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An overview on the effect of ultrasonication duration on different properties of nanofluids

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Abstract

Preparation of nanofluid is of prime importance to obtain better thermal and physical properties. Different preparation parameters used in nanofluid preparation sometimes perform contrarily even if prepared with same nanoparticles and base fluid. Stability, thermal conductivity, and viscosity of the nanofluid are significantly affected by the cluster (agglomerate) size of nanoparticles in the base fluid which deteriorate thermal performance. In order to break the agglomerates and improve the dispersion of nanoparticles, ultrasonication is a more prevalent method. Nanofluids react differently for different sonication time and the reaction of the nanofluid with the change in sonication time varies for different nanofluids, which is dependent on various factors. In this regard, research works pertinent to the effect of ultrasonication on different properties of nanofluids are confined. In this paper, review of investigations carried out on experimentally evaluated ultrasonication effects on thermal properties and various physical properties of nanofluid. It is found that with an increased sonication time/energy, reduces the particle size and thus aids in obtaining a better dispersion leading to enhancement of stability, thermal conductivity and reducing viscosity. However, the longer ultrasonication duration was not found to be better in all cases where best performance was obtained for an optimum duration of ultrasonication.

Abbreviations

Al_2O_3	Alumina
CTAB	Cetyl trimethyl ammonium bromide
CNT	Carbon nanotube
DMF	Dimethylformamide
DW	Double walled
EG	Ethylene glycol
FW	Few walled
FE	Field emission
GNP	Graphene nanopowder
GA	Gum arabic
MW	Multi-walled
$Mg(OH)_2$	Magnesium hydroxide
o-DCB	Ortho-dichlorobenzene
PU	Poly-urethane
SDS	Sodium dodecyl sulfate
SW	Single walled
SEM	Scanning electron microscopy
TEM	Transmission electron microscope
TiO_2	Titania
Vol%	Volume concentration percentage
W	Water
XRD	X-ray powder diffraction
ZnO	Zinc oxide

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Introduction

Nanofluids consist of particles that are of nanometer size known as nanoparticles dispersed in the fluid. These nanoparticles are generally metals, carbides, oxides, carbon nanotubes etc. [1–4]. Water, glycerol, oil, and ethylene glycol (EG) have been used as base fluids to suspend these nanoparticles [5–9]. Nanofluids have potential applications

in electronics cooling system, fuel cells, heat exchangers, refrigeration systems, pharmaceutical processes, solar collectors, chillers, machines for temperature management and many others [10–13]. Uniform distribution of nanoparticles in the base fluid is a critical factor in deciding the behavior of nanofluid. Nanoparticles tend to agglomerate and form clusters in the base fluid, which is a setback in the performance of the nanofluids. This is observed due to high surface energy of nanoparticles that leads to sedimentation causing a reduction in performance and further affecting its thermophysical properties like viscosity, thermal conductivity, and pressure drop. [14–17].

Therefore, to reduce the agglomeration and sedimentation of nanoparticles, they must be properly dispersed and stabilized. Stability of a nanofluid is the main concern before preparing it. The stability of the nanofluid is the ability of nanoparticle to stay dispersed in the base fluid without forming any clusters. Stability of a nanofluid depends on various parameters such as particle size, surfactant used, sonication time, volume concentration, and type of sonication (pulse or nonplused). [18–23]. Zeta potential gives a measure of effective electric charge on the surface of the nanoparticle suspended in any fluid. The magnitude of the zeta potential provides information about particle stability. Particles with higher magnitude zeta potentials exhibit increased stability due to a larger electrostatic repulsion between particles [24–28]. The higher agglomeration size leads to change in density and they tend to settle down hence reducing stability. Agglomeration also effects thermal conductivity of the nanofluid. Therefore, the agglomeration is to be subdued as much as possible [29–35].

Sonication of nanofluid is achieved by providing sound energy to agitate the nanoparticles in the suspension. Sonication breaks the nanoparticles in the base fluid to obtain more uniform finer-sized particles. More than 20 kHz of ultrasonic frequencies are applied to the solution leading to the commonly known process as ultrasonication [36–38]. Bath-type and probe-type ultrasonicators are employed nowadays. Probe type is found to be more efficient than bath-type sonicator due to its high intensity of sonication [39–42]. The stability of a nanofluid can be improved by using surfactants. Again, stability is also dependent on surfactant type and its concentration. It is always a challenge to obtain a low viscous fluid with better dispersion. As the dispersion is better the more the viscous the fluid becomes. In most cases, use of surfactant increases the viscosity of nanofluid. However, the effect of surfactant is out of the scope of this study to make the review focused on ultrasonication effect only. Nevertheless, the effects of surfactants in conjunction with ultrasonication time/energy are considered here.

Various scientific instruments and machines are used by the researchers to study the stability, particle distribution, cluster size of the nanoparticles in the base fluid after the preparation of nanofluid. Some of the largely used devices include X-ray powder diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, field emission scanning electron microscopy (FESEM), thermogravimetry analysis (TGA), Brunauer–Emmett–Teller (BET) surface area analysis, chemical analysis (elemental analysis), Raman spectrum, laser granulometry, transmission electron microscope (TEM), UV–Vis spectrometer, etc. [31, 42–51].

Fig. 1 Outline of the review
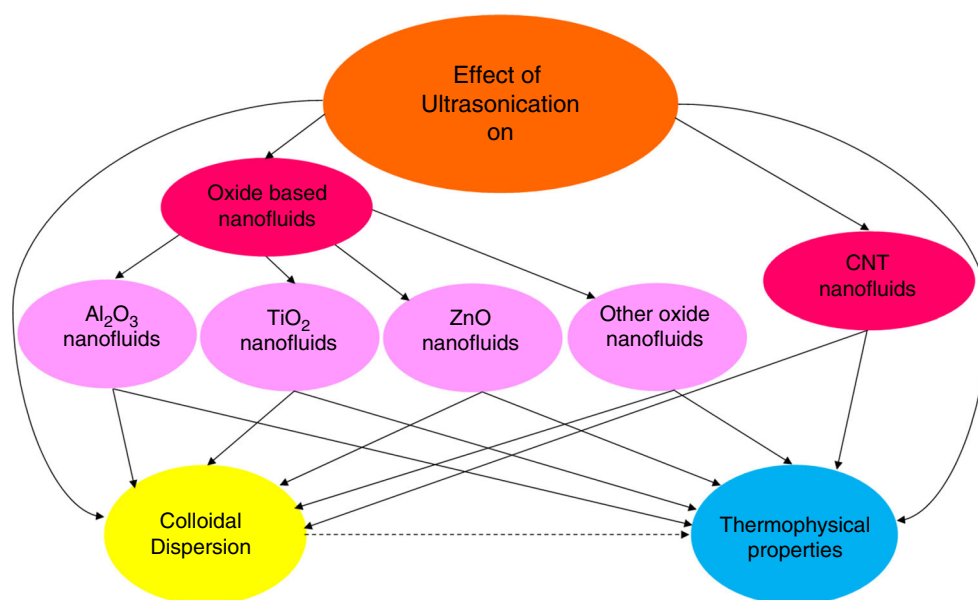
There is no concrete solution on how much ultrasonication time/energy is required to homogenize a suspension to get better and prolong stability. One of the approaches now being recently practiced to enhance stability is by ultrasonicating the nanofluid for longer durations. However, some researchers obtained better stability after a certain duration of ultrasonication and after which stability parameters were found to be reduced. Many studies are reported in literature in which effect of ultrasonication time on the thermal, physical and chemical properties of nanoparticles are experimented [22, 41, 43, 44, 52–61]. Hence this article is intended to review the same. Various ultrasonication techniques are used to stabilize the nanoparticles dispersed in the nanofluids. Among the nanoparticles studied to enhance the stability and other properties include Al$_2$O$_3$ (alumina), TiO$_2$ (titania), carbon nanotubes (CNTs) and few others. TiO$_2$ and Al$_2$O$_3$ are most widely investigated nanoparticles as they have a huge application ranging from solar heaters to food industry [15, 16, 62]. The following sections include information of the nanofluid preparation methods, experimental works about ultrasonication effect on some common nanofluids. Each section contains information about the effect of ultrasonication on colloidal dispersion and thermophysical properties of that type of nanofluids. The outline of this review is expressed in Fig. 1.

Preparation of nanofluids

Stable nanofluid preparation is the one of the major step and key issue in assessing the thermophysical properties of nanofluids for any application. Wu et al. [63] described the nanofluids preparation aspects by three different methods: kinetic stability, dispersion stability, and chemical stability. The determination of nanoparticles and right base fluid will help to get rid of chemical stability for the working environment. Henceforth, these all parameter should be considered for the preparation of nanofluids to obtain good stability by reducing the expansion of nanoparticles inside the base fluid and avoid the sedimentation for longer durations.
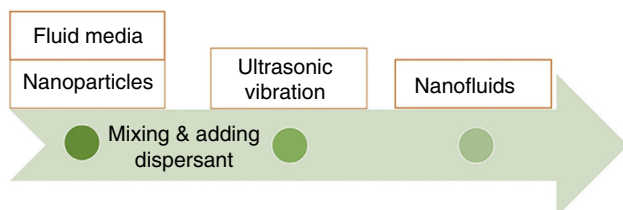

