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A comprehensive review

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Effect of sonication characteristics on stability, thermophysical properties, and heat transfer of nanofluids: A comprehensive review

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ABSTRACT

The most crucial step towards conducting experimental studies on thermophysical properties and heat transfer of nanofluids is, undoubtedly, the preparation step. It is known that good dispersion of nanoparticles into the base fluids leads to having long-time stable nanofluids, which result in having higher thermal conductivity enhancement and lower viscosity increase. Ultrasonic treatment is one of the most effective techniques to break down the large clusters of nanoparticles into the smaller clusters or even individual nanoparticles.

The present review aims to summarize the recently published literature on the effects of various ultrasonication parameters on stability and thermal properties of various nanofluids. The most common methods to characterize the dispersion quality and stability of the nanofluids have been presented and discussed. It is found that increasing the ultrasonication time and power results in having more dispersed and stable nanofluids. Moreover, increasing the ultrasonication time and power leads to having higher thermal conductivity and heat transfer enhancement, lower viscosity increase, and lower pressure drop. However, there are some exceptional cases in which increasing the ultrasonication time and power deteriorated the stability and thermophysical properties of some nanofluids. It is also found that employing the ultrasonic horn/probe devices are much more effective than ultrasonic bath devices; lower ultrasonication time and power leads to better results.

1. Introduction

Historically, the concept of dispersing the nano-sized particles in conventional fluids, such as water, ethylene glycol (EG), oil, glycerol, and so forth, to achieve better thermal properties has been introduced by Choi and Eastman [1] at the annual meeting of the American Society of Mechanical Engineers (ASME) in 1995. After that, many researchers tried to improve the understanding of mechanisms, which leads to improving the thermophysical properties and heat transfer performance of nanofluids [2–4]. Moreover, researchers tried to characterize different properties of various combinations of nanoparticles into different base fluids; viscosity [5,6], thermal conductivity [7,8], heat transfer efficiency [9–11] and employing the artificial neural networks (ANN) to predict the thermophysical properties of nanofluids [12–14].

Dispersing the nano-sized particles in conventional working fluids has numerous advantages compared to dispersing the millimeter- and

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micrometer-sized particles such as better dispersion stability, higher thermal conductivity, lower viscosity, lower pressure drop, and lower erosion [15]. These advantages will be achieved if the nano-suspension possesses excellent stability. It is known that suspensions with poor stability even leads to deteriorating the thermophysical properties of the resultant fluids (nanofluids). Thus it can be concluded that the dispersion of nanoparticles into the base fluid is the most crucial step towards experimentally studying the thermophysical properties and heat transfer of nanofluids. Nanoparticles, naturally, tend to be agglomerated and forming clusters, which are by far larger than individual nanoparticles in size. Forming the clusters leads to increasing the sedimentation rate which results in deteriorating the thermophysical properties (i.e., viscosity and thermal conductivity), thermal performance, and increasing the pressure drop. Thus, various techniques have been thus far employed to making a long-time stable nanofluid with high-quality dispersion; mechanical stirring, surface charge, adding surfactants, and ultrasonic treatment are amongst the most popular techniques [16]. Literature shows that amongst the mentioned techniques, the ultrasonic treatment is the most popular and effective technique to prepare a long-time stable (at least two weeks) and homogenous dispersion in preparation of nanofluid employing two-step method. However, various parameters are affecting the dispersion of nanofluid by employing ultrasonic treatment such as ultrasonication type, direct (ultrasonic horn/probe) or indirect ultrasonication (ultrasonic bath), ultrasonication time, ultrasonication power, continuous and discontinuous ultrasonication, and so forth.

Many attempts have been made to prepare a long-time stable and homogenous nanofluids employing various techniques. However, the results in the available literature are pretty discrete. Moreover, many reviews have been performed on different aspects of progresses in the preparation methods applying different techniques [15–17], advances in modeling and simulation of nanofluids [18,19], preparation methods and thermophysical properties of oil-based nanofluids [20], viscosity [21], thermal conductivity [22], heat transfer [23], mixed convection of nanofluids in different cavities [24], entropy generation [25], and employing nanofluids in different applications [26–28]. However, there is no comprehensive review reported the effects of different ultrasonication methods (direct or indirect and continuous or discontinuous), ultrasonication time, and power on colloidal dispersion, thermophysical properties, heat transfer efficiency, and pressure drop of various nanofluids. Thus the lack of such a review on the state-of-the-art in the field of ultrasonication techniques and the associated effects on stability and thermal properties of nanofluids is greatly felt.

The present review focuses on the effective parameters of ultrasonication technique on colloidal dispersion and thermal properties of various nanofluids. The review starts by presenting the most important literature on the effect of ultrasonic treatment and the effective parameters on the dispersion quality and stability of various nanofluids. The most commonly used methods in the literature for characterizing the dispersion quality, cluster size, and stability of nanofluid are introduced. Furthermore, a summary of the literature on the effect of ultrasonication on the stability of nanofluids is presented in a table denoting the most important features of the studies. Then, the effects of various ultrasonic parameters on thermophysical properties, heat transfer, and pressure drop are presented and discussed. Finally, the findings in the literature are summarized, and the possible future path is introduced.

2. Preparation technique

It is known that the most important and challenging step towards studying different properties of nanofluids is the preparation step. Various techniques have been employed by researchers to prepared long-time stable nanofluids with minimum sedimentation such as surface functionalization [29,30], using surfactants [31,32], controlling the pH value [33,34], applying ultrasonic vibration [35,36], and so forth.

Among the presented techniques, ultrasonication is the most popular technique which showed great potential in breaking down the clusters of particles, which leads to increasing the stability of the suspension. The ultrasonic treatment uses for different purposes, such as dispersing the nanoparticles into the base fluids, de-agglomeration of particles, particle size reduction, particle synthesis and precipitation, and surface functionalization [37]. The focus of the present review is on the effects of ultrasonication on the stability, thermophysical properties, and heat transfer of different nanofluids.

2.1. Type of ultrasonication device

Ultrasonication process can be done using a probe-type ultrasonic homogenizer or an ultrasonic bath device. Both the techniques/devices apply ultrasonic to the samples. However, there are considerable differences in efficiency, process capabilities, and effectiveness. It is known that the desirable effects of the ultrasonication, such as homogenization, dispersion, deagglomeration, sonochemical effects, and so forth, are caused by cavitation. In ultrasonic bath devices, the cavitation takes place uncontrollably distributed in fluids. In other words, the ultrasonication effect is of low intensity and unevenly spread. On the other hand, in ultrasonic probe devices, the intense ultrasonication zone is directly under the probe, so the ultrasonication effects are more intense and focused. Moreover, the process is fully controllable, reproducible, and the intensity is evenly distributed. Among these two methods of ultrasonication, the probe sonication is more effective and powerful than the ultrasonic bath in the application of nanoparticles dispersion; the ultrasonic bath device can provide a weak ultrasonication with approximately 20–40 W/L and a very non-uniform distribution while the ultrasonic probe device can provide 20,000 W/L into the fluid. Thus, it means that an ultrasonic probe device excels the ultrasonic bath device by the factor of 1000 [31,38–40].

2.2. The effects of ultrasonication time and power

Literature indicated that different nanofluids show a different reaction to the ultrasonication time and power [17]. Thus it is one of the most important concerns of researchers to find the optimum ultrasonication time and power to achieve the best stability, higher thermal conductivity, and lower viscosity.

The stability of nanofluids can be determined by different methods such as measuring the zeta potential, which measures the effective electric charge on the surface of the suspended nanoparticles in the base fluid. Apart from that, there are also some other instruments to investigate the stability, cluster size, and particle distribution in the working fluids. The most widely used techniques and instruments in the literature are the X-ray powder diffraction (XRD), which can determine the crystalline structure of nanomaterials [39,41], dynamic light scattering (DLS), which can quantify the nanoparticle and agglomeration size in nano-suspensions [7,42], Fourier transform infrared (FTIR) [39], and different electron microscopy techniques, which can provide different information related to the morphology of nanoparticles which helps to identify the particle size, shape, ductility, and strength. The most common electron microscopy techniques are the field emission scanning electron microscopy (FESEM) [38,43], transmission electron microscopy (TEM) [44,45], scanning electron microscopy (SEM), which determine the structure and agglomeration size of nanoparticles [46,47].

In the followings, the literature investigated the effects of ultrasonication time and power on the stability of various nanofluids will be reviewed, and the most important findings will be presented and discussed. Moreover, a summary of the published literature on the effects of ultrasonication on the stability of various nanofluids has been presented in Table 1.

The effects of ultrasonication time on the stability of the CNT-EG

Table 1
A summary of the published literature on the effects of ultrasonication time and power on the stability of nanofluids.

Reference	Nanofluid	Ultrasonication type/time/power	Particle size	Study method
Amrollahi et al. [48]	CNT-EG	Probe/0.25–24 h/250 W	Inside dimeter:0.8–1.1 nm, Outside diameter: 1–4 nm	TEM and settling time
HaiTao et al. [49]	$CaCO_3$-water	Probe/1–40 min/120 W	20–50 nm	TEM, SEM, and particle size distribution
Nasiri et al. [31]	CNT-water	Bath and Probe/45 min/130 W	Type of CNT: SWNT; DWNT; FWNT; MWNT1; MWNT2 Outer dimeter: 1–2; 2–4; 5; < 10; 10–20 Mean length: 10; 10; 10; 10; 10	FT-IR and Zeta potential
Nguyen et al. [50]	Al_2O_3-water	Probe/	13 nm	Zeta potential, particle size distribution,
Mondragon et al. [33]	Silica-water	Probe/3–6 min/	Not stated	Particles size distribution, zeta potential, and light backscattering
Yu et al. [35]	SWCNT-water	Probe/20–120 min/20–120 W	0.025 vol%	Dispersion behavior
Tajik et al. [51]	TiO_2-water Al_2O_3-water	Probe (continues and discontinues pulse)/ 30 min/400 W	TiO_2: 30–40 nm Al_2O_3: 27–43 nm	FESEM
Ruan and Jacobi [32]	MWCNT-EG	Probe continuous and discontinuous/ 0–500 min/150 W	Outer diameter: 10–30 nm Inner diameter: 5–10 nm Length: 10–30 μm	SEM, TEM
Silambarasan et al. [52]	TiO_2-water	Probe, discontinuous/0–7 h/130 W	61 nm	Particle size distribution, Zeta potential, SEM, XRD
Sonawane et al. [53]	TiO_2-water TiO_2-EG TiO_2-paraffin oil	Probe/20–120 min/1200 W	5 nm	XRD, TEM
Ismay et al. [54]	TiO_2-water	Probe/10 min/400 W	21 nm	Zeta potential, DLS, TEM, SEM
Mahbubul et al. [43]	Al_2O_3-water	Probe (discontinuous)/1–5 h/500 W	13 nm	TEM, SEM, PSD, Zeta potential,
Leena and Srinivasan [34]	TiO_2-water	Bath/1–6.5 h/50 W	15 nm	XRD, FESEM, FT-Raman,
Adio et al. [55]	Al_2O_3-glycol	Probe/1–8 h/200 W	γ- Al_2O_3: 20–30 nm α- Al_2O_3 (MK Nano): 80 nm α- Al_2O_3 (US Nanomaterial): 100 nm	TEM, XRD, UV–visible spectra, zeta potential, DLS
Mahbubul et al. [38]	TiO_2-water	Probe/0–180 min/500 W	21 nm	FESEM, TEM, zeta potential,
Sharifalhoseini et al. [39]	ZnO-glycerol	Sample1: Probe/40 min Sample2: Bath/40 min	Not stated	XRD, TEM, UV–Vis spectroscopy, FTIR spectroscopy,
Choudhary et al. [36]	Al_2O_3-water	Probe/30–180 min/750 W	20 nm	Zeta potential, visual inspection
Siddiqui et al. [56]	Cu/Al_2O_3-water, Cu-water, Al_2O_3-water	Probe/0.5–3 h/130 W	Al_2O_3: 13 nm Cu: 25 nm	Zeta potential, UV–Vis spectroscopy, TEM, Sedimentation velocity

