of maximum thermal conductivity attained. Similar conclusions were also drawn by Shahsavar et al. [35], who used water-based Fe_3O_4/CNT hybrid nanofluids to study the sonication effects on its thermal conductivity. Xian et al. [36] obtained a better dispersion of graphene nanoplatelets–TiO_2 (GnP–TiO_2) hybrid nanoparticles in water-ethylene glycol mixture after only 90 min of sonication using cetyltrimethylammonium bromide (CTAB) as a surfactant. From aforesaid, it can be understood that, although the ultrasonication period is one of the important factors, its effect on the thermo-physical properties colloidal needs further investigation.

The present study, therefore, explores the effects of the sonication period on the dispersion behavior and heat transfer characteristics of aqueous Al_2O_3 nanofluids. The

experimental results are also compared with the literature and a possible explanation has been provided on the basis of experimental results. Moreover, a new correlation function for thermal conductivity with the volume fraction of dispersoid has been reported.

Experimental procedure

Materials

Al_2O_3 nanoparticles of average particle size 13 nm were procured from Sigma Aldrich. Polyvinylpyrrolidone (PVP) (MW: 40,000) was also obtained from the Sigma Aldrich company for use as a surfactant during the synthesis of the nanofluid. Distilled water was used as the base fluid in the synthesis of nanofluids.

Nanofluid synthesis

Water-based Al_2O_3 nanofluids have been synthesized using the two-step method. Although the two-step synthesis method of nanofluids has the advantages of being low cost and easily scalable, it does suffer from poor stability. Due to the very high surface area of nanoparticles, agglomeration takes place at a fast rate during the dispersion stage. Hence, the addition of a suitable surfactant and ultrasonication process [25] have been employed to improve the stability by de-agglomerating the nanoparticles in the base fluid. Based on the literature available on water-based Al_2O_3 nanofluids, surfactants like CTAB [37], SDS [38] SDBS [39], and PVP [40] have been used to maintain the stability. For water-based Al_2O_3 nanofluids, PVP is the widely used polymeric dispersant because of its higher stability when compared to other surfactants [5, 41]. The long polymer chains help to interact with the nanoparticle and restrict the formation of aggregates, thereby leading to a stable and more uniformly dispersed nanofluid. Furthermore, PVP can also be used at higher temperatures making it a suitable choice for high temperature applications.

Desired amounts of Al_2O_3 nanopowder, calculated using Eq. (1) were initially mixed in the base fluid and stirred by a magnetic stirrer for 1 h, which is followed by sonication for 3 h [29]. Ultrasonication was carried out with a probe type ultrasonic processor (SONOPROS PR-1000MP) having a frequency of 20 ± 3 kHz and power of 1000 W using the OSCAR ULTRASONICS equipment. To avoid excess heat generation during the sonication, a water bath is maintained at 27 °C and replaced at regular intervals with fresh water. The as-prepared Al_2O_3 nanofluid is kept aside for around 20 min to attain a steady state and equilibrium condition. For the thermal conductivity and viscosity measurements, required volume of nanofluid is collected from top section of nanofluid. Here,

$$\phi = \frac{\left(\frac{w_{Al_2O_3}}{\rho_{Al_2O_3}}\right)}{\left(\frac{w_{Al_2O_3}}{\rho_{Al_2O_3}} + \frac{w_{bf}}{\rho_{bf}}\right)} \times 100, \quad (1)$$

where $w_{Al_2O_3}$ and w_{bf} denote the weight of Al_2O_3 nanoparticles and base fluid in g; $\rho_{Al_2O_3}$ and ρ_{bf} are the density of Al_2O_3 nanoparticles and base fluid in g/cm^3.