Fig. 2 Two-step method of nanofluids preparation. (Reprinted from [20], copyright (2017) with permission from Elsevier)
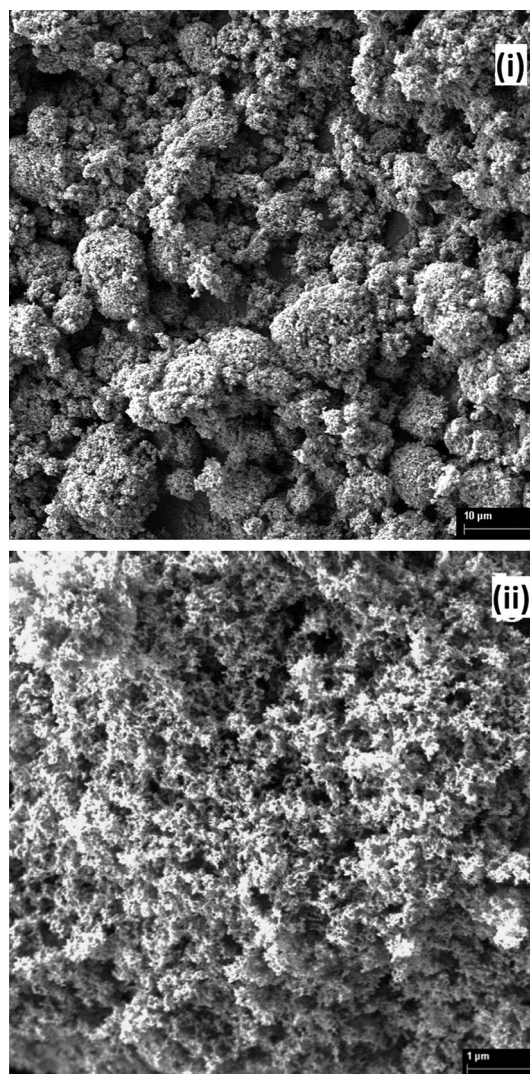

Fig. 3 Al$_2$O$_3$ nanoparticles as observed in FESEM **i** 10 μm scale and **ii** 1 μm. (Reprinted from [39])

Preparation of nanofluids is not as straightforward as adding nanoparticles into base liquid. There are two distinct systems primarily utilized for combining nanoparticles into a base fluid: single-step process and two-step method. In single-step method, the nanoparticles are directly dispersed and condensed in the based fluid solution at a single/one time [20]. Normally, physical vapor deposition (PVD) procedure/fluid compound technique/VEROS (vacuum evaporation to a running oil substrate) is utilized for single-step processing technique. This technique has favorable circumstances, for example, stability increment and limited agglomeration.

Figure 2 illustrates the two-step method which is generally adopted for the preparation of graphite nanofluids. In a two-step method, nanoparticles are at first arranged and then dispersed into the fluid medium by ultrasonication or
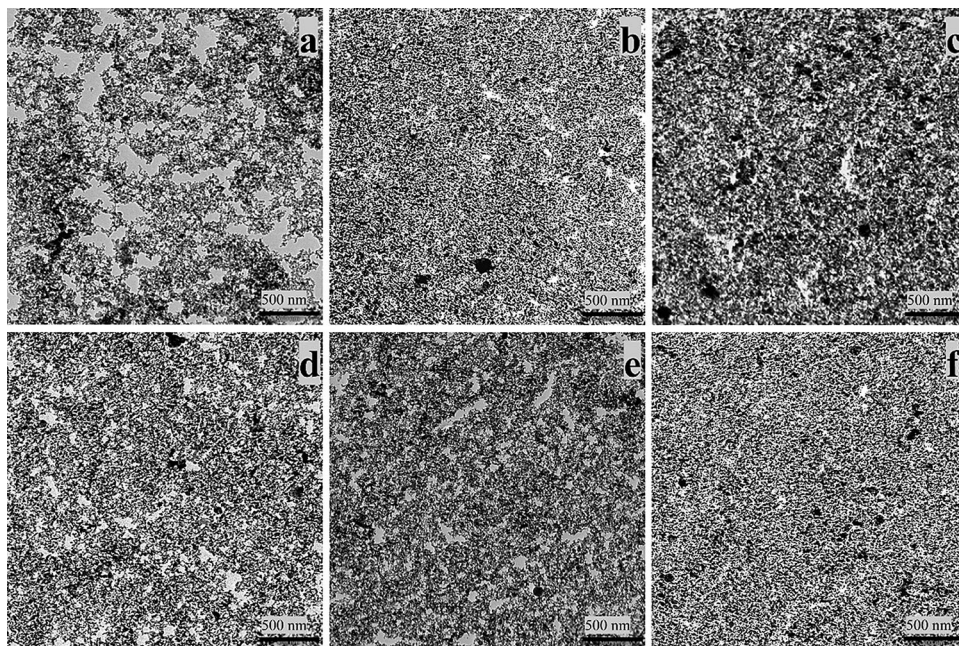
Fig. 4 Al$_2$O$_3$–W nanofluid microstructure captured by TEM after sonicating for **a** 30 min, **b** 60 min, **c** 90 min, **d** 120 min, **e** 150 min and **f** 180 min. (Reprinted from [39])
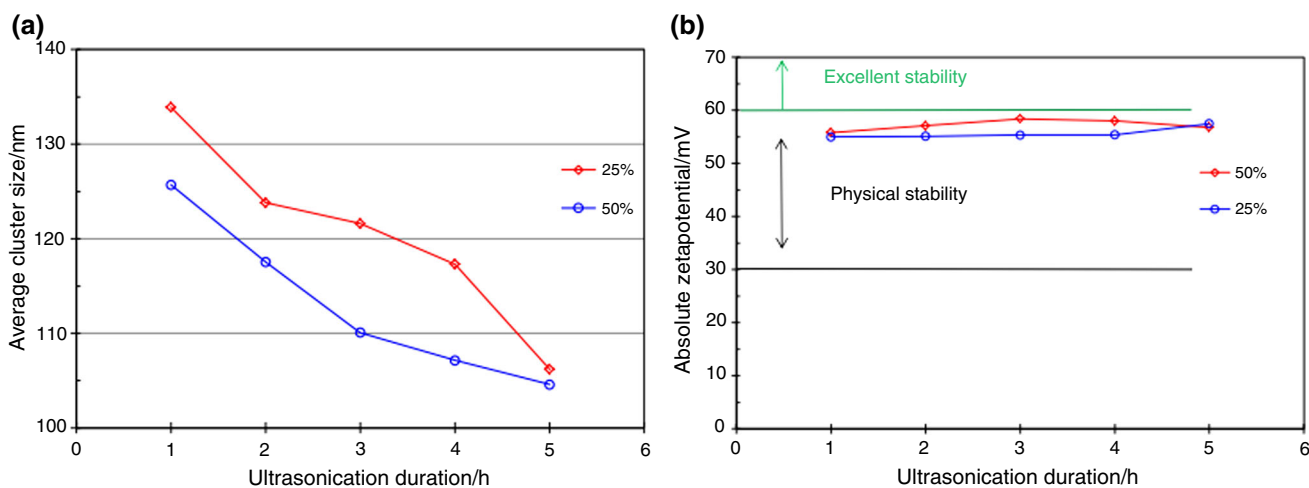

Fig. 5 Variation in properties of Al$_2$O$_3$–W nanofluid for different ultrasonication duration **a** average cluster size and **b** zeta potential. (Reprinted from [40], copyright (2015) with permission from Elsevier)

other processes. Nowadays, accessibility of nanoparticles from various sources makes two-step method genuinely appealing to the researchers. Two-step method functions efficiently for different oxide nanoparticles. A large number of investigators used two-step dispersion technique to get proper and homogeneous mixture and stability of nanofluids [63–70].

An ultrasonicator is used to prepare nanofluid by ultrasonication to disperse nanoparticles in the base fluid. For nanofluids prepared by any method are initially calculated for volume fraction (φ) of nanoparticles by,

$$\varphi = \frac{\frac{w_n}{\rho_n}}{\frac{w_n}{\rho_n} + \frac{w_b}{\rho_b}} \tag{1}$$

where w_n is the weight of nanoparticle, ρ_n is the density of nanoparticles, w_b and ρ_b are weight and density of base fluid, respectively.
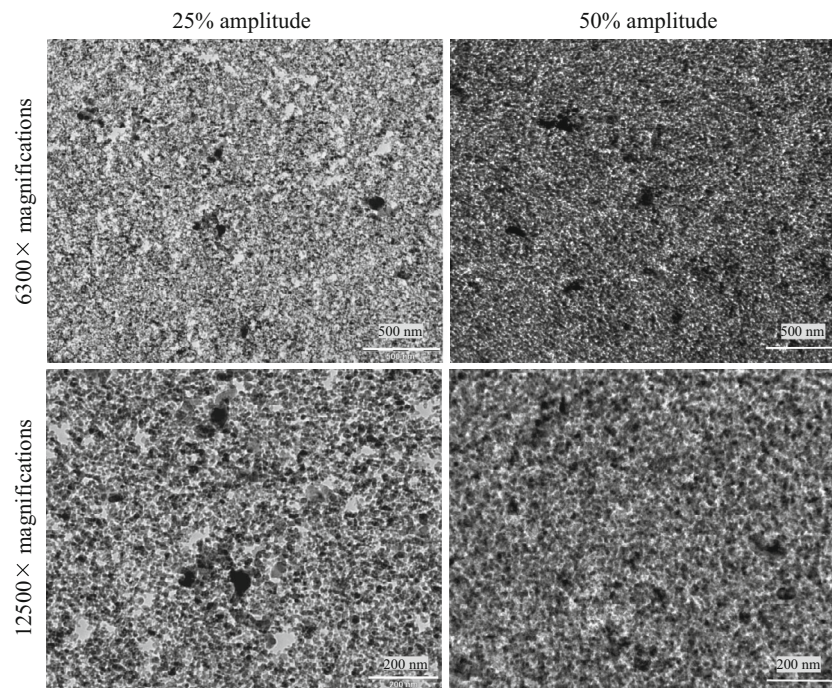
25% amplitude   50% amplitude

Fig. 6 TEM images of Al_2O_3–water nanofluid samples after 5 h of ultrasonication. (Reprinted from [40], copyright (2015) with permission from Elsevier)

Effect of ultrasonication on oxide nanofluids

Effect of ultrasonication on Al_2O_3 nanofluids

The effect of ultrasonication duration on the stability (as zeta potential) of Al_2O_3–water nanofluid was studied in [50] and found zeta potential to increase with ultrasonication time and reached a maximum at 5 h of duration and later reduced. Nguyen et al. [71] investigated the effect of dispersion stability and ultrasonication on the cluster size of alumina nanofluid. The increased ultrasonication time on suspended nanoparticles in aqueous solution could lead to nanoparticle re-agglomeration. In work [52], the ultrasonication effect on Al_2O_3–W nanofluid was analyzed. Their results showed that the dispersion was dependent on ultrasonication time. Sufficient sonication time aided in obtaining better stability and less agglomeration, insufficient sonication time lead to lower stability and agglomeration. The results also show that sedimentation % of nanoparticles was more for nanofluid prepared by longer storage duration. The particle size diameter reduced with the increase in ultrasonication duration.