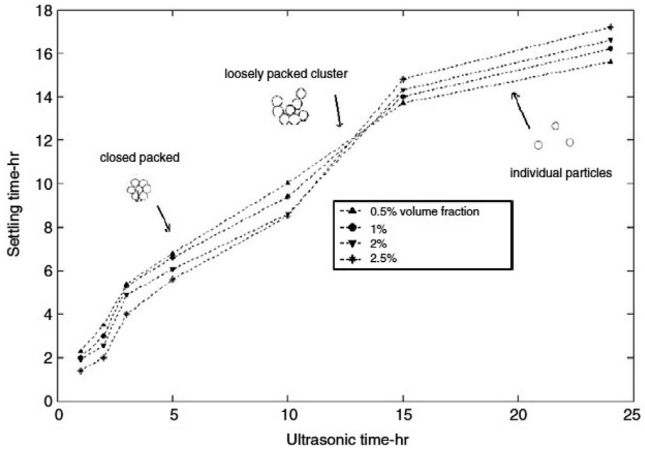

Fig. 1. The effect of different ultrasonication time on the settling time of the CNT-EG nanofluid [48].

nanofluid has been studied by Amrollahi et al. [48]. They prepared the samples through the two-step method in different solid concentrations ranging from 0.5 to 2.5 vol%. Applying 0.25 to 24 h of sonication, they studied the settling time of the nanoparticles in different solid concentrations. They observed that in the ultrasonication time up to 10 h, the settling time of the higher solid concentrations is higher than those of the lowers. However, in ultrasonication times higher than 10 h, the trend is entirely different; the higher solid concentrations showed longer settling time as the ultrasonication time increased (Fig. 1). It is stated that increasing the sonication time results in having more individual nanoparticles rather than clusters; sonication process breaks down the large clusters of nanoparticles to the smaller cluster or even separate them to individual particles. They also stated that at higher particle concentrations, the random collisions between nanoparticles are higher than those of the lowers concentrations, which leads to having higher settling time for higher concentrations. To investigate the effect of ultrasonication time on the particle size of the CNTs in EG, the TEM analysis has been performed in the solid concentration of 2.5 vol% at the sonication time of 0.25, 5, and 20 h. The results showed that increasing the sonication time results in decreasing the cluster size, which leads to having more stable nanofluid.

The effect of using different preparation methods, functionalization and bath and probe ultrasonication, on the stability of different CNTs in water has been examined by Nasiri et al. [31]. They conducted the experiments in a fixed ultrasonication time of 40 min to study the effect of different ultrasonication methods on the stability on nanofluids. They evaluated the stability of the nanofluid by conducting the zeta potential analysis and observed that the best results achieved by functionalization, probe ultrasonication, and bath ultrasonication, respectively.

The effects of different sonication times, tips, and powers on the dispersion behavior of SWCNT-water in the presence of surfactant have been investigated by Yu et al. [35]. They presented the results of the atomic force microscopy (AFM) and UV–vis-NIR absorption spectra analysis to discuss the diameter and length of the nanotubes, dispersion quality, and unbundling degree. Based on the results of the UV–vis-NIR absorption spectra, it is observed that there is a strong dependency between the optical absorption and ultrasonication time and power; considerable enhancement in the magnitude of absorption has been observed for the sonication power higher than 80 W (Fig. 2). This would be because of the fact that increasing the sonication time leads to a sharpening of the optical absorption peaks and, as a result, the resolution of the spectra from different SWCNT species is enhanced. They also investigated the effect of the ultrasonication tip on the absorption spectra. The presented results in Fig. 2 is related to the ultrasonic tip with a diameter of 3 mm. Changing the ultrasonic tip and use the 6 mm tip results in having higher optical absorption spectra under the same ultrasonication powers, as presented in Fig. 3. They concluded that increasing the diameter of the ultrasonication tip leads to having a larger contact area with the base fluid. Thus, more energy can be transferred, and as a result, the SWCNT particles can overcome the interaction with each other. The effect of sonication power and time has also be investigated, and it is reported that increasing both the sonication time and power results in decreasing the length of the nanotubes.

Zhu et al. [49] studied the effect of ultrasonication time on the particle size distribution of $CaCO_3$ (20–50 nm)-water nanofluid. They conducted the experiments in different ultrasonication times ranging from 1 to 40 min and observed that increasing the ultrasonication time leads to decreasing the particle size distribution in the nanofluid. They reported that increasing the ultrasonication time to 20 min results is reaching the average particle size of 36 nm, which implies that the clusters have been broken up to the original size of the nanoparticles. As can be seen in Fig. 4, increasing the ultrasonication time has no noticeable impact on the particle size distribution of the particles in the base fluid. Thus, 20 min of ultrasonication is the optimum time to reach the best stability and particle distribution for the studied nanofluid.

The effects of various parameters of ultrasonication such as time, power, and irradiation modes (continuous or pulsed) on the cluster size and stability of the Al_2O_3-water nanofluid have been studied by Nguyen et al. [50]. They started the experiments at room temperature applying the ultrasonication pulse ratio on/off 0.1/0.2 (s/s). They observed that although the size distribution of the alumina nanoparticles was bimodal before applying the ultrasonication (showed large agglomerations), applying relatively low energy for the short processing time of 14 s leads to breaking down the agglomeration of particles to the smaller size (Fig. 5). They also investigated the effects of vibration amplitude on the size distribution of the particles. It is observed the classical power-law dependence between the ultrasonication time and the increase in specific energy (Fig. 6). They concluded that the optimum efficiency in breaking down the clusters is at the vibration amplitude of 30% and increasing the vibration amplitudes showed no significant improvement in breaking down the clusters.

The effects of applying different type of ultrasonic vibrations, continuous and discontinuous ultrasonication, on the particle size distribution of TiO_2 and Al_2O_3 dispersed in water has been studied by Tajik et al. [51]. They adjusted the ultrasonic vibration pulse to 50% and 100% for a discontinuous and continuous pulse, respectively. It is observed that applying the continuous pulses results in breaking down the clusters into the smaller sizes and achieving the more uniform particles size compared to the results achieved by applying the discontinuous pulses (Fig. 7). They concluded that continuous ultrasonication is more effective than the discontinuous method in preparing the uniform suspension of the studied nanoparticles in water.

The optimum ultrasonic condition to achieve the best colloidal dispersion of Al_2O_3-water has been investigated by Mahbubul et al. [43]. They prepared the samples applying 1–5 h ultrasonication at different amplitudes of 25 and 50%. Investigating the microstructure of the dispersion, they found that the best dispersion would be achieved by applying 3 h ultrasonication at the 50% amplitude while it would be achieved by applying 5 h ultrasonication at the 25% amplitudes. The average cluster size concerning ultrasonication in different amplitudes has also been investigated, and it is observed that increasing the ultrasonication time results in decreasing the average cluster size (Fig. 8A). It is also observed that 50% amplitude results in having a lower cluster size compared to that of the 25% amplitude. It is reported that further ultrasonication time would not decrease the average cluster size. The results of the zeta potential analysis indicated that both the samples have the best physical stability. It is found that the optimum ultrasonication time by applying 25% and 50% amplitudes of ultrasonic power is 5 h and 3 h, respectively, as can be seen in Fig. 8B.

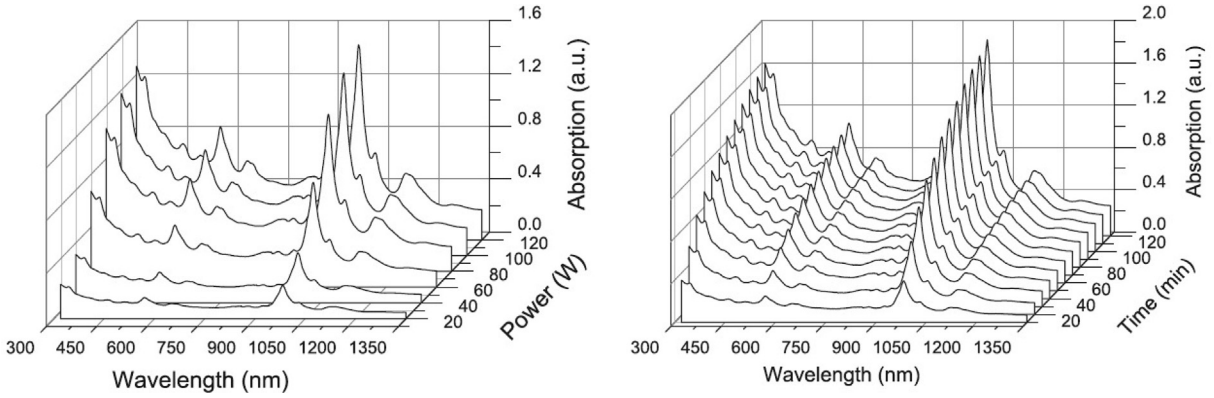

Fig. 2. The variations of the UV–vis-NIR absorption spectra concerning ultrasonication time and power in different wavelength [35]. It is reprinted with permission from Elsevier with the license number 4553100176604.

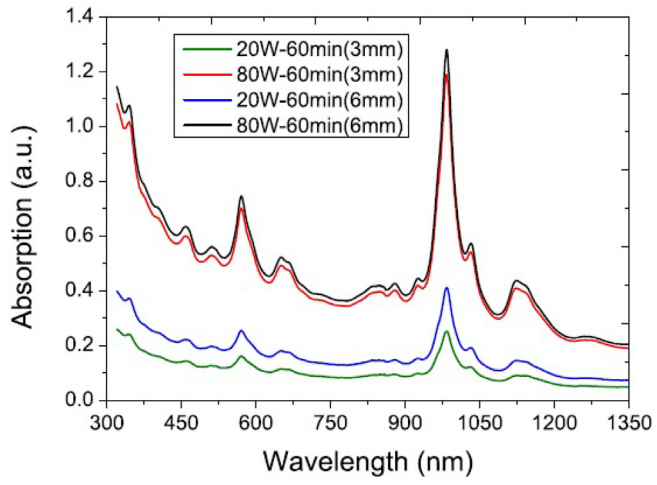

Fig. 3. The effect of changing the diameter of the ultrasonication tip on the optical absorption spectra in different sonication powers [35]. It is reprinted with permission from Elsevier with the license number 4553100176604.