Characterization of nanofluids

The nanofluids of Al_2O_3 dispersoids have been characterized by different methods. The Al_2O_3 nanoparticles were characterized by Advance X-Ray Diffractometer (BRUKER D8, Germany) using Cu-Kα radiation (wavelength, $\lambda = 1.54$ Å). The powder sample for this analysis is placed on a Perspex slide in a groove of 1–2 mm depth and 10 mm × 10 mm area. The diffraction angle covered was 20°–80° at a scan speed of 0.05°. The phases present in the powder, have been identified by correlating the XRD spectrum with the XRD data compiled by International Center for Diffraction Data (ICDD). Philips X'pert High score Plus software has been used to identify the phases that are present in the diffraction pattern. Particle size and morphology of Al_2O_3 nanoparticles have been obtained from the bright field images of the powder particles observed by a JEOL JEM 2100 (JEOL, Japan) transmission electron microscope (TEM). It was operated at an accelerating voltage of 200 kV. A minute drop of the nanofluid is placed on a carbon coated copper grid of 3 mm size, which is later dried at room temperature. Using Zetasizer Nano ZS apparatus (Malvern instrument, UK) that operates on dynamic light scattering (DLS) principle, the particle size distribution of Al_2O_3 in the nanofluids is determined. A monochromatic light (laser) is incident onto the sample, and the light is scattered in all directions when it hits the nanoparticles undergoing Brownian motion in the fluid. The random changes in the intensity of the scattered light have been analyzed to calculate the size distribution of the dispersoids. All the measurements were done at 27 °C, and the time required for each measurement is 2 min. Viscosity measurements were performed using Physica MCR 101 rheometer (Anton Paar, Graz, Austria). Peltier system (P-PTD 200) at the lower plate was used for achieving constant temperature. A nanofluid sample of 20 ml was used for each viscosity measurements. The thermal conductivity of Al_2O_3 nanofluids have been measured using LAMBDA (Flucon fluid control GmbH, Germany) apparatus which works on the transient hot-wire (THW) principle. A Teflon-coated platinum wire (diameter = 100 µm) serves here as a temperature sensor and a heating element. A cylindrical

shaped vial of length 90 mm and diameter 35 mm holds the nanofluid sample in which the platinum wire is immersed. The platinum wire is initially maintained at thermal equilibrium with its surrounding fluid. A voltage applied to the wire induces an electrical current flow through it which heats the fluid. The thermal conductivity is then calculated based on the transient temperature rise in the fluid, in a given time interval. The mathematical model that defines the temperature rise $\Delta T\,(r, t)$ over the platinum wire [42]:

$$\Delta T(r,t) = \frac{q}{4\pi k}\ln\frac{4at}{r^2C}, \tag{2}$$

where r is the diameter of the wire; q is constant heat produced per unit time and per unit length; a is the thermal diffusivity; C is the Euler's constant. The thermal conductivity (k) is then calculated from the slope (c) of the linear section of the plot $\Delta T\,(r, t)$ vs ln (t).

$$k = \frac{q}{4\pi c}. \tag{3}$$

For every thermal conductivity measurement, a total of ten readings were recorded. The uncertainty (u) was estimated using the mean and standard deviation (s) calculated from the set of measured thermal conductivity data using the following equation:

$$u = \frac{s}{\sqrt{n}}, \tag{4}$$

where n = total number of readings. The uncertainty was found to be well within 3%.

Table 1 gives a detailed summary of the experimental conditions used in the present study.

Results and discussion

Figure 1 shows the XRD pattern of Al_2O_3 nanoparticles recorded in the range between 20° and 80°. The observed peaks in Fig. 1 correspond to the γ-Al_2O_3 phase which is in conformity with the JCPDS-ICDD data file no. 290063. The average crystallite size of the γ-Al_2O_3 calculated by the modified Williamson–Hall method [42] was ~ 7 nm.