Another research study [72] carried out on properties of Al_2O_3–W nanofluids for ultrasonication with two types of pulses and found that continuous pulses developed more stable solution than discontinuous pulses for similar sonication time. The effect of ultrasonication duration on
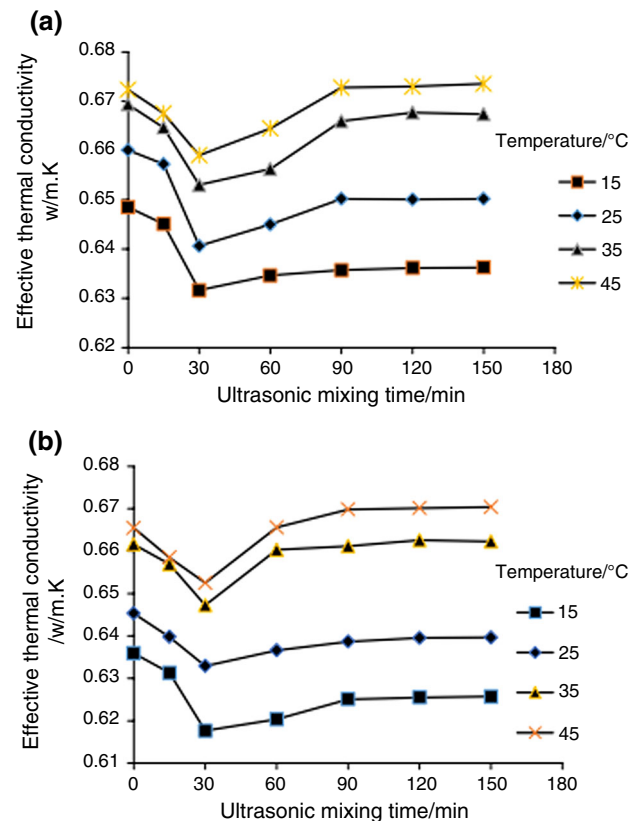

Fig. 7 Thermal conductivity variation of alumina nanofluid for **a** vol% of 3 and **b** vol% of 2. (Reprinted with permission from [73]. Copyright © 2014, Springer-Verlag Berlin Heidelberg)

Fig. 8 Effect on **a** viscosity and **b** density of Al_2O_3–W nanofluid for different ultrasonication duration and temperature. (Reprinted from [70], copyright (2015) with permission from Elsevier)
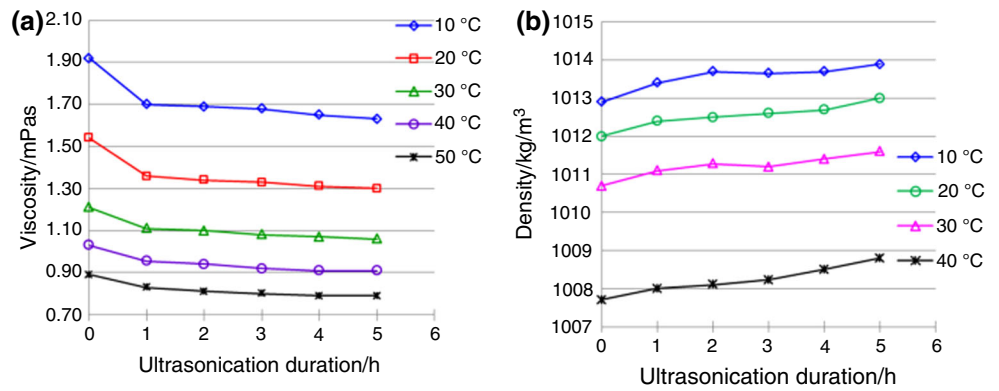

Fig. 9 Effect of ultrasonication duration on flow behavior index of the nanofluid [74]. (Reprinted from [70], copyright (2015) with permission from Elsevier)
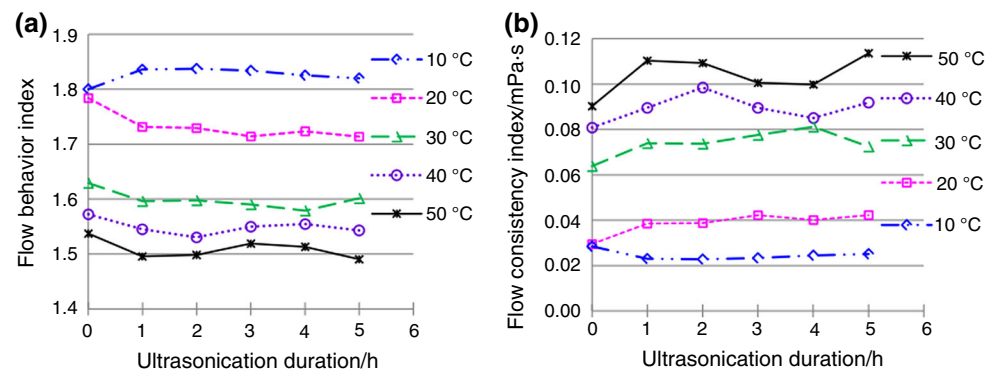

Fig. 10 Variation in shear stress of Al_2O_3–W nanofluid for different ultrasonication duration **a** 0 h, **b** 1 h, **c** 2 h and **d** 3 h. (Reprinted from [74], copyright (2015) with permission from Elsevier)
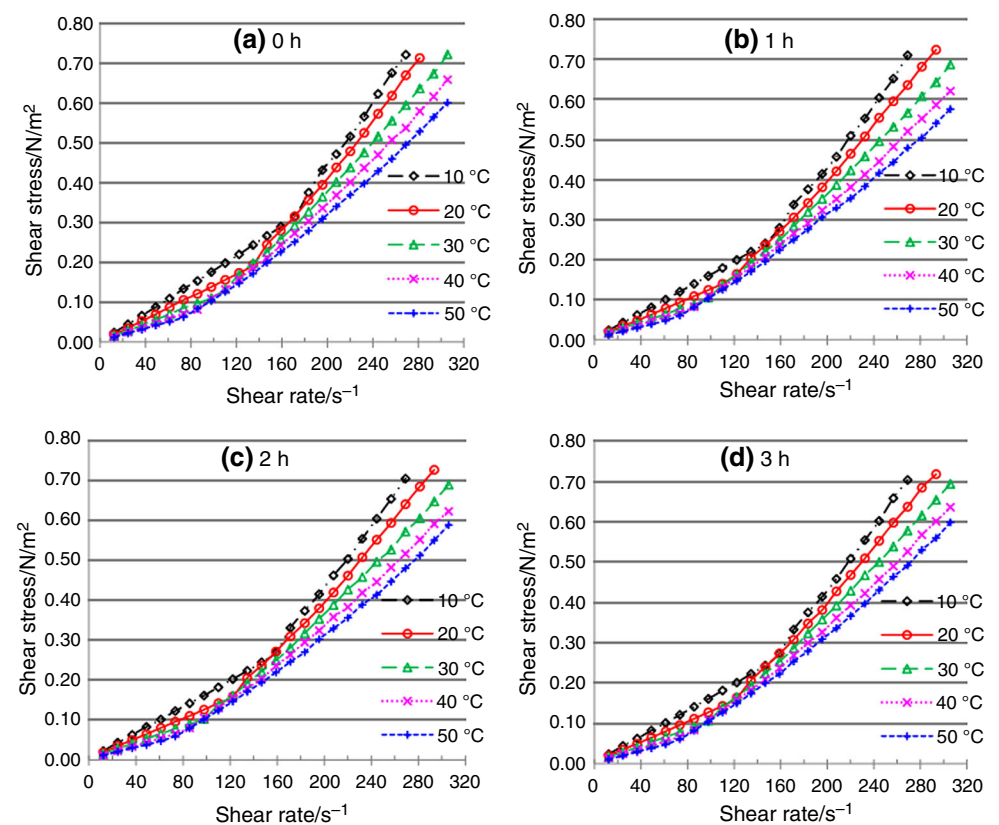
Table 1 Studies available about the effect of ultrasonication on Al_2O_3 based nanofluids