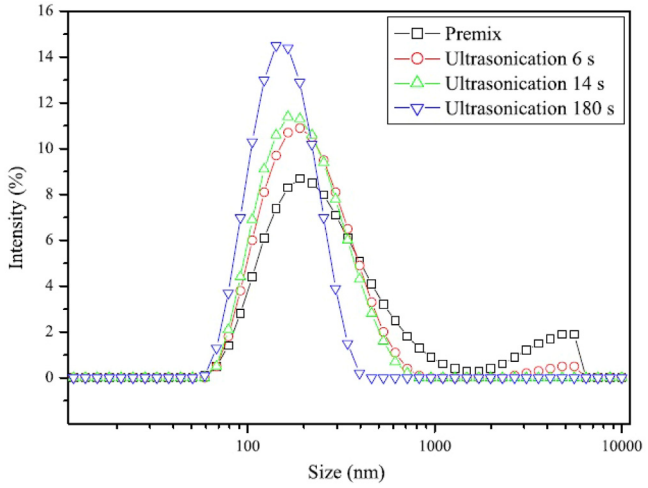

Fig. 5. Particle size distribution at 30% vibration amplitude [50]. It is reprinted with permission from Elsevier with the license number 4553091415107.

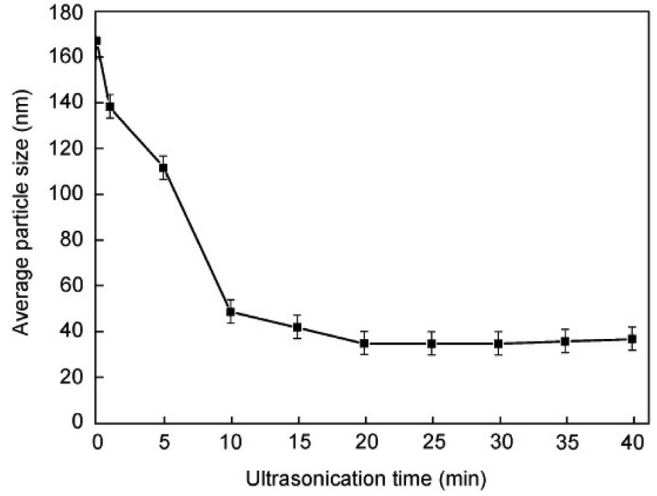

Fig. 4. The variations of the particle size distribution concerning the ultrasonication time [49]. It is reprinted with permission from Springer Nature with the license number 4553091202335.

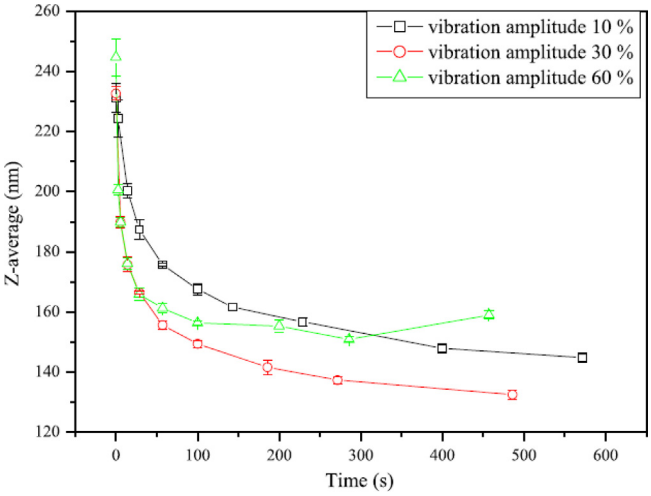

Fig. 6. The variation of the mean particle size concerning time in different vibration amplitudes [50]. It is reprinted with permission from Elsevier with the license number 4553091415107.

2.3. Discussion on the effects of ultrasonication on stability and particle size distribution

Based on the reviewed literature, it can be concluded that applying the ultrasonic treatment results in breaking down the large clusters of nanoparticles into the smaller clusters or even the individual nanoparticles. The mechanism of the ultrasonic treatment can be better understood by the aid of Fig. 9. It is also reported that the ultrasonication process would affect the structure and surface of the

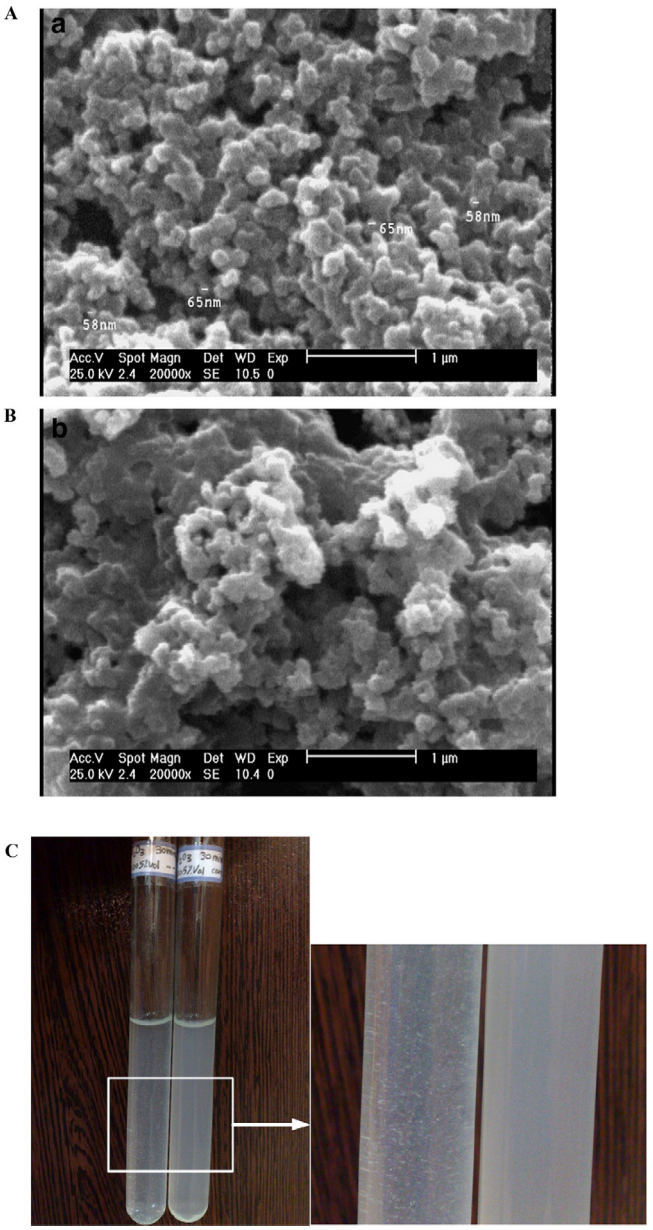

Fig. 7. The SEM images of the Al_2O_3 nanoparticle applying 30 min A) continuous ultrasonication and B) discontinuous ultrasonication. C) The left sample has been exposed to discontinuous ultrasonication, and the right sample has been exposed to continuous ultrasonication [51]. It is reprinted with permission from Elsevier with the license number 4553100326587.

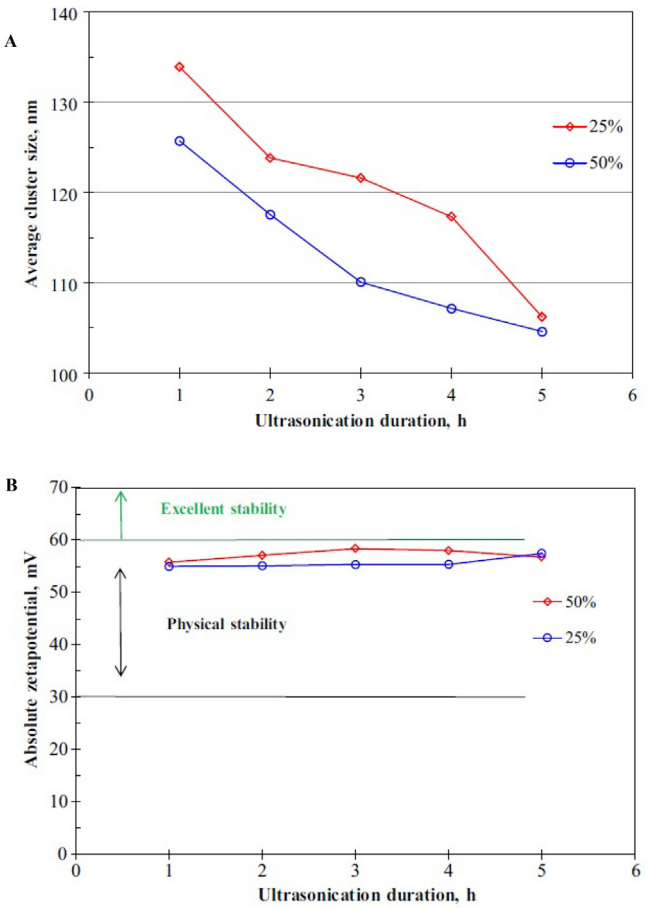

Fig. 8. The variations of A) average cluster size and B) zeta potential concerning ultrasonication time in different ultrasonication amplitudes [43]. It is reprinted with permission from Elsevier with the license number 4553100531679.

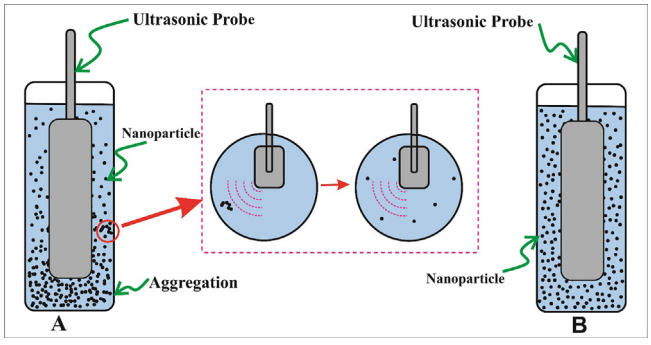

Fig. 9. A schematic view of the process of ultrasonication on how it breaks down the agglomerations of nanoparticles.

nanoparticles, which leads to preventing the clusters from growth and results in having more stable nanofluids [15,43]. However, it is seen in the literature that different nanofluids show different dispersion behavior by applying ultrasonication. Thus it is necessary to determine the specific ultrasonication condition for different nanofluids. Another point is that it is advised in the literature that in order to disperse the dry powder of nanoparticles into the base fluid, the direct ultrasonication, which refers to horn/probe ultrasonication, is much more effective than the indirect ultrasonication technique (ultrasonic bath) [38,39].

It is suggested that researchers conduct a benchmark study on the effective parameters in ultrasonication, such as ultrasonication time, power, type of ultrasonication (probe or bath), the diameter of the ultrasonication probe, and so forth, for different kind of nanoparticles (i.e., oxide, metal oxide, carbon nanotubes, graphite, etc.) to get the best dispersion. Moreover, it is suggested to find the optimum ultrasonic condition in which the nanofluids show the lowest viscosity increase and the highest thermal conductivity increase.