To obtain an insight into the effect of ultrasonication time on the thermal conductivity of Al_2O_3 nanofluids, the thermal conductivity has been measured at different ultrasonication periods using the transient hot-wire method. Figure 2a shows the thermal conductivity improvement of Al_2O_3 nanofluids

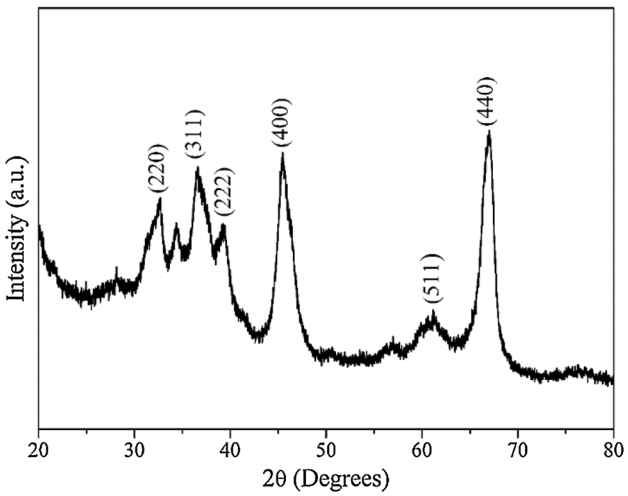

Fig. 1 XRD patterns of Al_2O_3 nanoparticles

Table 1 Experimental conditions used for the synthesis and characterization of nanofluids

S. no	Characterization techniques	Experimental conditions
1	Nanofluid properties	Density of Al_2O_3 nanoparticles 3.9 g/cm^3
		Average size of Al_2O_3 nanoparticles: 13 nm
		Density of water (base fluid): 997 kg/m^3
		Viscosity of water (base fluid): 0.861 mPa s
2	Thermal conductivity measurements	Ultrasonication period: 30–150 min
		Al_2O_3 concentration: 0.5–2 vol%
		Room temperature (~ 27 °C)
3	Viscosity measurements	Ultrasonication period: 30–120 min
		Al_2O_3 concentration: 1.5 vol%
		Shear rate range: 0–122/s
		Room temperature (~ 27 °C)
4	HR-TEM analysis	Ultrasonication period: 0, 90 min, 150 min
		Al_2O_3 concentration: 1.5 vol%
5	DLS analysis	Ultrasonication period: 30–120 min
		Al_2O_3 concentration: 1.5 vol%
		Room temperature (~ 27 °C)

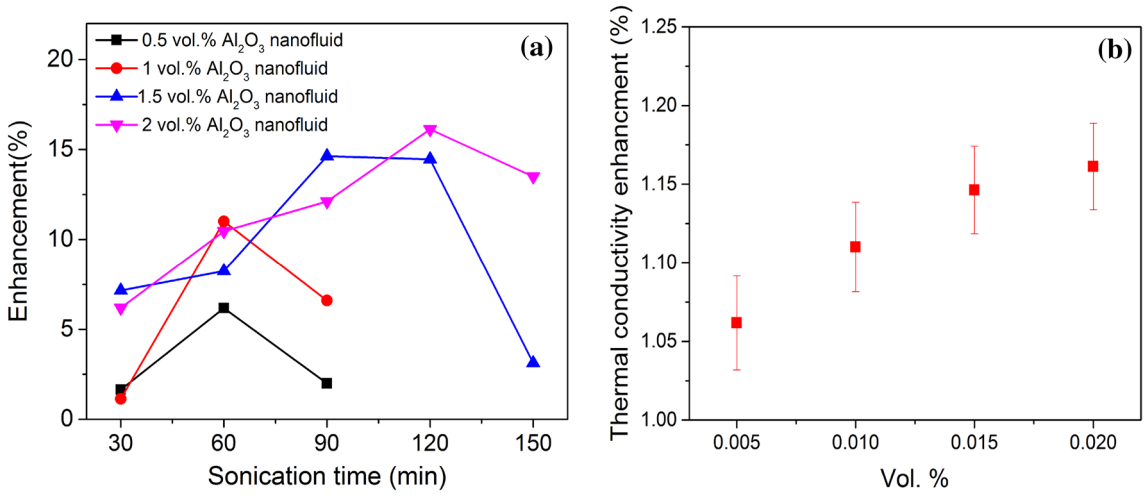

Fig. 2 Effect of **a** sonication time, and **b** volume concentration on the thermal conductivity enhancement of Al_2O_3 nanofluids