Nanofluid type	Time period	Variable parameter	Imaging type	Analyzed parameter	Remarks and observations	References
Al_2O_3–W	0, 5, 20, 30 h	0.01–0.3 vol%. Temperature: 21–39 °C	TEM	Viscosity, thermal conductivity, zeta potential	Ultrasonicating the nanofluid for more than 5 h is best for better dispersion of alumina with little trace of aggravations	[50]
Al_2O_3–W (13 nm)	0–200 s	Vibration amplitude: 10%, 30%, 60% Pulse ratio on/off: 0.1/2.0 (s/s), 1.0/1.0 (s/s), 0.1/0.1 (s/s)	TEM	Particle size distribution and mean size	The lowest size of alumina nanoparticle in aqueous solution can be obtained by continuous and pulsed ultrasonic irradiation. Higher amplitude of vibration did not show any betterment in breakage process. Optimum breakage vibration is 30%	[71]
Al_2O_3–W	1, 2, 3 h	0.5–1.5 vol%. Temperature: 15–40 °C	TEM	Thermal conductivity, convective heat transfer coefficient	Increased sonication time helped in obtaining better stability and less agglomeration, whereas insufficient sonication time leads to lower stability and agglomeration	[52]
Al_2O_3–W (13 nm)	0–180 min	Ultrasonication time, temperature	FESEM, TEM, photo capturing	Average cluster size, average particle size, absolute zeta potential, viscosity	The sonication was conducted for 0–180 min, the viscosity after sonication was measured at different temperatures and was better at a temperature range of 15–45 °C. Lower precipitation, better particle size, and higher zeta potential were observed with higher sonication time. The final conclusion was that the more stable and better viscosity of nanofluids were found at sonication for 90 min or higher	[39]
Al_2O_3– glycerol (80 nm)	0, 1, 2, 3, 4, 5, 6, 7, 8 h	Particle diameter, vol%, temperature, particle size	TEM, XRD, UV–vis spectra, photo capturing	Particle count, intensity, absorbance, viscosity, energy density, zeta potential	3 h is the optimized ultrasonication time for 80 nm and 100 nm particle. Optimum ultrasonication energy density for 80 nm and 100 nm nanofluids was found to be 3.0×107 kJ m^{-3} for 20–30 nm nanofluid and 1.5×107 kJ m^{-3}. With the optimum energy density, the viscosity was found to be minimum. The results have shown that the viscosity was found to be higher for smaller particle size	[51]
Al_2O_3–W (25 nm)	0, 1, 2, 3, 4, 5, 6 h	Ultrasonication time, temperature,	TEM	Absolute zeta potential, average cluster size, thermal conductivity, viscosity, density	The thermal conductivity, dispersion, and density were found to be better with higher ultrasonication time and viscosity was found to decrease. A minimum of 2 h of sonication is required for better properties of nanofluids	[70]
Al_2O_3–W (13 nm)	0, 1, 2, 3, 4, 5, 6 h	Ultrasonication time, amplitude (25% and 50%)	TEM	Absolute zeta potential, particle size distribution	The better zeta potential, particle size distribution, and smaller aggregate sizes were found at an ultrasonication range of 3–5 h	[40]

Table 1 (continued)

| Nanofluid type	Time period	Variable parameter	Imaging type	Analyzed parameter	Remarks and observations	References
Al_2O_3–W (25 nm)	15, 30, 60, 90, 120, 150 and 180 min	1, 2, 3 vol%. Temperature: 15, 25, 35, 45 °C	UV–vis spectrometer, Dynamic light scattering	Stability, zeta potential, nanocluster size, UV absorbency	150 min was found to be the optimum ultrasonication time. UV absorbency depended on nanocluster size in nanofluid and concentration	[73]
Al_2O_3–W (13 nm)	0, 1, 2, 3, 4, 5 h	Shear rate, sonication time, temperature	TEM	Shear stress, yield stress, flow behavior index, microstructure	High agglomeration was found till 3 h of ultrasonication observed in TEM. 4 h of ultrasonication was good for proper distribution of nanoparticles	[74]
Al_2O_3–W	30 min	Temperature: 20–75 °C, 0.005, 0.15 and 0.2 vol%	SEM	Ultrasonic properties	Different vol% of nanomaterials had similar fluctuations and for some concentration, solid nanoparticles did not lose ultrasonic velocity. Continuous ultrasonic pulses developed more stable solution than discontinuous pulses for similar ultrasonication time	[72]
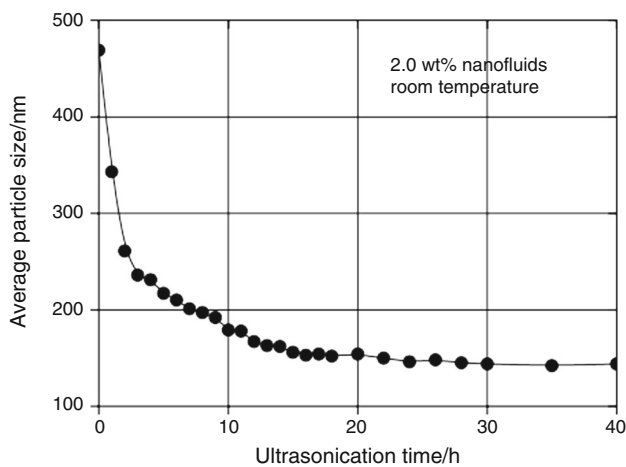
Fig. 11 Colloidal particle size decreasing with increasing ultrasonication time for TiO$_2$–W nanofluid. © Deutsche Physikalische Gesellschaft. (Reproduced from [64] by permission of IOP Publishing. CC BY-NC-SA)

Fig. 12 Effect of ultrasonication duration on settling time of nanoparticles in the base fluid. (Reprinted from [75], copyright (2012) with permission from Elsevier)

colloidal structure and viscosity of alumina–water nanofluid was investigated by [39]. The effect of sonication time on colloidal structure, stability and temperature-dependent viscosity of nanofluids were the main focus of the study [39]. Cluster size or agglomeration size of the nanoparticles in the nanofluids is high before sonication and is dispersed after ultrasonication for specific time as shown in Fig. 3. Colloidal dispersion was not uniform till 150 min of sonication but was more uniform for 180 min of ultrasonication as shown in Fig. 4 [39]. In another study focused to find the effective ultrasonication process for better colloidal dispersion of nanofluid. The main aim of
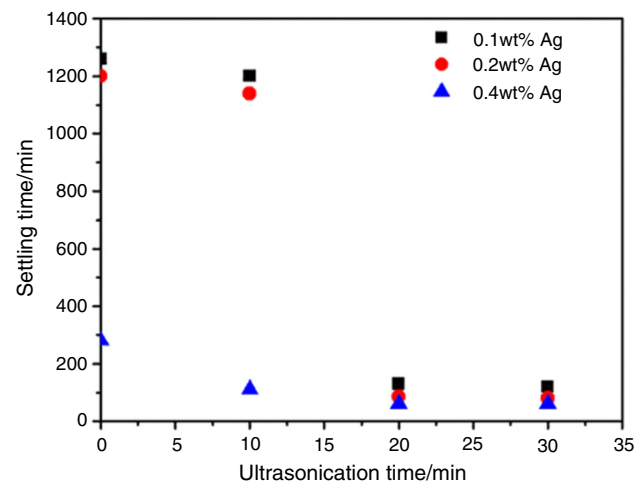
this research is to get a better stable nanofluid. The samples were sonicated for 1–5 h. The particle size distribution analyses showed that the agglomerated size was decreased with increase in sonication duration, the sample sonicated at 50% amplitude had a better zeta potential and the same are shown in Fig. 5 [40]. However, erosion of the sonicator tip was observed when the sonication was carried out 5 h with 50% amplitude, which can be seen in Fig. 6.

Adio et al. [51] noted the influence of ultrasonication energy on the dispersion consistency of aluminum oxide–glycerol nanofluid based on viscosity data, and model development for the required ultrasonication energy density in this experiment. Using viscometer the optimum
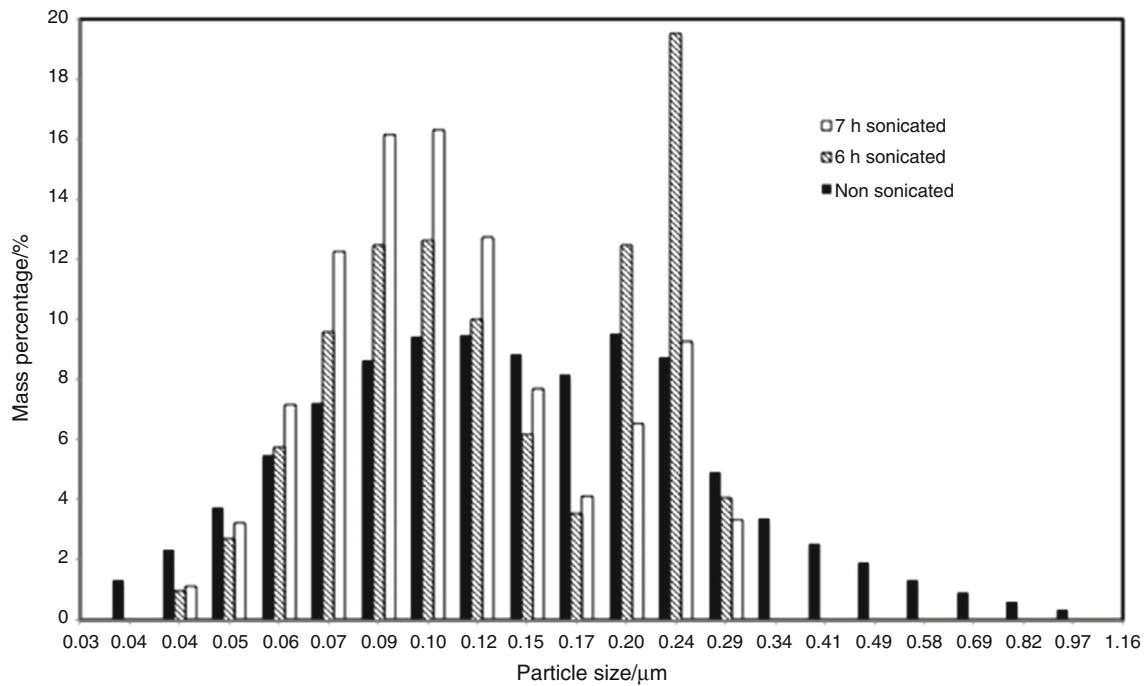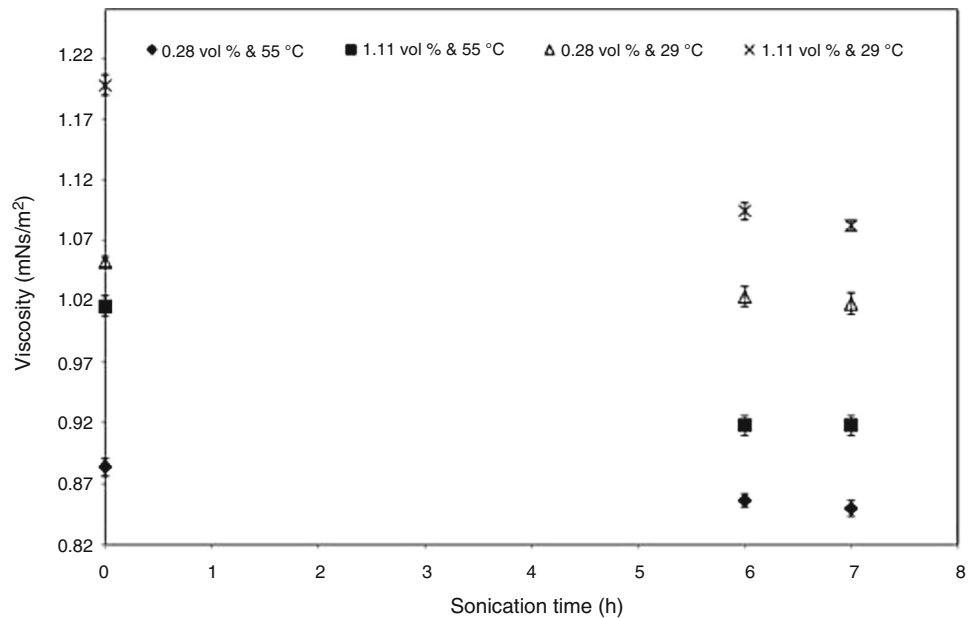
Fig. 13 Effect of probe sonication time on particle size of TiO_2–W nanofluid. (Reprinted from [76], copyright (2012) with permission from Elsevier)