3. The effective ultrasonication parameters on thermophysical properties and heat transfer of nanofluids

It is known that the thermophysical properties of nanofluids play a crucial rule in the convective heat transfer coefficient, which is one of the pivotal parameters in heat transfer applications; thermal conductivity indicates the heat transfer effectiveness, specific heat represents the capability of the nanofluid in storing and moving the

generated heat away of the heat source, and dynamic viscosity has direct effect on the pumping power and pressure loss. Thus having a nanofluid with enhanced thermal conductivity with the minimum increase in dynamic viscosity is highly desirable in heat transfer applications. In the followings, the effects of ultrasonication time on thermophysical properties of nanofluid will be reviewed and discussed. Table 3 presents a summary of the recently published literature on the effects of ultrasonication time on colloidal and thermophysical properties and heat transfer of different nanofluids.

3.1. Thermal conductivity

The effects of sonication time on the thermal conductivity of MWCNT-EG nanofluid has been investigated by Ruan and Jacobi [32]. They have done the experiments over different ranges of sonication time (0–500 min) both in continues and pulse mode. They also used 0.25 wt% surfactant (gum Arabic) and 0.5 wt% MWCNT. The effects of continues and pulse mode ultrasonication on thermal conductivity of the nanofluid has been investigated, and the results revealed that the sonication mode has a negligible effect on thermal conductivity of the nanofluid. Furthermore, they observed that increasing the sonication time leads to increasing the thermal conductivity of the nanofluid; it is observed that over the first 160 min of the sonication process, the increase in thermal conductivity is more significant compared to the rest of the sonication time. They reported that the maximum thermal conductivity enhancement took place approximately in 22 h of sonication by 23%. They also compared their results with those of Amrollahi et al. [48] and reported that by 22 h sonication, the thermal conductivity enhancement is 5% larger than the enhancement achieved but Amrollahi et al. [48].

Ghadimi and Metselaar [57] investigated the effects of ultrasonication on thermal conductivity of TiO_2-water nanofluid at the solid concentration of 0.1 wt% with 0.1 wt% using Sodium Dodecyl Sulfate (SDS) as an anionic surfactant. They used both ultrasonic bath and ultrasonic horn on the ON/OFF pulse mode with 15 min ON pulses. They conducted the experiments in six different preparation conditions, which are presented in Table 2. It is reported that the highest enhancement in relative thermal conductivity of the nanofluid achieved by applying either 3 h ultrasonic bath or 15 min ultrasonic horn (sample 6 and 4) by adding surfactant by 1.008. It can be concluded that while the ultrasonication process has a direct effect on thermophysical of the nanofluid, the effect of adding surfactant on these properties should not be ignored. It should be highlighted that simultaneous use of the proper amount of surfactant and applying ultrasonication would result in increasing the thermal conductivity.

So far, it is seen that the thermal conductivity of nanofluids have a direct relationship with the ultrasonication time, and there is an optimum point after which thermal conductivity starts to deteriorate. Thus, it is of paramount importance to find the optimum ultrasonication time to achieve the highest thermal conductivity by adding different nanoparticles.

In this regards, Shahsavar et al. [58] conducted an experimental investigation to find the optimum sonication time to reach the highest thermal conductivity of the Fe_3O_4-water nanofluid (ferrofluid) and Fe_3O_4/CNT-water hybrid nanofluid over different ranges of temperatures (25–55 °C). They applied 2.5, 5, 7.5, and 10 min sonication and observed that 5 min of sonication is the optimum time in which the thermal conductivity reached the highest point by approximately 0.85 W/mK. It would be because of the fact that in the case of 2.5 min sonication, the sufficient energy and time did not provide to make the magnetic particles physically attached to the CNTs and make a homogeneous suspension while in the case of 5 min sonication, the time was sufficient to makes that happened. Increasing the sonication time resulted in thermal conductivity deterioration. The main reason would be that increasing the sonication time (higher than 5 min) leads to reducing the aspect ratio and as a result lowering the quality of the 3D network of CNTs [58–61].

Buonomo et al. [62] investigated the effect of sonication time and temperature on thermal conductivity of Al_2O_3-water nanofluid over different ranges of solid concentrations (0.1–20%) and temperatures (25–65 °C). They found that variations of sonication time have no considerable effect on the thermal conductivity of the nanofluid.

The effects of sonication time (ranging from 0 to 5 h) on the thermal conductivity of Al_2O_3-water nanofluid at the solid concentration of 0.5 vol% and different temperatures (10–50 °C) has been experimentally investigated by Mahbubul et al. [63]. They observed that in the studied range of sonication time, the 5 h sonication is the optimum time in which the thermal conductivity of the nanofluid has the highest value by 0.71 W/mK. However, it is also observed that applying 4 h sonication resulted in almost the same enhancement in the thermal conductivity. They found that 1 h sonication deteriorates the thermal conductivity of the nanofluid; the thermal conductivity of the nanofluid with 1 h sonication is less than the prepared sample without ultrasonication. The main reason would be that in the case of the sample prepared without ultrasonication, the agglomeration of the particles is very strong which leads to having a larger cluster, which results in having a nanofluid that is not suitably homogenized. They also reported that the thermal conductivity enhancement is more intense in higher temperatures (40 and 50 °C) for the ultrasonication times higher than 2 h.

The effects of sonication time on thermal conductivity of the Mg$(OH)_2$-water nanofluid over different ranges of solid concentrations (0.4, 1, and 2 vol%) and sonication times in the presence of surfactant has been studied by Asadi et al. [64]. They observed a decreasing trend in the relative thermal conductivity of the nanofluid as the sonication time increases (Fig. 10). They declared that the decrease in the relative thermal conductivity is more noticeable in higher solid concentration. They stated that in the presence of a surfactant, there would be an optimum sonication time in which the thermal conductivity has its highest value and after that it starts to deteriorate. They suggested that further investigations should be conducted to find the optimum sonication time.

A series of experimental tests have been conducted by Nasiri et al. [31] to investigate the effects of ultrasonic probe and bath accompanied by adding surfactant and functionalization on the effective thermal conductivity of the different CNTs (SWCNT, DWNT, FWNT, MWNT) dispersed in water. They prepared the samples in three different ways; applying 45 min of ultrasonication probe, applying 45 min ultrasonication bath, and without ultrasonication. Moreover, they measured the thermal conductivity of different samples throughout 400 h after the preparation. They observed that during the first 50 h after the preparation, although the thermal conductivity showed a decreasing trend, the difference between the values of the thermal conductivities of the samples prepared by different methods are almost the same. However, the difference between the thermal conductivity of different samples is more tangible as the elapsed time increases. It is observed that the sample containing the functionalized CNT showed higher thermal conductivity compared to the rest of the samples. However, it is also observed that the ultrasonic probe has a better impact on thermal

Table 2
Different preparation processes of the samples [57].

Sample	Preparation process	k_{nf}/k_{bf}	μ_{nf}/μ_{bf}
1	0.1 wt.%TiO_2, a simple mixture	1	1.001
2	0.1 wt% SDS and TiO_2, a simple mixture	1.008	1.05
3	0.1 wt% TiO_2 prepared by 15 min ultrasonic horn	1.009	1.04
4	0.1 wt% TiO_2 and SDS prepared by 15 min ultrasonic horn	1.01	1.045
5	0.1 wt% TiO_2 prepared by 3 h ultrasonic bath	1.008	0.989
6	0.1 wt% TiO_2 and SDS prepared by 3 h ultrasonic bath	1.01	1.05

Table 3
A summary on the published literature considering the effects of ultrasonication time on different thermophysical and colloidal properties of nanofluids.

References	Nanofluid	Ultrasonication time	Studied parameter
Ruan and Jacobi [32]	MWCNT-EG	0–500 min	Agglomeration and particle size, thermal conductivity, and viscosity
Amrollahi et al. [48]	CNT-EG	15 min to 24 h	Thermal conductivity and colloidal dispersion
Ghadimi and Metselaar [57]	TiO_2-water	3 h ultrasonic horn/probe and 15 min ultrasonic bath	Stability, particle size, thermal conductivity, and viscosity
Mahbubul et al. [69]	Al_2O_3-water	0–180 min	Colloidal structure and viscosity
Shahsavar et al. [58]	Fe_3O_4-water and Fe_3O_4/MWCNT-water	2.5, 5, 7.5, and 10 min	Stability and thermal conductivity
Buonomo et al. [62]	Al_2O_3-water	0–120 min	Thermal conductivity
Mahbubul et al. [63]	Al_2O_3-water	0–5 h	Colloidal dispersion, thermal conductivity, viscosity, density
Mahbubul et al. [70]	Al_2O_3-water	0–5 h ultrasonic horn/probe	Rheological behavior; shear stress, yield stress, consistency index, and flow behavior index
Mahbubul et al. [74]	Al_2O_3-water	0–5 h ultrasonic horn/probe	Rheological behavior; shear stress, consistency index, and flow behavior index
Kumar et al. [47]	MWCNT-solar glycol	30–120 min	Stability and viscosity
Asadi et al. [64]	$Mg(OH)_2$-water	10–160 min	Stability and thermal conductivity
Gangadevi et al. [46]	CuO-water Al_2O_3-water	1–4 h	Thermal conductivity
Gangadevi et al. [65]	Cuo-water	1–4 h	Thermal conductivity, viscosity, and thermal and electrical efficiency of a PVT solar collector
Shah et al. [66]	Al_2O_3-EG/water	30–80 min	Thermal conductivity, viscosity, and zeta potential
Li et al. [71]	Cu-EG	0–75 min	Stability and viscosity
Delouei et al. [72]	Al_2O_3-water	Continues sonication during the experiments	Heat transfer performance and pressure drop
Adio et al. [55]	Al_2O_3-Glycerol	1–8 h	Viscosity
HaiTao et al. [49]	$CaCO_3$-water	0–40 min	Stability
Meibodi et al. [75]	CNT-water	20–80 W	Stability and thermal conductivity
Nasiri et al. [31]	Different CNTs-water	45 min ultrasonic horn/probe and ultrasonic bath	Thermal conductivity
Mondragon et al. [33]	Silica-water	3–7 h ultrasonic probe	Viscosity and stability
Kole and Dey [67]	ZnO-EG	4–100 h	Stability and thermal conductivity
Silambarasan et al. [52]	TiO_2-water	0–7 h	Stability, Viscosity, and thermal conductivity
Sonawane et al. [53]	TiO_2-water, TiO_2-EG, and TiO_2-paraffin oil	20–120 min	Thermal conductivity
Ismay et al. [54]	TiO_2-water	10 min, 1, and 2 h	Thermal conductivity
Rayatzadeh et al. [73]	TiO_2-water	With and without continuous sonication	Heat transfer performance
Hewitt et al. [76]	MWCNT-water	0–18 h	Electrical conductivity
Garg et al. [61]	MWCNT-water	20–80 min	Viscosity, thermal conductivity, and heat transfer performance
Siddiqui et al. [56,77]	Al_2O_3-water, Cu-water, Al_2O_3/Cu-water	0.5–3 h	Dispersion stability, Thermal conductivity, density

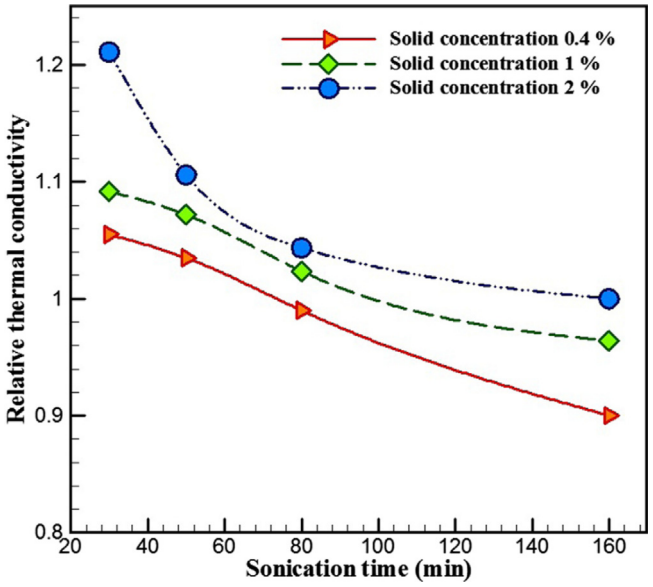

Fig. 10. The variations of relative thermal conductivity concerning sonication time in different solid concentrations [64]. It is reprinted with permission from Elsevier with the license number 4557001047668.

conductivity compared to the ultrasonic bath (Fig. 11).