containing 0.5–2 vol% of Al_2O_3 with increasing ultrasonication time. In case of 0.5 vol% Al_2O_3 nanofluid, the thermal conductivity shows an improvement of 6.2% after 60 min of ultrasonication, but when the fluid is subjected to further sonication, the thermal conductivity enhancement deteriorated. A similar trend has also been observed for other particle concentrations of Al_2O_3 in the nanofluids. Moreover, it is also clear that with the increase in volume fraction of Al_2O_3 in the nanofluids, the ultrasonication time required for uniform distribution of nanoparticles to yield the maximum increment in thermal conductivity increases. For example, 2 vol% Al_2O_3 in nanofluid takes 120 min of sonication to obtain a 16.1% thermal conductivity enhancement, while for a lower concentration of Al_2O_3 like 1.5 vol%, the highest thermal conductivity enhancement is achieved after sonication for only 90 min. A similar phenomenon has been reported by other researchers [27, 30]. Figure 2b shows the maximum thermal conductivity enhancement of Al_2O_3 nanofluid attained for each Al_2O_3 volume concentration.

To further investigate why this kind of behavior of the thermal conductivity of Al_2O_3 nanofluids is manifested, the HR-TEM studies have been performed. 1.5 vol% Al_2O_3 nanofluid has been used for this purpose, which is then further diluted to get the desired concentration required for TEM studies. Figure 3 shows the TEM images of Al_2O_3 nanofluids at different instants of ultrasonication. It shows that with the increase in ultrasonication time homogenous dispersion is achieved after 90 min, and later the nano-Al_2O_3 starts re-agglomerating with further ultrasonication. A careful look reveals less clustering after 90 min of ultrasonication (Fig. 3b). These results can be related to the reduction in thermal conductivity enhancement as observed in Fig. 2a. Li et al. [32] also reported similar results for nano-CuO dispersion in EG-based nanofluids. They stated that the coalescing

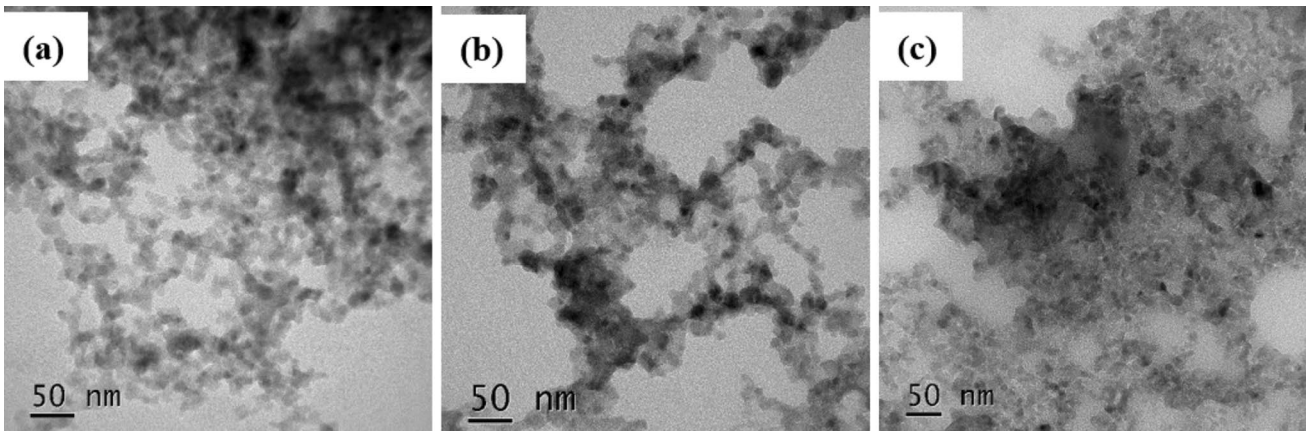

Fig. 3 TEM images of Al_2O_3 nanofluids after **a** 0 min, **b** 90 min, **c** 150 min of ultrasonication

of nanoparticles due to their high surface energy had led to the formation of bigger clusters after longer ultrasonication times. These big clusters might be the reason for the decrease in thermal conductivity after longer ultrasonication.