Fig. 14 Reduction in viscosity due to increase in probe sonicating time of TiO_2–W nanofluid. (Reprinted from [76], copyright (2012) with permission from Elsevier)

energy density necessary for preparing homogeneous nanofluids was found for all particle sizes. And the volume fraction by energy density model was derived using dimensionless analysis considering the interaction/binding energy in the base fluid. The stability of alumina nanofluid was studied by UV–vis spectrum in [73]. The results showed that increase in sonication time caused cluster size to reduce, whereas further sonication leads to constant cluster size. Effective thermal conductivity reduced as cluster size decreased and then improved. At higher temperature enhancement of effective thermal conductivity was higher as shown in Fig. 7 [73]. The study [39] showed that the higher relationship exists between the sonication and viscosity of the fluid. It was found that the maximum viscosity was found at 60 min of sonication and then it was found to lean toward the base fluid viscosity. Another study
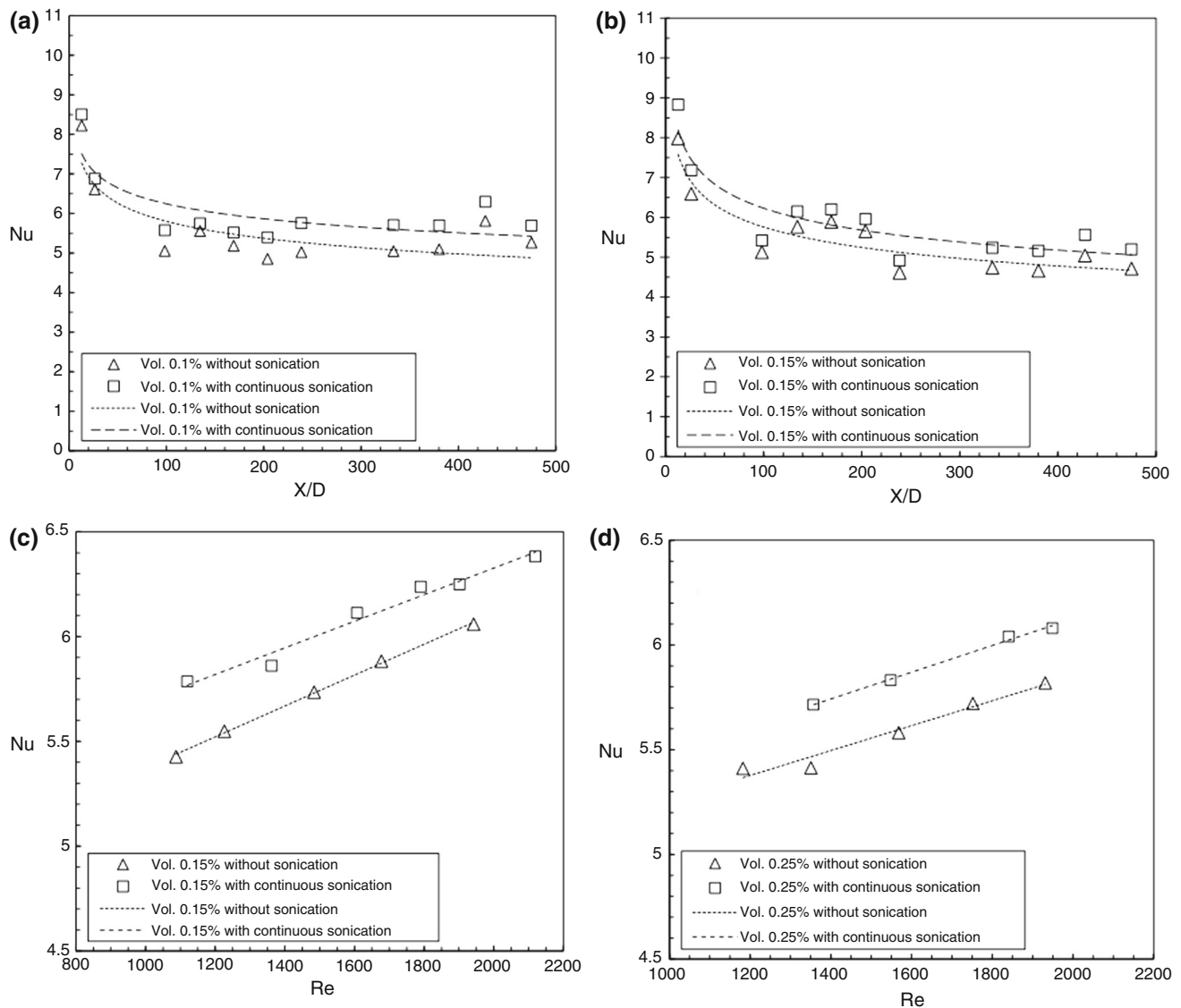
Fig. 15 Ultrasonication effect on local Nusselt number (*Nu*) for different vol% of nanoparticles at **a**, **b** different axial distance and **c**, **d** different Reynolds number (*Re*). (Reprinted from [77], copyright (2013) with permission from Elsevier)

[70], investigated the effects of ultrasonication duration on colloidal dispersion and thermophysical properties of alumina–water nanofluids. The particle size distribution analysis showed that the decrease in cluster size was due to the increase in sonication time. Initially, the decrease was rapid but the absolute zeta potential was maximum at the sonication duration of 3 h. Viscosity and density also changed with the change in sonication time and temperature as shown in Fig. 8 [70]. The relation between yield stress and ultrasonication period of nanofluids are studied in [74] and found that non-Newtonian flow characteristics were noticed and also the yield stress was found to be decreased with the increase of the fluid temperature. The flow characteristics as flow behavior index and the shear stress at various shear rates were studied for different

temperatures from 10 to 50 °C which are shown in Figs. 9 and 10, respectively. The consistency index, the yield stress and the flow behavior index were studied using the Herschel–Bulkley rheological model. It was noticed that the decrease of yield stress was rapid at the beginning of ultrasonication time and further the decrease was retarded [74]. Many more details related to alumina nanofluids are provided in Table 1.

Effect of ultrasonication on TiO₂ nanofluids

Chen et al. [64] studied the rheological behavior of EG-based TiO₂ nanofluid for different temperature and ultrasonication time. The results indicated that the nanofluids
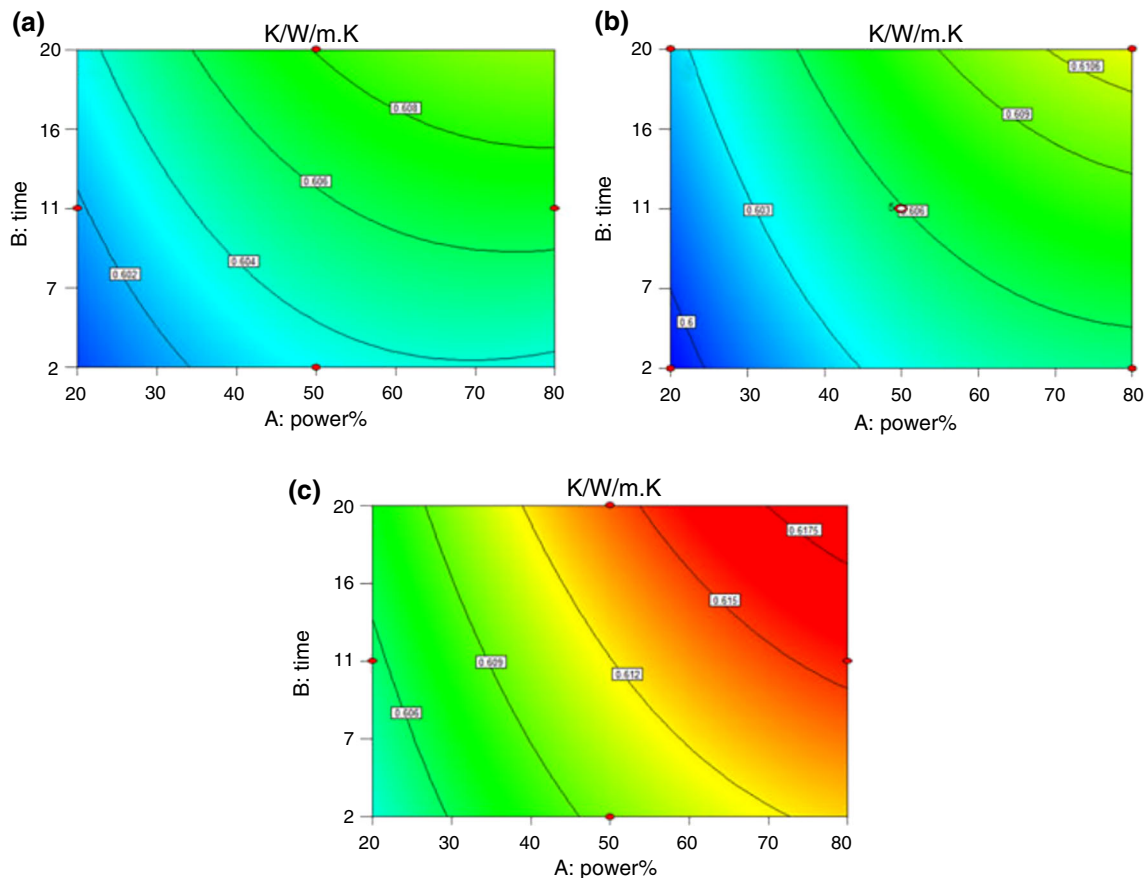
Fig. 16 Contour plots of TiO_2–W nanofluid thermal conductivity at different sonication time and energy for **a** 0.1 vol%, **b** 0.55 vol% and **c** 1 vol%. (Reprinted with permission from [79]. Copyright © 2012, Springer Science + Business Media Dordrecht)