Sonawane et al. [53] studied the effect of sonication time (20–120 min) on thermal conductivity of three different nanofluids; TiO_2-water, TiO_2-EG, and TiO_2-paraffine oil over different ranges of solid concentrations (3–6%). They reported that increasing the sonication time results in increasing the thermal conductivity of the nanofluid until a certain point after which the thermal conductivity decreases. It is observed that the maximum increase in thermal conductivity took place at the 60 min of sonication time, which is the optimum point. After the optimum sonication time, the thermal conductivity of the samples showed a decreasing trend (Fig. 12).

There are also some other papers which investigated the effect of ultrasonication time on the thermal conductivity of different nanofluids [46,54,56,65–68] and observed that the thermal conductivity increases as the sonication time increases. Some studies in the literature revealed that for a range of sonication time, there is a point in which the thermal conductivity is maximized. In other words, sonicating the suspension more than this specific time leads to thermal conductivity reduction [53,61]. There are also other references that reported the increase in sonication time leads to increases in the thermal conductivity without referring to an optimum sonication time. Moreover, it is seen in the reviewed literature that different nanoparticles such as CNTs, oxide, and metal oxide nanoparticles, showed different behavior in the thermal conductivity enhancement concerning the sonication time. Thus, based on the available literature, no certain conclusion can be drawn for the optimal sonication time. It is suggested that researchers conducted a systematic studies on the effects of ultrasonication time on

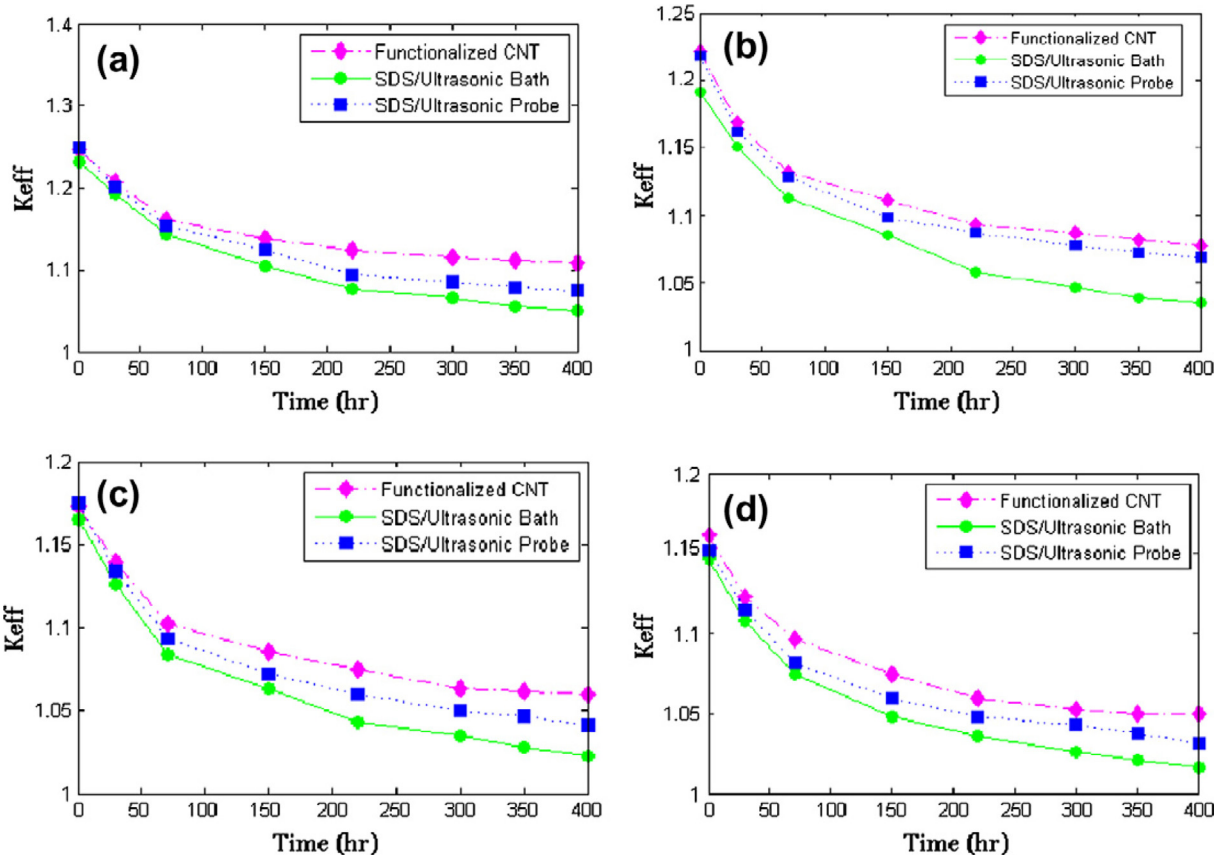

Fig. 11. The variations of the effective thermal conductivity concerning the elapsed time at the temperature of 25 °C and solid concentration of 0.25 wt% A) DWNTs, B) FWNTs, C) MWNTs1, and D) MWNTs2 [31]. It is reprinted with permission from Elsevier with the license number 4553210017032.

thermal conductivity of various nanofluids (different nanomaterials in different base fluids) to reached a certain conclusion on the effects of ultrasonication time on thermal conductivity and proposing a guideline on how different nanofluids (based on the type of materials and the base fluid) behave by applying the ultrasonication process.

3.2. Viscosity

The effects of sonication time have been investigated on the viscosity of the MWCNT-EG by the Ruan and Jacobi [32]. They reported that the viscosity of the nanofluid reached its highest point at 40 min sonication by just higher than 1 Pa.s, and it showed a decreasing trend by increasing the shear rate. They have also observed that at higher sonication time (higher than 40 min), the viscosity experienced gradual decrease and approached the viscosity of the base fluid (EG) at 1355 min of sonication. The main conclusion of this research [32] would be that increasing the sonication time leads to decreasing the viscosity of the studied nanofluid, which is highly desirable in engineering application because viscosity increase has a direct effect on the pumping power and pressure drop. Furthermore, increasing the sonication time also leads to increasing the thermal conductivity, which is also highly desirable in engineering application since increasing the thermal conductivity leads to increasing heat transfer performance. Fig. 13 presents the variations of relative viscosity with respect to thermal conductivity in different sonication times.

In another experimental study, the effects of ultrasonication time on the dynamic viscosity of the Al_2O_3-water nanofluid has been investigated by Mahbubul et al. [69]. They prepared the nanofluid by adding 0.5 vol% of the nanoparticle and applied different sonication time ranging from 0 to 180 min. Then, the viscosity of the nanofluid has been experimentally measured over different ranges of temperatures (15–45 °C). They observed that as the sonication time increases, the viscosity of the nanofluid considerably decreases in all the studied temperatures. However, at the 60 min of sonication, the viscosity reached the highest point at the temperatures higher than 15 °C and then followed the decreasing trend. The maximum decrease in the viscosity was at 180 min of sonication in all the studied temperatures. They declared that the reason for this decrease by increasing the sonication time would be that ultrasonication helps the nanoparticles to distribute homogeneously in water and it breaks down the agglomeration of the nanoparticles, which would not happen in the samples without ultrasonication. They also observed that after 120 min sonication, the viscosity decrease became more gradual until 180 min of sonication. The main reason would be that after 120 min of sonication, the nanofluid reached the excellent possible homogeneity. However, increasing the temperature results in a noticeable decrease in the viscosity. Based on this result, it can be concluded that more energy is required for the nanofluid to achieve the best dispersion quality, especially at higher temperatures. Fig. 14 shows the results of the viscosity variations concerning sonication time at different temperatures.

Mahbubul et al. [63] investigated the effects of sonication time on the dynamic viscosity of the nanofluid and reported a considerable decrease in dynamic viscosity by increasing the sonication time. They observed that the dynamic viscosity experienced a sharp decrease over the first hour of ultrasonication. However, further ultrasonication resulted in a gradual decrease in dynamic viscosity (Fig. 15). As can be seen, as an example, the viscosity at the temperature of 10 °C varies from 1.92 mPa.s at 0 h ultrasonication to 1.63 mPa.s at 5 h ultrasonication. Another observation was that the temperature and ultrasonication time has a close relationship with the viscosity; more ultrasonication is needed at the lower temperatures to achieve the lowest

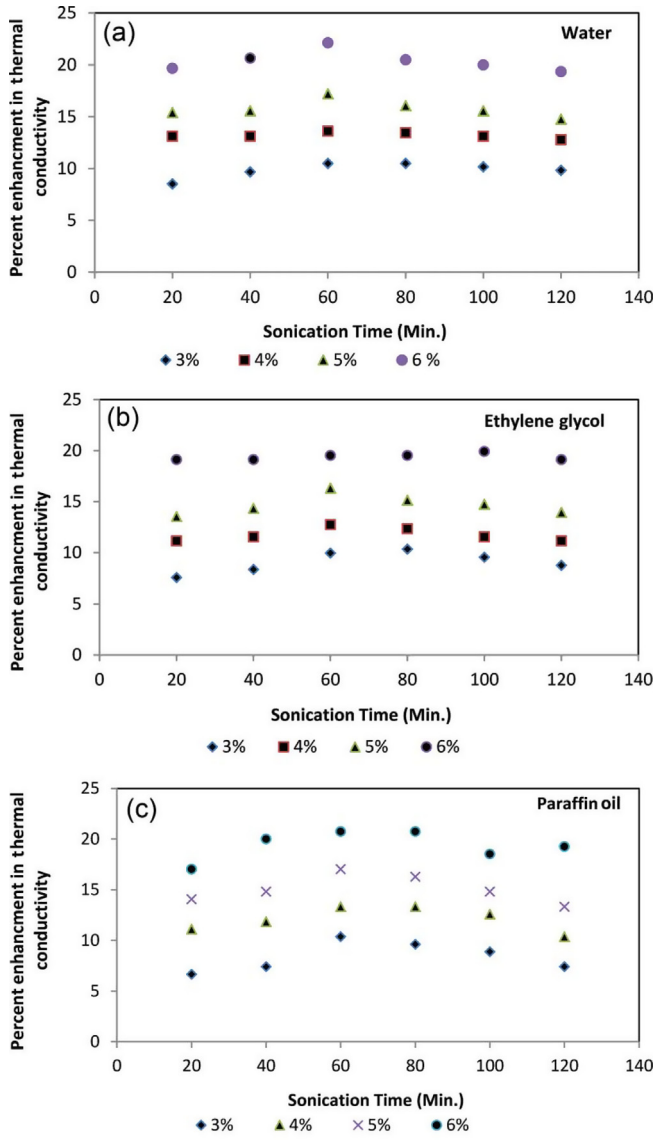

Fig. 12. The variations of thermal conductivity enhancement of TiO_2 nanoparticles dispersed in water, EG, and paraffin oil concerning sonication time in different solid concentrations [53]. It is reprinted with permission from Elsevier with the license number 4553210161328.

viscosity increase while at higher temperatures, it is the opposite. They concluded that in the applications of high temperatures, longer ultrasonication time is not necessary to reach the minimum viscosity increase.