DLS analysis has been performed to confirm the re-agglomeration of Al_2O_3 nanoparticles in water beyond an optimum ultrasonication time. A similar concentration of Al_2O_3 nanofluid used for TEM analysis has been used for conducting the DLS study. Figure 4 shows the particle size distribution of Al_2O_3 nanofluid measured at a constant interval of 30 min up to a total of 120 min of ultrasonication time. The initial 30 min of ultrasonication on the Al_2O_3 nanofluids gives a particle size distribution in the range of 68– 255 nm. The particle size distribution shows a shift towards the left i.e., lower particle size range with increasing ultrasonication period. After 90 min of ultrasonication, Al_2O_3 manifests a bimodal distribution with the first and second peak in the range 50–90 nm and 164–342 nm, respectively. The higher intensity for the second peaks is mainly due to the scattering intensity measured during DLS measurement being proportional to $\sim r^6$ (r is the radius of the dispersed particle). Thus, even a slight presence of larger aggregate results in higher intensity. Finally, at 120 min, a wider range in the particle size distribution towards the higher particle size is observed (Fig. 4). The DLS confirms the re-agglomeration of Al_2O_3 nanoparticles during extended ultrasonication, and these results are in confirmity with the TEM data.

To gain an insight into the effect of sonication time on the dispersion behavior of Al_2O_3 nanoparticles in water, the viscosity measurements have been carried out on 1.5 vol% Al_2O_3 nanofluid over shear rates varying from 0 to 122/s. Figure 5 shows the viscosity of 1.5 vol% Al_2O_3 nanofluids measured at increasing ultrasonication periods from 30 to

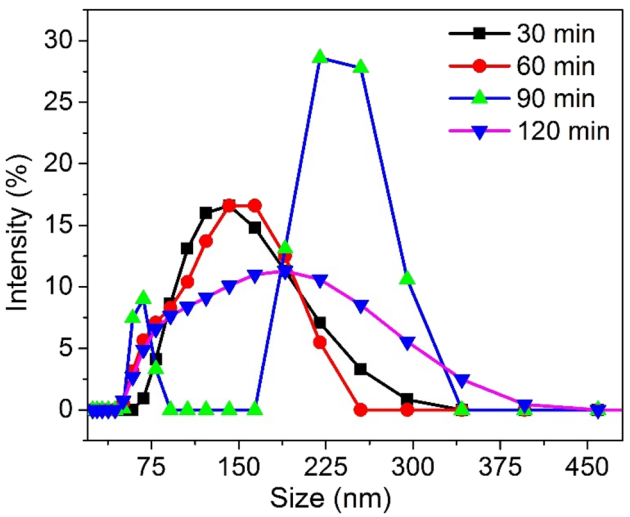

Fig. 4 DLS analysis of nanofluids as a function of ultrasonication time

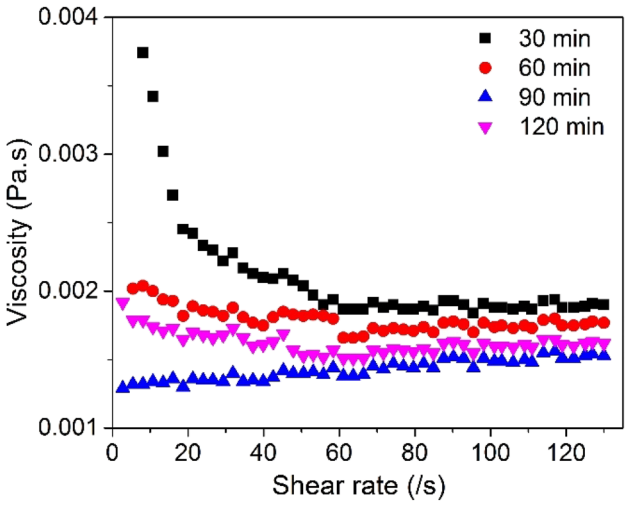

Fig. 5 Viscosity vs. shear rate of Al_2O_3 nanofluid measured at different ultrasonication times