were Newtonian and the shear viscosity was found to be the strong function of the temperature and particle concentration. Average nanoparticle size reduced with the increase in ultrasonication time as can be seen in Fig. 11 [64]. An experimental investigation was done [75] on addition of Ag nanoparticles to TiO_2 nanofluid to achieve recyclability of nanofluid and retract the nanoparticles from the used waste base fluid. Segregation and recycling of waste fluid by rapid settling of TiO_2 using increasing Ag nanoparticles and sonication was achieved. It was found that the settling time reduced very much for a particular concentration of Ag nanoparticles and for a particular value of sonication time as shown in Fig. 12 [75]. In [76], the researchers prepared TiO_2–W nanofluid by stirred bead milling and ultrasonication, and checked viscosity and thermal properties of the nanofluid. Dispersions of submicron agglomerations of lower viscosity and increased thermal conductivity were obtained with more ultrasonication duration. Particle size and viscosity reduced significantly for increased ultrasonication time, which are shown in Figs. 13 and 14, respectively.

The effect of adding TiO_2 nanoparticles into distilled water with continuous sonication and without sonication was investigated in [77]. The experiment was conducted for laminar flow region up to 0.1, 0.15 and 0.25 of vol%. It was noticed that the heat transfer improved significantly for the vol% considered due to continuous sonication. Heat transfer improvement in terms of Nusselt number (Nu) for different ultrasonication duration is shown in Fig. 15 [77]. In another study [72] on ultrasonic properties of TiO_2–W found similar effects of obtaining more stable nanofluid by using continuous pulses sonication [72]. An experimental study on the significance of ultrasonic processing and surfactant on thermal conductivity, viscosity, and stability of Titania nanofluid (TiO_2 nanoparticles of 25 nm diameter) is reported in [78]. They found that the addition of surfactant is beneficial to obtain highly stable nanofluid along with improved thermal conductivity [78]. Box–Behnken model was utilized in [79] to investigate thermal conductivity and stability of TiO_2 (25 nm) nanofluid. Their result revealed that the nanofluids became stable and by low power and with lower sonication period for low concentrations with no change in thermal conductivity. Whereas, high thermal conductivity (Fig. 16) and stability of nanofluids coincided at 1 vol%, i.e., at higher concentrations [79].

Scales

500 nm   200 nm   100 nm
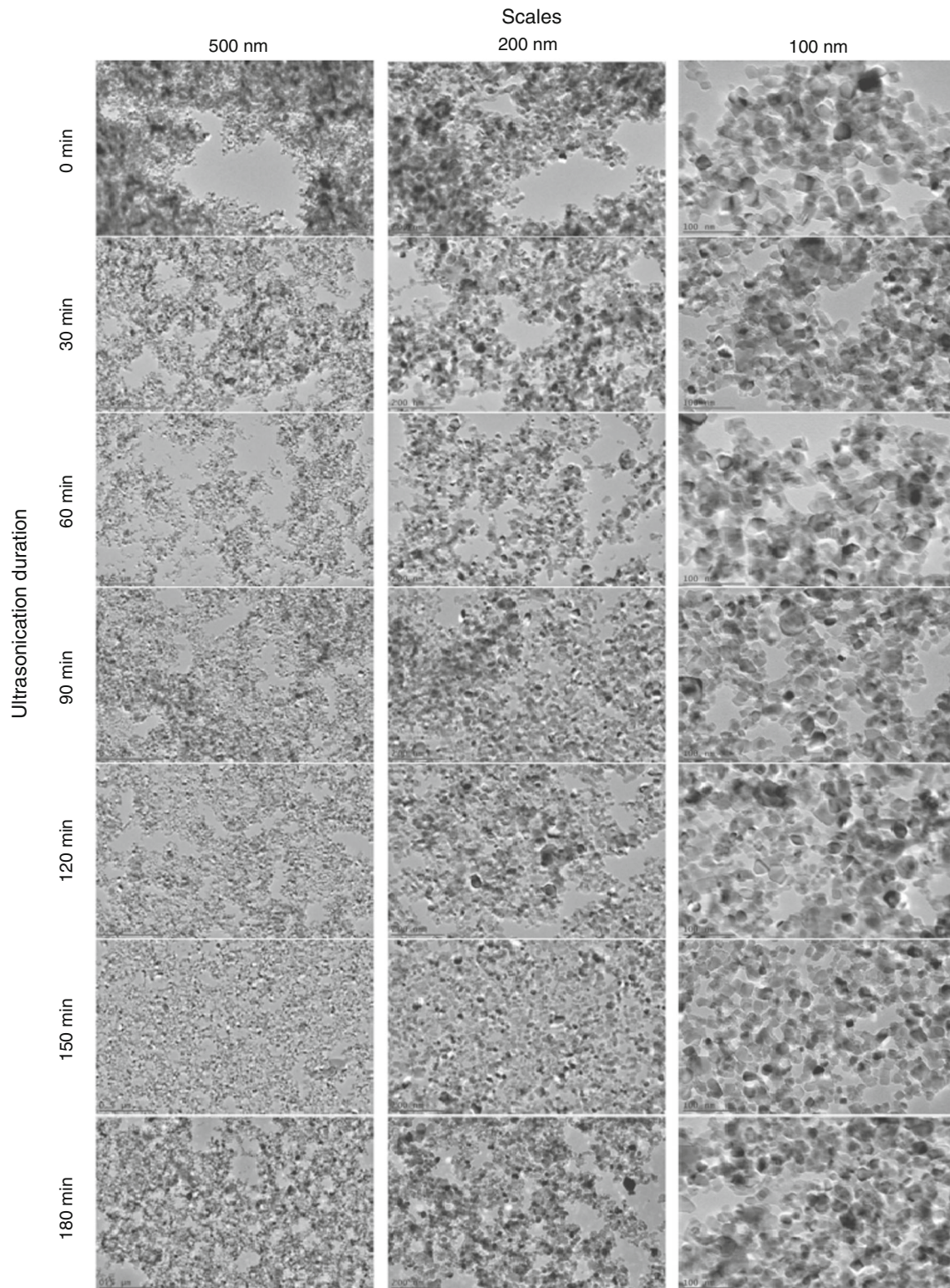
Fig. 17 Microstructure variation of TiO$_2$–W nanofluid as seen in TEM for different sonication time. (Reprinted from [80], copyright (2013) with permission from Elsevier)

Leena and Srinivasan synthesized TiO$_2$–W nanofluid using sol–gel method and carried out ultrasonic investigation on the same. They observed an increase in ultrasonic velocity of the nanoparticles during ultrasonication due to surface effect. This surface effect is nothing but the hydrogen bonding between the base fluid molecules and

Fig. 18 Zeta potential of TiO$_2$–W nanofluid for different sonication time. (Reprinted from [80], copyright (2013) with permission from Elsevier)
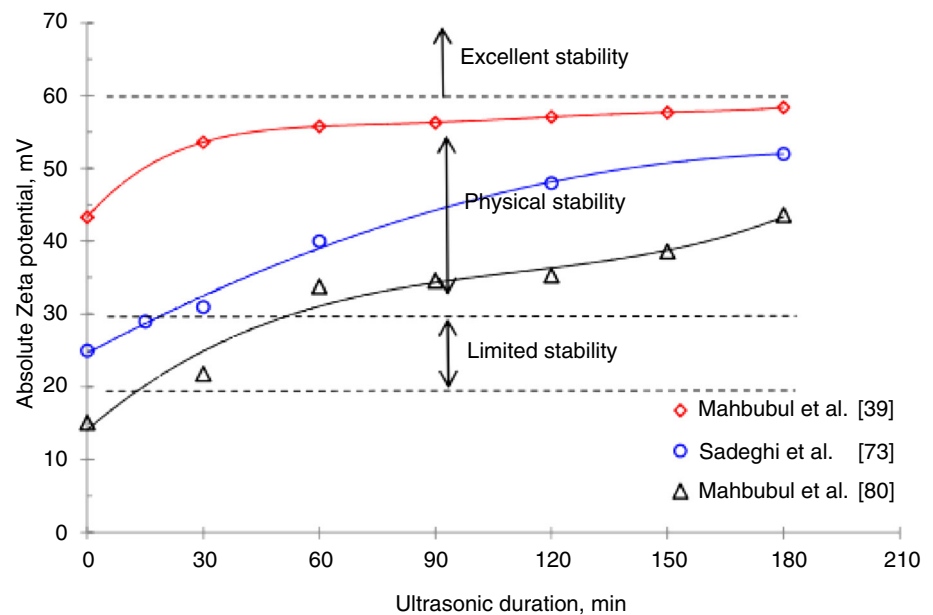
TiO$_2$ nanoparticles [41]. Ultrasonication effect on thermal conductivity of synthesized TiO$_2$ nanofluid with different base fluids using sol–gel method was determined experimentally and theoretically in [54].