The effect of ultrasonication time on the yield stress of Al_2O_3-water nanofluid at the solid concentration of 0.5 vol% has been experimentally studied by Mahbubul et al. [70]. They conducted the experiments in six different sonication times of 0, 1, 2, 3, 4, and 5 h over different ranges of shear rates and temperatures. They declared that the shear stress of the nanofluid showed almost the same behavior in different sonication times. It is observed that the shear stress decreased as the sonication time increases at the start of the ultrasonication process. However, the values of the shear stress were approximately similar to the sonication time increases. They also studied the effects of ultrasonication time on the yield stress and observed that increasing the sonication time leads to the rapid decrease in the yield stress until 1 h of sonication, but after that, the yield stress gradually decreased by increasing the sonication time. The main reason for this variation can be better understood by the aid of Fig. 23. The variations of the yield stress

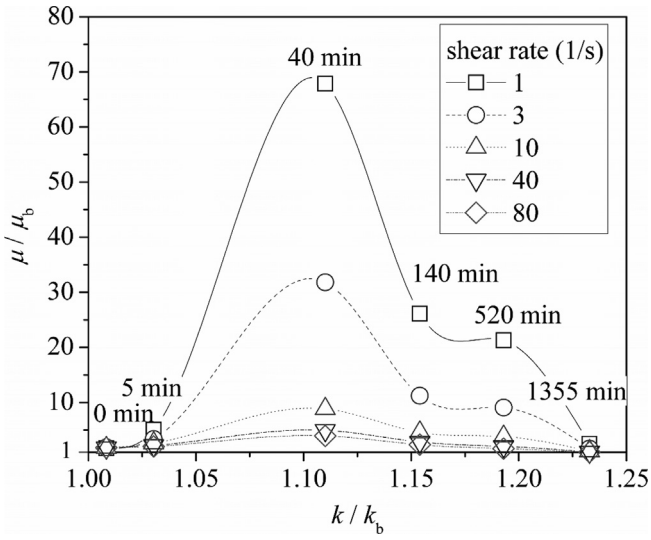

Fig. 13. The variations of the relative viscosity concerning relative thermal conductivity in different sonication times [32].

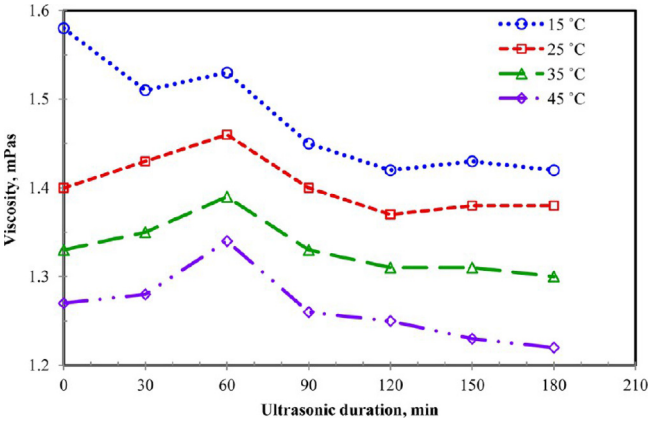

Fig. 14. The viscosity variations concerning ultrasonication time at different temperatures [69].

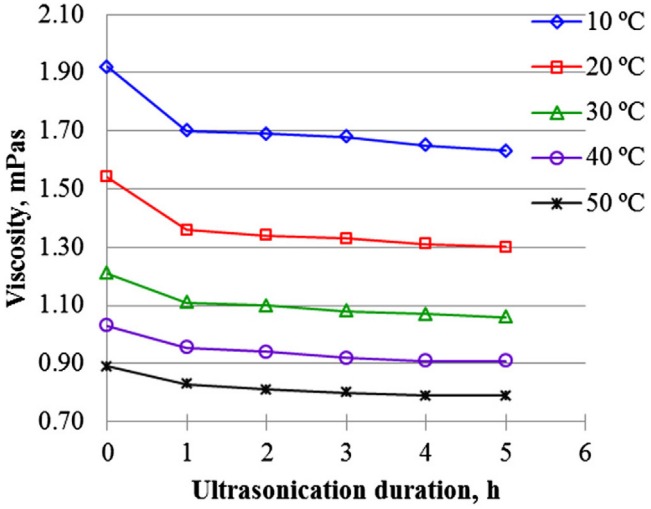

Fig. 15. The variations of dynamic viscosity concerning ultrasonication time in different temperatures [63]. It is reprinted with permission from Elsevier with the license number 4553191432173.

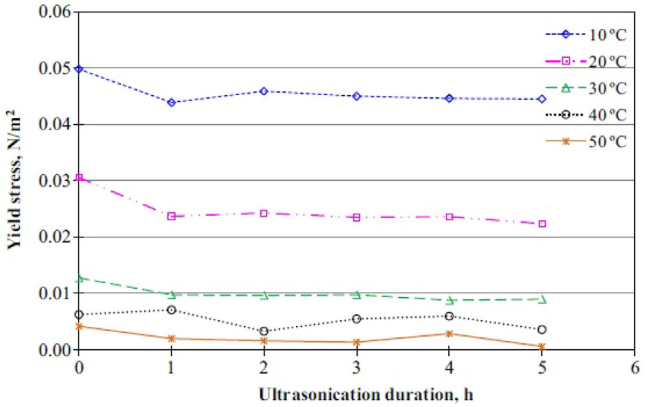

Fig. 16. The variations of the yield stress concerning the ultrasonication time in different temperatures [70]. It is reprinted with permission from Elsevier with the license number 4553200081663.

with respect to the ultrasonication time in different temperatures is presented in Fig. 16.

Kumar et al. [47] studied the effects of ultrasonication period on the viscosity of the MWCNT-solar glycol nanofluid using gum Arabic surfactant. They conducted the experiments over different ranges of ultrasonication times (30–120 min) and temperatures (30–50 °C). They observed that the nanofluid is a non-Newtonian fluid with share thinning behavior in all the studied sonication times. They reported that the viscosity of the nanofluid showed a considerable decrease by increasing the ultrasonication time (Fig. 17). They stated that the main reason for this increase would be due to the de-clustering of the MWCNT bundle. It is observed that increasing the sonication time results in breaking the MWCNTs into the shorter MWCNTs that leads to decreasing the viscosity of the nanofluid.

Li et al. [71] investigated the effect of sonication time on the viscosity of Cu-EG nanofluid over different ranges of sonication time (0–75 min) and solid concentrations (1, 2, and 3.8 wt%). They observed that increasing the sonication time leads to decreasing the viscosity of the nanofluid until a certain point (45 min of sonication) and after that, increasing the sonication time resulted in increasing the viscosity. They summarized the effects of sonication time on the viscosity into two categories:

1- The main reason for decreasing the viscosity by increasing the

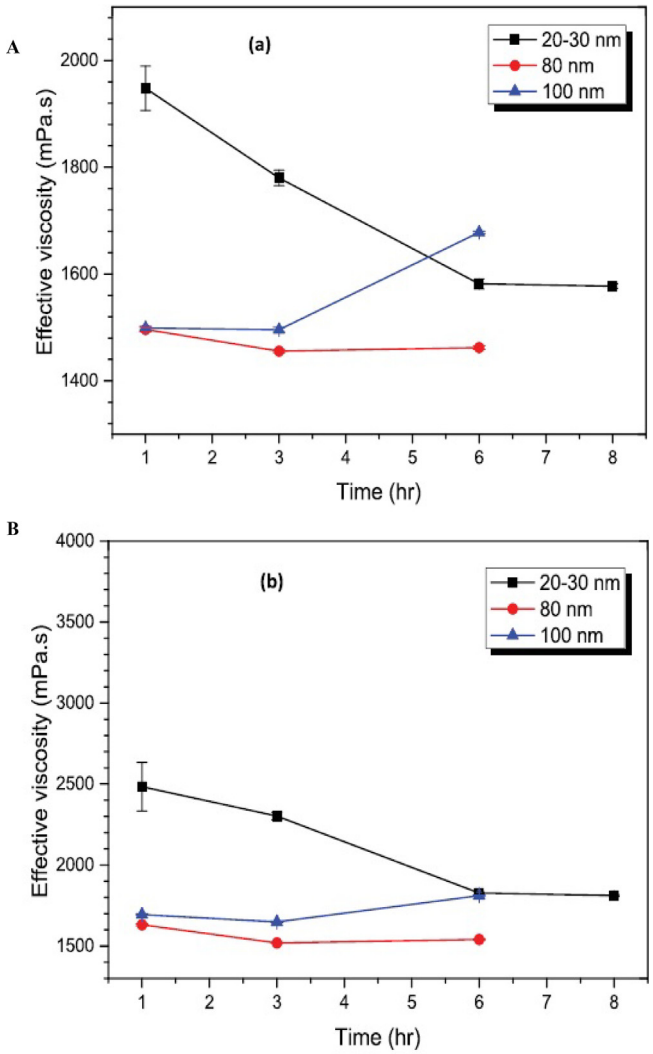

Fig. 18. The variations of viscosity by applying different sonication time at solid concentrations of A) 2 vol% and B) 3 vol% [55]. It is reprinted with permission from Taylor & Francis with the license number 4553200337003.

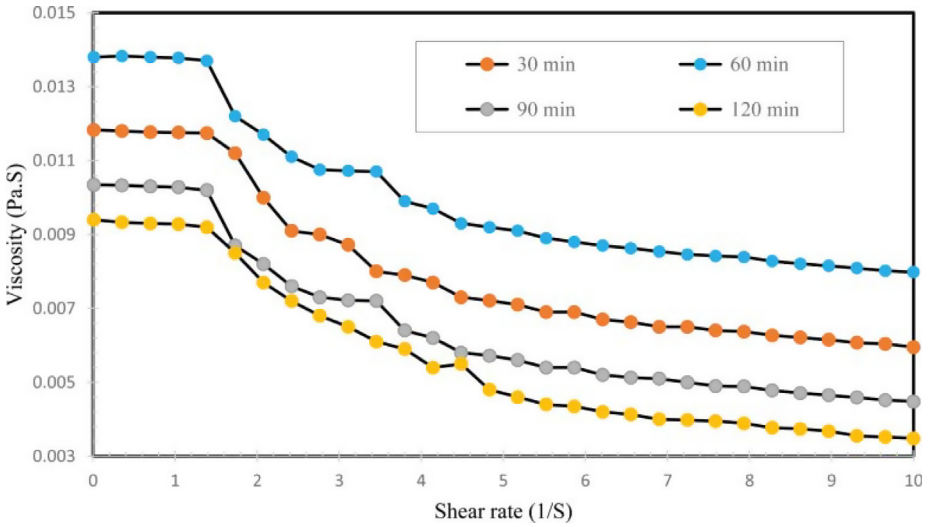

Fig. 17. The variations of viscosity concerning shear rate in different ultrasonication time. It is reprinted with permission from Taylor & Francis with the license number 4556990317625.