120 min and at a temperature of 27 °C. It is clear from Fig. 5 that the viscosity of the nanofluid reduces with an increase in the ultrasonication time from 30 to 90 min. With further increase in the ultrasonication time, the viscosity increases as also observed in other works [43–46]. This can also be explained by the TEM images shown in Fig. 3. From the TEM images, it is clear that a homogeneous dispersion is achieved at 90 min of ultrasonication. The Al_2O_3 nanoparticle cluster splits into smaller particles due to the additional ultrasonic energy as the sonication time increases from 0 to 90 min. Such smaller particles offer less resistance to flow in nanofluids, which results in low viscosity. These smaller particles tend to re-agglomerate because of high surface energy, with further increase in sonication time. Due to re-agglomeration, more force is required for the nanoparticle to overcome the flow resistance, thus resulting higher viscosity. Precisely, the viscosity of the nanofluid decreases significantly by 33% with an increase in the sonication time from 30 to 90 min. However, further extension of sonication by 30 min causes the viscosity of Al_2O_3 nanofluid to increase by 13%. Therefore, it can be said that for a 1.5 vol% Al_2O_3 nanoparticles, an optimum sonication period of 90 min will achieve uniform dispersion and thereby better stability.

A possible explanation for the observed variation in the particle size distribution, thermal conductivity, and viscosity with ultrasonication time can be put forward as follows: the process of ultrasonication not only involves deagglomeration in the close vicinity of the ultrasonication probe, but also a convective flow of the nanofluid which brings agglomerated clusters closer to the probe as depicted in Fig. 6.

It is well known that the viscosity of nanofluid greatly depends on the average particle size of the dispersed nanoparticles [47–50]. With the increase in the sonication time,

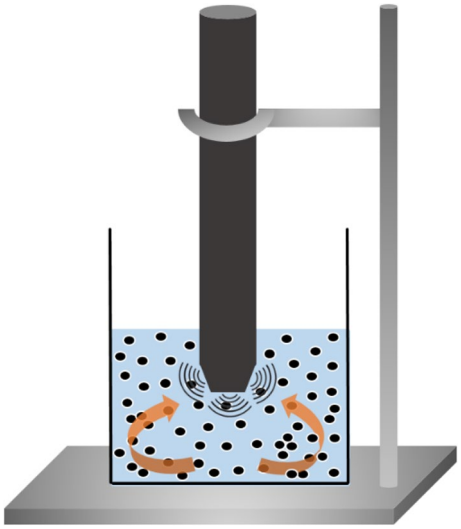

Fig. 6 Schematic representation of Al_2O_3 nanofluid

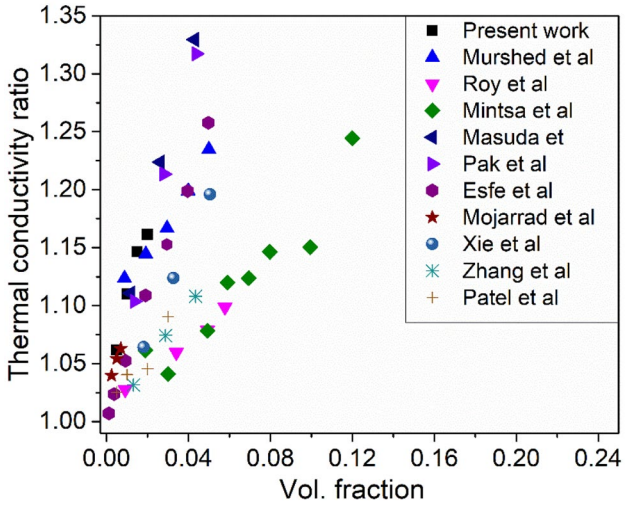

Fig. 7 Experimental thermal conductivity of Al_2O_3 nanofluid in comparison with results reported in the literature