Ethylene glycol, paraffin oil and water were the base fluids used to disperse TiO$_2$ nanoparticle. Effect of sonication on different concentrations (3–6%) of nanoparticle was also performed. They found a pronounced effect of sonication on thermal conductivity of the prepared nanofluid. Till 60 min of sonication time, the thermal conductivity of nanofluids increased and there on decreased. Intermolecular force and Brownian motion increased after 60 min of sonication which leads to clustering of nanoparticles and intern reducing the surface area. This caused a decrease in thermal conductivity of the nanofluids. However, water based nanofluid showed more improvement in thermal conductivity till 60 min of sonication. Thermal conductivity of all the nanofluids was also more with increasing concentration of nanoparticles from 3 to 6% [54]. The optimum ultrasonication time for stability and dispersion of TiO$_2$ nanofluid was studied by [80] as shown in Fig. 17. They learnt that the nanoparticles re-agglomerated after 150 min of ultrasonication and the ultrasonication time required to get optimum dispersion is a multivariate parameter dependent on ultrasonic treatment, type and characteristics of nanofluid. The stability of the nanofluid was checked through zeta potential factor and compared the results with [39, 73], as shown in Fig. 18 [80]. Table 2 gives the various details like vol%, sonication time, temperature range, parameters studied, etc., of research works carried out on TiO$_2$ based nanofluids.

Effect of ultrasonication on ZnO nanofluids

Chung et al. [81] synthesized ZnO–W nanofluid of varying purity by different preparation methods and checked the effectiveness of dispersion. Their result showed that ultrasonic horn was effective in reducing particle size, sedimentation rate and in obtaining minimum achievable size than other types of sonication method [81]. Effect of ultrasonication on thermal conductivity of ZnO–EG nanofluids was studied in [82]. They observed that excess sonication broke the particles into finer segments and better dispersion of ZnO, as observed by light scattering intensity % and TEM images of the nanofluid, which are shown in Figs. 19 and 20, respectively. Variation in thermal conductivity at different sonication hours obtained is shown in Fig. 21 [82]. More details of investigations carried out related to ZnO nanofluids are presented in Table 3.

Effect of ultrasonication on other oxide based nanofluids

A work on copper oxide nanoparticles (10–30 nm) dispersed in ethylene glycol and experimented for viscosity and thermal conductivity is reported in [83]. TEM images showed prolate spheroid shaped particles having an aspect ratio of 3, and despite of sonicating for a long time particles were still in aggregated state. Thermal conductivity increased only when the particle concentration was under dilute limit [83]. A study on agglomeration and stability of Silica–W nanofluid prepared using ultrasonic probe is found in [56]. Necessary ultrasonication time required to completely disperse the nanoparticles in the base fluid was 5 min at a pH of 10. Asadi et al. [84] experimented the

Table 2 Studies available about effect of ultrasonication on TiO_2 based nanofluids

Nanofluid type	Time period	Variable parameter	Surfactant	Imaging type	Analyzed parameter	Remarks and observations	References
TiO_2– EG	0, 10, 20, 30, 40 h	0.1, 0.21, 0.42, 0.86, 1.8 vol%, temperature 20–60 °C, shear stress		SEM	Average particle size, viscosity, shear rate, nanoparticle relative viscosity	Shear thinning behavior and non-Newtonian behavior were observed. Average size of the nanoparticle reduced when ultrasonication time was increased	[64]
TiO_2–W	0–7 h (probe)	Temperature: 29–55 °C. 0.27–1.39 vol%		SEM, XRD	Viscosity, stability, thermal conductivity	Reduction in viscosity is observed with increase in ultrasonication time from 0 to 7 h which was clearly due to reduced agglomerate size	[76]
TiO_2–W and Ag (25–70 nm)	0, 5, 10, 15, 20, 25, 30, 35 min	(0.1, 0.2, 0.4 vol%), pH value of solution		SEM, photograph, XRD	Zeta potential, settling time, surface potential and distance	It was found that increasing the Ag nanoparticle concentration and the ultrasonication time the dispersion stability was reduced	[75]
TiO_2–W		Ru, non-dimensional axial distance	CTAB	Atomic force microscopy (AFM)	Nu, Heat transfer	3.1% improvement in Nusselt number (Nu) was seen for 0.15 vol% with no ultrasonication. Whereas, due to continuous ultrasonication, 8% increase in Nu was obtained. The reason for improvement in Nu is by prevention of nanoparticle agglomeration due to ultrasonic waves	[77]
TiO_2–W (25 nm)	1, 2, 3 h (horn and bath)	Surfactant 0.007–0.012 vol%. Horn time and bath sonication time	Sodium dodecyl sulfate (SDS)	UV–vis spectrometry, TEM, photo capturing	Thermal Conductivity, Stability, Viscosity, zeta potential	Addition of surfactant elevated stability along with enhanced thermal conductivity. The deposition rate is dependent on the method used for homogenization. Maximum ultrasonication is best to obtain higher stability	[78]

Table 2 (continued)

Nanofluid type	Time period	Variable parameter	Surfactant	Imaging type	Analyzed parameter	Remarks and observations	References
TiO$_2$–W	2, 11, 20 min	Ultrasonic power: 20, 50, 80%. Nanoparticle. 0.1, 0.55, 1 vol%		UV–Vis spectrophotometer	Stability, thermal conductivity	Stability and thermal conductivity are inversely related. Sonication power is more significant than ultrasonication time on stability of nanofluid	[79]
TiO$_2$–W		0.04–0.20 vol%		XRD, HRSEM, FT-Raman spectroscopy, UV–visible spectrometer, X-ray spectroscopy	Stability, adiabatic compressibility, intermolecular free length and acoustic impedance	In water, molecular interaction is pronounced due to the good association of solute and solvent molecules in water. Ultrasonication provides a homogeneous suspension of titania oxide nanofluids	[41]
TiO$_2$–W, TiO$_2$–EG, TiO$_2$–Paraffin oil (5 nm)	20, 40, 60, 80, 100, 120, 140 min	0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07 vol%		XRD, TEM	Thermal conductivity	Using longer ultrasonication (till 60 min) duration provided an improvement in thermal conductivity of nanofluids	[54]
TiO$_2$–W (21 nm)	30, 60, 90, 120, 150, and 180 min			FESEM, TEM, DLS	Particle size and distribution, Zeta potential	The optimum time for ultrasonication was found to be 150 min. Ultrasonicating for more than 150 min resulted in re-agglomeration of nanofluids. Zeta potential increased for increasing ultrasonication time. The decrease in cluster size with ultrasonication time was not same for each time interval. Particle size ceased decreasing after 150 min of ultrasonication	[80]

effect of sonication time and surfactant on stability and thermal conductivity of Mg(OH)$_2$ nanoparticle for varying solid concentration, sonication time and for different surfactant. They realized that cetyl trimenthyl ammonium bromide (CTAB) surfactant improved stability compared with other surfactants. The zeta potential of the nanofluid with surfactant after a week is shown in Fig. 22 and relative thermal conductivity for different sonication time is shown in Fig. 23 [84]. Table 4 gives studies carried out on
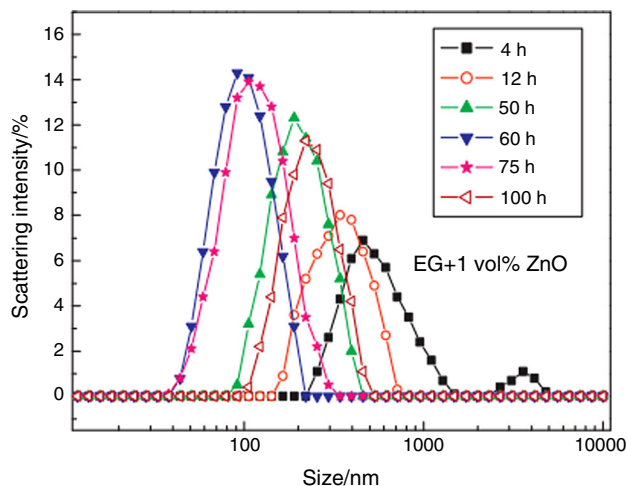
Fig. 19 Dynamic light scattering intensity % of ZnO nanofluid for different ultrasonication durations. (Reprinted from [82], copyright (2013) with permission from Elsevier)

different nanofluids and details are mentioned in different columns.

Effect of ultrasonication on CNT nanofluids

Yang et al. [85] investigated the rheological and thermal properties of MWCNTs dispersed in olefin oil by varying sonication energy and time. They found that the nanoparticle agglomeration and its colloidal suspension has major
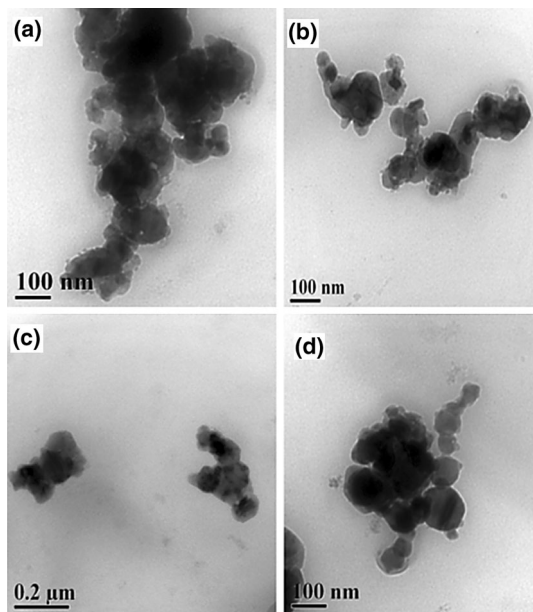