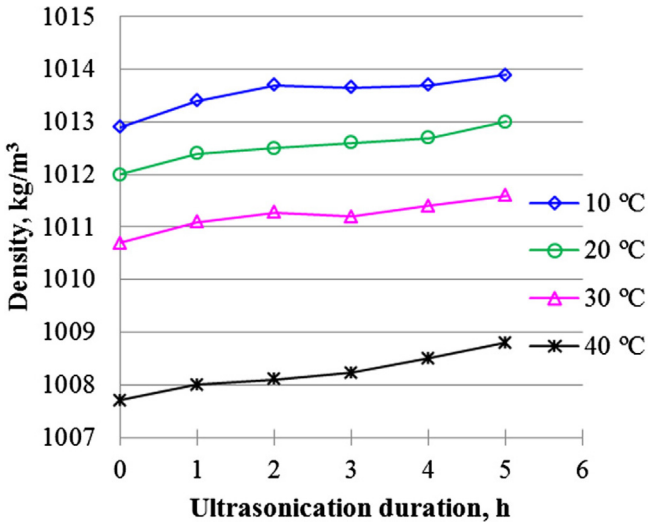

Fig. 19. The variations of the density of the Al2O3-water nanofluid with 0.5 vol % of nanoparticles concerning ultrasonication time [63]. It is reprinted with permission from Elsevier with the license number 4553191432173.

sonication time to 40 min would be that the sonication leads to breaking down the large cluster of Cu nanoparticles. As a result, the Cu nanoparticles homogeneously dispersed into the base fluid, which results in lower flow resistant, and the viscosity decreases.

2- Increasing the sonication time leads to re-clustering of the nanoparticles. The main reason for the re-clustering of the nanoparticles would be that increasing the sonication time increases the surface energy. As a result, the viscosity of the nanofluid starts to rise.

Adio et al. [55] conducted an experimental investigation on the influence of sonication time and energy on dynamic viscosity of Al_2O_3-glycerol over different ranges of temperatures (20–70 °C) and solid concentrations up to 5 vol%. They used the Al_2O_3 nanoparticles with three different diameters; 20–30, 80, and 100 nm. They observed that for the nanoparticles with the mean diameter 20–30 nm, 6 h of sonication with the energy of 1.5×10^7 (kJ/m^3) is the optimum sonication time to achieve the best dispersion. Increasing the sonication time from 1 to 6 h results in decreasing the effective viscosity of the nanofluid, and after that until 8 h of sonication, the viscosity showed no changes. This trend was similar for all the studied solid concentrations (Fig. 18). They also observed that for the nanoparticles with the diameters of 80 and 100 nm, the optimum sonication time is different; it is around 3 h sonication which is corresponding to 1.5×10^7 (kJ/m^3) and after this point, the viscosity showed an increasing trend (Fig. 18).

The effects of ultrasonication on the viscosity of sub-micron TiO_2-water nanofluid has been investigated over the sonication time ranging from 0 to 7 h by Silambarasan et al. [52]. They stated that since the ultrasonication treatment changes the size distribution of the studied nanofluid sub-micron dispersion, the dynamic viscosity of this sub-micron dispersion would be influenced by ultrasonication. Thus, they conducted experiments to investigate the effect of sonication time on the viscosity of the sub-micron dispersion in two different solid

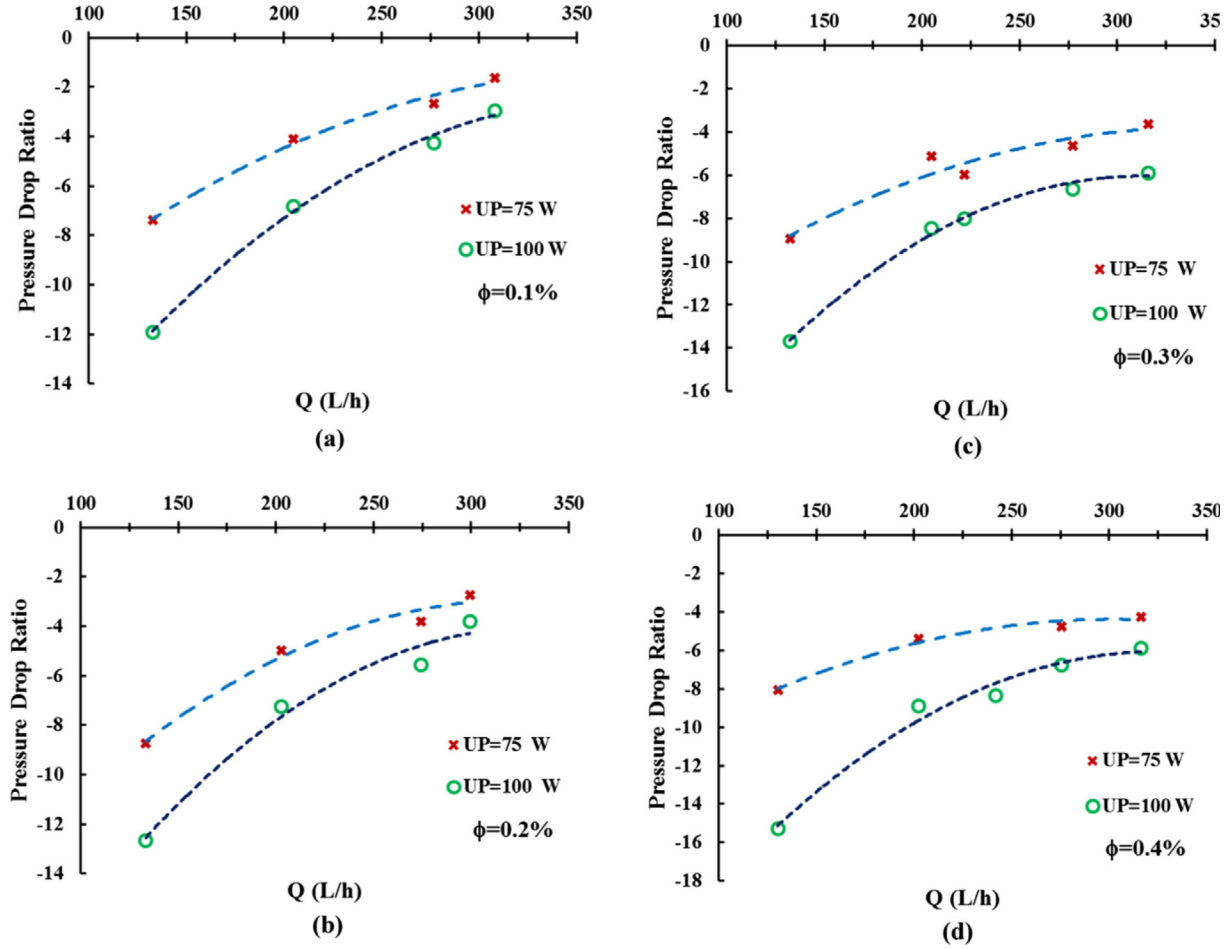

Fig. 20. The effects of ultrasonic power on the variation of pressure drop concerning flow rates in different solid concentrations [72]. It is reprinted with permission from Elsevier with the license number 4553200493805.

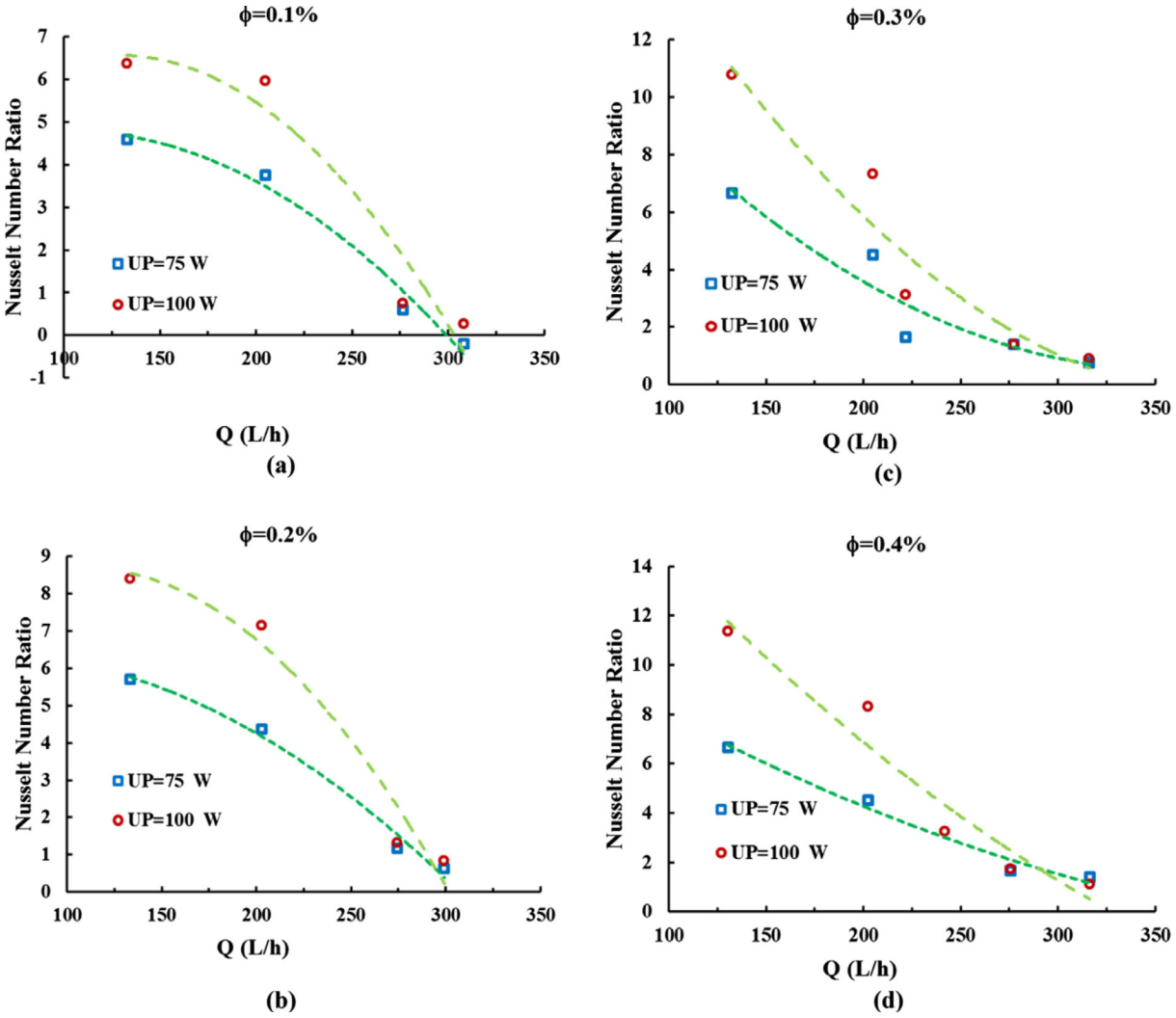

Fig. 21. The effects of ultrasonic power on the variation of Nu number concerning flow rates in different solid concentrations [72]. It is reprinted with permission from Elsevier with the license number 4553200493805.

concentrations and temperatures. They reported a reduction in viscosity by increasing the sonication time in all the studied conditions. They also observed that at higher solid concentrations, the effect of sonication is more tangible. They stated that the main reason behind the decrease in viscosity by increasing the sonication time would be attributed to the fact that increasing the sonication time results in decreasing the agglomeration size. Thus, it can be concluded that ultrasonication treatment is a vital step in the preparation of the sub-micron suspensions.