the state of agglomeration and the average particle size decreases significantly, thereby decreasing the viscosity [27, 29, 51]. But beyond an optimum ultrasonication period, viscosity is observed to increase as shown in Fig. 5. This increase in the viscosity is expected to obstruct the convective flow during the ultrasonication and keep away from the probe a substantial portion of the nanofluid. This portion of nanoparticles which remains away from the probe is where re-agglomeration is likely to occur, resulting in an increase in the average particle size which ultimately leads to a decrease in the thermal conductivity of the nanofluid.

Comparison of present experimental results with literature

Results of different researchers [37, 52–60] on water-based Al_2O_3 nanofluids have been compiled and compared with the present experimental results in Fig. 7. From Fig. 7, it is evident that the thermal conductivity enhancement of the nanofluids increases with the increase in volume fraction of nano-Al_2O_3. The following points emerge from the comparison with the present experimental results.

- A simple two-step method for the synthesis of nanofluids was adopted by the majority of researchers and the THW technique was used for measuring the thermal conductivity of Al_2O_3 nanofluids.
- It is observed that the results of Masuda et al. [60], Pak et al. [55], and Mojarrad et al. [54] closely follow the present experimental results. The nanoparticle size used by them was in the range of 13–30 nm, which is closer to the size of the nanoparticles used in the present study. It is evident that in the case of Esfe et al. [53], the use of very small size (5 nm) Al_2O_3 nanoparticles did not result in higher thermal conductivity enhancement when compared with others. This might be due to the phonon scattering taking place because of the very small size of Al_2O_3 nanoparticles leading to the reduced thermal conductivity of the nanoparticle resulting in a decrease in the effective thermal conductivity of nanofluids [61]. Moreover, using very small sized nanoparticles increases the probability of aggregation due to increased Van der Waals force, which further reduces the thermal conductivity of nanofluids.
- The other set of researchers like Patel et al. [56], Xie et al. [57], Mintsa et al. [58] have used Al_2O_3 nanoparticles of comparatively bigger size like 150 nm, 47 nm, and 60.4 nm, respectively. The decreased surface area, as well as, the Brownian velocity for such larger nanoparticles, might be the reason for the decreased thermal conductivity [62].
- Although the basic synthesis procedure (two-step method) was similar for all the works, other detailed factors like techniques used for achieving the stability vis., sonication period, sonication power, etc. varied from one researcher to the other.

Proposed correlation

The thermal conductivity of Al_2O_3 nanofluids of present work has been compared with the results from other theoretical models such as Maxwell [63], Hamilton–Crosser [64] Mintsa [58], Timofeeva [65], Buongiorno [66], and Maiga [67] in Fig. 8a. From the observations of Fig. 8a, it is clear that these models underestimate the experimental thermal