3.3. Density

A quite rare and valuable study in the literature on the effects of ultrasonication time on the density of a nanofluid has been done by Mahbubul et al. [63]. They reported that increasing the ultrasonication time leads to an increase in the density of the nanofluid. The variation of the density with respect to ultrasonication time at different temperature has been presented in Fig. 19. They indicated that there is approximately a linear relationship between the density increase and the ultrasonication time.

It is known that the density meters available in the market are designed to measure the density of the liquids. Moreover, when the nanoparticles are not homogeneously dispersed into the base fluid, the device can not consider the effects of a large settled cluster of particles. Thus, increasing the sonication time results in having more homogenous nanofluid with less/no aggregation and sedimentation. This would be better understood by the aid of Fig. 21.

3.4. Heat transfer and pressure drop

The effects of ultrasonic power level on heat transfer and pressure drop of the Al_2O_3-water nanofluid in turbulent flow has been experimentally investigated by Delouei et al. [72]. They performed the experiments in two different ultrasonic powers of 75 and 100 W over different ranges of Reynolds numbers (Re). They observed that in high solid concentration and low flow rates, ultrasonic vibration leads to decreasing the pressure drop by up to 15.27%. Moreover, they reported that increasing the flow rate (Re number) results in weakening the effect of ultrasonication in all the studied solid concentrations (Fig. 20). They also studied the effect of ultrasonic power on the Nusselt (Nu) number and reported the positive effect of ultrasonication on the heat transfer performance of the nanofluid by up to 11.37%; higher ultrasonic power has a significant impact on the Nu number in the lower flow rates although, in higher flow rates, there is no considerable effect (Fig. 22).

The effects of continuous sonication on the heat transfer performance of the TiO_2-water nanofluid in a laminar flow regime have been experimentally studied by Rayatzadeh et al. [73]. They prepared the

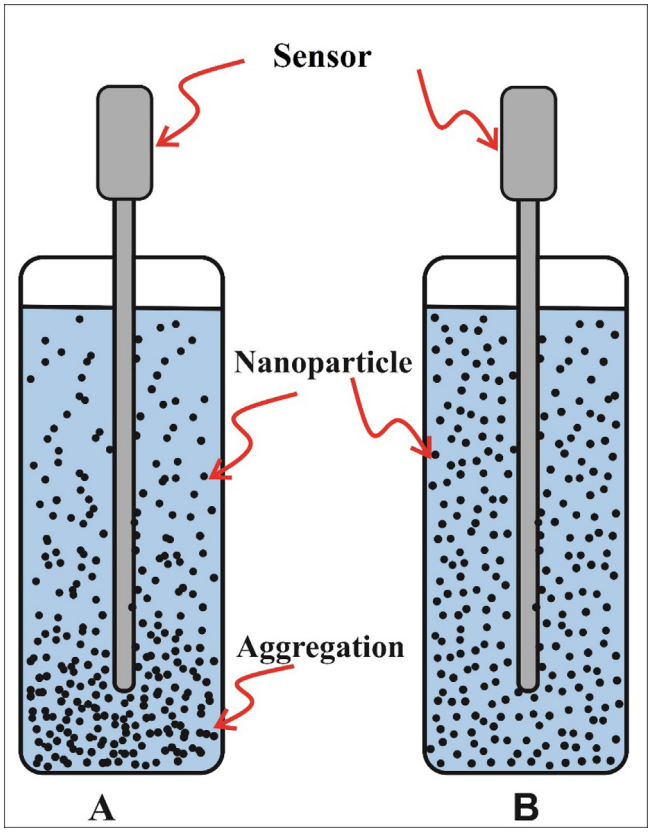

Fig. 22. The schematic view of the responsible mechanism influenced by ultrasonication on thermal conductivity; A) Without or having low ultrasonication time; strong aggregation and larger clusters, B) Higher ultrasonication time; no aggregation.

samples in three different solid concentrations of 0.1, 0.15, and 0.25 vol % and performed the experimental tests in different Re numbers. They applied continuous ultrasonication to the buffer tank where the nanofluid stored before pumping to the test rig and investigated the effect of ultrasonication on the Nu number. It was observed that the local Nu number is higher when the ultrasonication is applied during the tests compared to the condition without applying ultrasonication. They reported that the continuous ultrasonication has a better effect on the Nu number in higher solid concentration compared to those lowers.

3.5. Discussion on the effects of ultrasonication on thermophysical properties and heat transfer of nanofluids

The main reason of increasing the thermal conductivity by increasing the sonication time would be that higher sonication time results in breaking down the aggregation of nanoparticles and having a small-size cluster, which would be better understood by the aid of the Fig. 22. Based on this figure, it can be concluded that the homogenous dispersion of nanoparticles leads to having a nanofluid with higher thermal conductivity.

The main reason for decreasing the dynamic viscosity with increasing the ultrasonication time would be better described by the aid of Fig. 23. As can be seen, homogeneous dispersion of the particles in the base fluid, which is started after 1 h sonication, leads to having less or no aggregation (Fig. 22B). This way, the nanoparticles contribute to the flow, which leads to making less resistance for the spindle of the viscometer. They also ease the movement of different layers of the nanofluid, and this way, the viscosity decrease.

Based on the reviewed literature on the effects of ultrasonication on heat transfer performance of nanofluids, it can be concluded that some agglomeration and sedimentation take place during the experimental tests which result in decreasing the Nu number. Moreover, it is reported that ultrasonication would break down the larger clusters of nanoparticles, which results in preventing the agglomeration and sedimentation of the particles. Therefore, the heat transfer rate enhances by applying ultrasonication.

4. Conclusion

In the present paper, it is tried to review the effects of different ultrasonication parameters on the colloidal dispersion, thermophysical properties, and heat transfer efficiency of various nanofluids. Various characterization methods of dispersion quality and stability measurements of nanofluids employed in the literature have been identified, and it is observed that TEM, SEM, zeta potential, DLS, and FT-IR are amongst the most common methods. The effects of direct (horn/probe) and indirect (bath) ultrasonication on the stability and particle size distribution has been reviewed, and it is found that direct ultrasonication has a better impact on breaking down the large clusters of nanoparticles into the smaller clusters. Moreover, the effects of ultrasonication time and power on the stability of the nanofluids have been reviewed. The reviewed literature indicated that increasing the ultrasonication time and power leads to increasing the stability of nanofluids and decreasing the size of the clusters. Another part of the presented paper devoted to reviewing the effective ultrasonication parameters on thermophysical properties and heat transfer performance of nanofluids. It is observed that the thermal conductivity of the nanofluids increases as the ultrasonication time and power increases except for some cases which reported that prolonging the ultrasonication time leads to decreasing the thermal conductivity. It must be noted that literature indicated that there is an optimum point at which the thermal conductivity increases and hits the highest point, and after that, it starts to decrease. However, this optimum point is different for different nanofluids, and no certain point has been reported in the literature for all nanofluids. As for viscosity, it is observed that increasing the ultrasonication time leads to decreasing the viscosity of nanofluids until a certain point, which is different for different nanofluids. There are also quite rare studies that investigated the effects of ultrasonication time on density of nanofluids. The results of heat transfer enhancement and pressure drop have been reviewed, and it is observed that employing ultrasonic treatment leads to increasing the heat transfer and decreasing the pressure drop. However, the available literature on the effects of ultrasonication time and power on heat transfer and pressure drop is by far less than the available literature on thermal conductivity and viscosity.

Further investigations could concentrate on conducting benchmark studies on the effects of ultrasonication time and power on colloidal dispersion and stability of nanofluids containing different types of nanoparticles (metallic, metal oxide, ceramic, graphite, carbon nanotubes, graphene, and so forth). The lack of such a study which reports the optimum ultrasonication time and power for different nanofluids is greatly felt in literature. Another research path would be focused on conducting systematic studies on finding the optimum ultrasonication time and power at which the nanofluids possess the highest increase in thermal conductivity and the lowest increase in viscosity. Such an optimum point is highly desirable in heat transfer applications, and it is quite rare in the literature.

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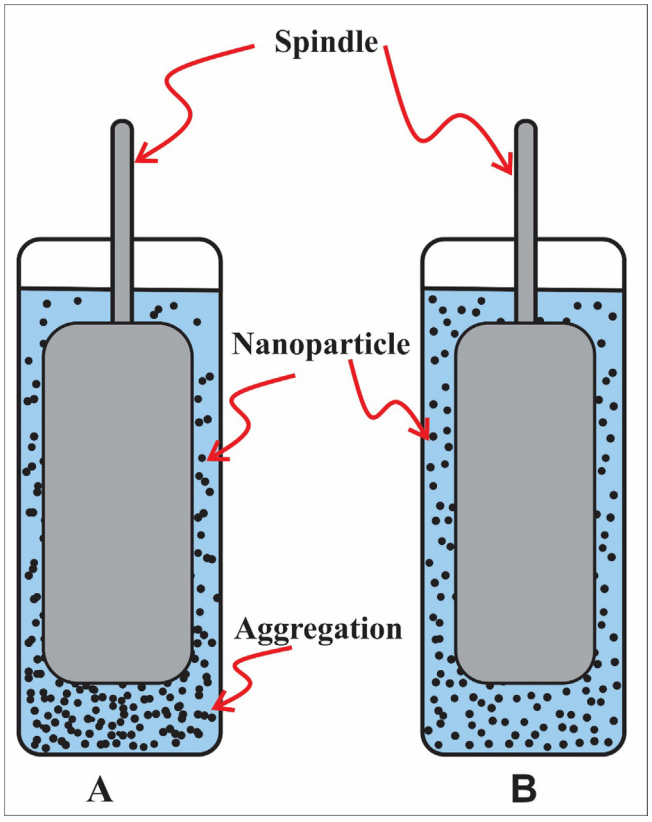

Fig. 23. The schematic view of the responsible mechanism influenced by ultrasonication on dynamic viscosity; A) Without/having low ultrasonication time; strong aggregation and larger clusters, B) Higher ultrasonication time; less/no aggregation.

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