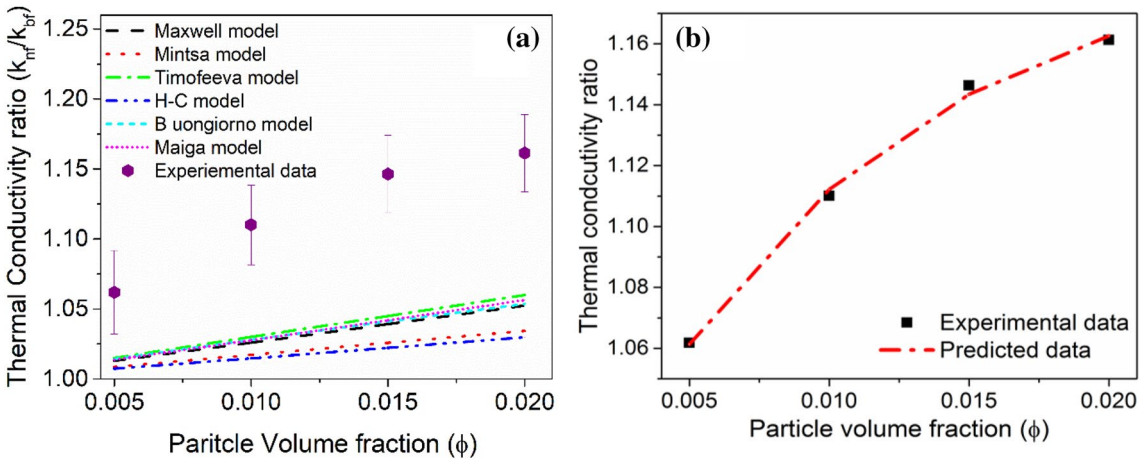

Fig. 8 Comparison of experimental thermal conductivity of Al_2O_3 nanofluid with **a** the existing models and **b** with the proposed correlation function

conductivity results. Some possible explanation may be put forward, e.g., H–C model does not consider different factors such as the effect of Brownian motion, particle size, nanolayer formation, particle clustering, etc., which play significant role in enhancing the effective thermal conductivity of nanofluids. Different researchers such as Chen et al. [68], Das et al. [69], and Mushed et al. [70] have suggested a similar outcome and have gone ahead and proposed new models and correlations. As shown in the figure below, even after considering the uncertainty of ~ ±3% (as shown by error bar) to the measured thermal conductivity, it is observed that the deviation of the measured thermal conductivity from the predictions of H–C and other models is significant.

Hence, a new correlation is proposed to estimate the thermal conductivity of Al_2O_3 nanofluids for different volume fractions. This correlation (Eq. (5)), developed by the curve fitting method can estimate the thermal conductivity with an R^2 value of 0.9924. The thermal conductivity estimated from the proposed correlation and the present experimental results are shown in Fig. 8b.

$$\text{Thermal conductivity ratio } = 1.1931 - 0.2146e^{\left(-\frac{\varphi}{0.01025}\right)}, \tag{5}$$

where φ is the volume fraction of nanoparticles in the nanofluid.

Conclusion

The present work aims to analyze the effect of ultrasonication period on the thermal conductivity and viscosity of aqueous Al_2O_3 nanofluids. Al_2O_3 nanofluids having particle concentrations varying from 0.5 to 2 vol% have been synthesized using a two-step method. Following conclusions are drawn based on the present results:

- Thermal conductivity enhancement of Al_2O_3 dispersed aqueous nanofluids having 0.5–2 vol% nanoparticles is measured after ultrasonication for 30–150 min showed an increasing thermal conductivity up to an optimum period of ultrasonication beyond which it shows a decline. The maximum thermal conductivity enhancement of 14.6% is attained for 1.5 vol% Al_2O_3 after ultrasonication for 90 min apparently due to the uniform dispersion of Al_2O_3 nanoparticles in water.
- The optimum ultrasonication time for attainting maximum thermal conductivity enhancement increased with increasing particle concentration.
- With increase in the ultrasonication time beyond an optimum period, the particle size distribution begins to shift towards the higher particle size range which indicates re-agglomeration of nanoparticles taking place during prolong ultrasonication.
- HR-TEM analysis reveals this re-agglomeration of Al_2O_3 nanoparticles beyond the optimum ultrasonication period.
- The viscosity of 1.5 vol% aqueous Al_2O_3 nanofluids measured over shear rates 0–122/s at fixed time intervals (30 min) decreases by 33% with the increase in ultrasonication time from 30 to 90 min. However, with a further increase in the ultrasonication time, the viscosity shows an increase.
- Re agglomeration occurs apparently due to the hindrance to convective flow caused by increase in viscosity after extended ultrasonication. This in turn leads to reduced thermal conductivity enhancement.
- A new correlation function has been proposed to predict the thermal conductivity of Al_2O_3 nanofluids with an R^2

value of 0.9924. The proposed correlation showed good agreement with the measured thermal conductivity data.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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