Fig. 20 1 vol% of ZnO–EG nanofluid in TEM images after ultrasonicating for **a** 4 h, **b** 12 h, **c** 60 h and **d** 100 h. (Reprinted from [82], copyright (2012) with permission from Elsevier)
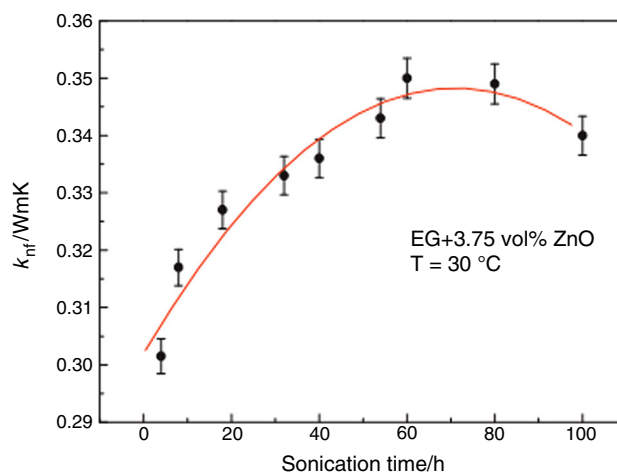

Fig. 21 Variation in thermal conductivity of 3.75% ZnO–EG nanofluid for different sonication time at 30 °C temperature. (Reprinted from [82], copyright (2012) with permission from Elsevier)

effect on heat transfer characteristics of the nanofluid. If the agglomeration of particle is high, it leads to increased thermal conductivity and more viscosity [85]. Effect of sonication time on the dispersion of MWCNT in water and factors which optimize the efficiency were studied using TEM and UV–vis in [86]. MWCNTs dispersed to its maximum when stabilized by SDS for a certain amount of sonication energy. The adsorbed SDS molecules on the surface of MWCNTs prevented agglomeration maintaining the colloidal stability for few months which were seen through TEM images as shown in Fig. 24 [86]. In [87], the investigation was done on influence of ultrasonication time, temperature and volume fraction on thermo-physical properties of carbon nanofluid using thin layer technique. They identified that the clustering in CNT is lesser than any other suspensions for same vol% and higher sonication time thus, increasing thermal conductivity and setting time of nanoparticles [87].
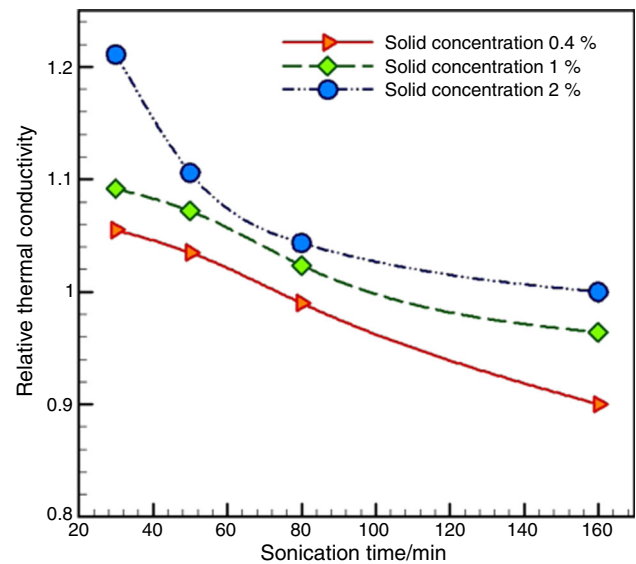
Garg et al. [88] experimentally analyzed the effect of ultrasonication on various thermal properties of 1.0 vol% of Multi-Walled Carbon Nanotubes (MWCNT). Power law viscosity model was used to discuss the shear thinning effect. They varied the time period of ultrasonication, the maximum improvement in thermal conductivity and convective heat transfer was found to be 20 and 32%, respectively. Thermal conductivity increased considerably above 24 °C up to some optimum time and deprived on increasing ultrasonication time further. Figure 25 shows the microstructure of MWCNT suspension in which 80 min of ultrasonication breaks the CNTs finely. The viscosity of nanofluid prepared by various sonication time was studied at different temperature and highest viscosity was observed for the nanofluid prepared by 40 min of

Table 3 Studies available about effect of ultrasonication on ZnO based nanofluids

Nanofluid type	Time period	Variable parameter	Surfactant	Imaging type	Analyzed parameter	Remarks and observations	References
ZnO–W (40–100 nm)	0–60 min	Depth of water in bath: 30–110 mm Horn and Probe bath	Ammonium polymethacrylate	TEM, Photo correlation spectroscopy, PCS dynamic light scattering	Particle size, sedimentation	The dispersion of ZnO particles was found to be due to fragmentation than erosion within particulate size of 50–300 nm. Ultrasonic field is larger in baths and are not intense but varies significantly and is intense in center floor location. Ultrasonic horn and highest ultrasonication duration are effective in reducing particle size and sedimentation rate of nanofluid	[81]
ZnO–EG	4, 12, 50, 60, 75 and 100 h	Temperature: 10–70 °C. ZnO. 0.5–3.75 vol%		XRD, TEM, dynamic light scattering	Thermal conductivity	Maximum thermal conductivity is attained in nanofluid ultrasonicated over 60 h	[82]
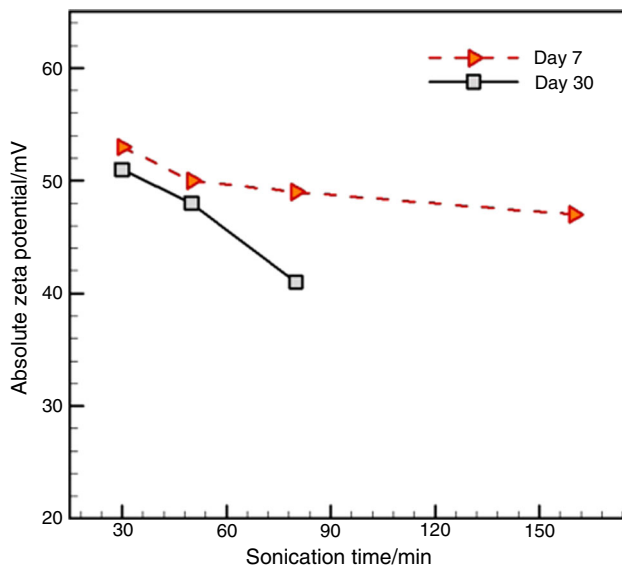
Fig. 22 Variation in zeta potential for different sonication time and at different days of $Mg(OH)_2$–W nanofluids. (Reprinted from [84], copyright (2016) with permission from Elsevier)

Fig. 23 Variation in relative thermal conductivity for different sonication time and at different solid concentrations of $Mg(OH)_2$–W nanofluids. (Reprinted from [84], copyright (2016) with permission from Elsevier)

ultrasonication, whereas flow behavior index remains almost constant as shown in Fig. 26 [88]. Dispersion behavior of SWCNTs using different dispersants (o-DCB and DMF) and due to the variation of sonication time from

20 to 220 s is reported in [89]. Sonication time improved the dispersion of SWCNT in the presence of both solvents. They found that the debundling and dispersion of SWCNT in these solvents was critically dependent on the

Table 4 Studies available about effect of ultrasonication on CNT based nanofluids

Nanofluid type	Time period	Variable parameter	Surfactant	Imaging type	Analyzed parameter	Remarks and observations	References
MWCNT–poly α–olefin oil	0–30 min	Stress, dispersant concentration, aspect ratio, dispersing energy, dispersing time, particle loading	Polyisobutene succinimide (PIBSI)	SEM, Carl Zeiss Axiotech microscope	Viscosity, frequency, aspect ratio, particle size distribution	The higher agglomerate size increases the thermal conductivity but ultrasonication process breaks the nanotubes, hence optimum ultrasonication must be employed	[85]
MWCNT–W	0–120 min by horn sonicator	Wavelength, energy, time	Sodium dodecyl sulfate (SDS)	UV–vis spectrometer, TEM	Absorbance, stability, dispersion, particle size	It was found that the time dependent ultrasonication reveals that the highest dispersion of MWCNT depends on the UV–vis absorbance of the solution; For higher dispersion of MWCNT higher concentration of surfactant should be used which would also decrease the required ultrasonication time; Ultrasonication time has a major impact on the dispersion of MWCNT	[86]
SWCNT–EG	5, 10, 15, 20, 25 h	Temperature: 25, 30, 35, 40, 45, 50 °C. 0.5, 2, 1.5, 2, 2.5, 3 vol%		TEM, Raman spectroscopy	Thermo-physical properties	Elapsed ultrasonication time increased thermal conductivity. Highest ultrasonication time is best	[87]
MWCNT–W	20, 40, 60 and 80 min (probe)	Flow rate: 40–80 mL min^{-1}. Temperature: 15–30 °C	Gum arabic	Wet-TEM	Viscosity, convective heat transfer, thermal conductivity	Using gum arabic as surfactant resulted in a stable solution lasting for months. Viscosity increased immensely for an optimum ultrasonication time and reduced thereafter. Thermal conductivity increased up to some ultrasonication time and later decreased by increasing the ultrasonic duration	[88]
SWCNT–W, MWCNT–W	15 min		Sodium dodecyl benzyl sulfate, gum arabic	TEM	Stability, thermal conductivity	Effect of various factors on stability and thermal conductivity of nanofluid depends on parameters such as pH, temperature, power of ultrasonication, nanoparticle size and surfactant type, vol% Thermal conductivity is dependent on ultrasonication time for shorter durations whereas it is independent for longer durations	[47]
SWCNT–o-DCB and DMF	20–220 s + 3 h bath	(0–0.1 vol%), vapor pressure, viscosity, surface tension	Chloroform, toluene, nitro methane, acetonitrile		Absorbance, aggregation fractions	The ultrasonication time critically affects the dispersing and debundling of SWCNT; The effectiveness of the cavitation process is much related to many solvent parameters, including vapor pressure, viscosity, surface tension and sonication frequency, intensity and time	[89]

Table 4 (continued)

Nanofluid type	Time period	Variable parameter	Surfactant	Imaging type	Analyzed parameter	Remarks and observations	References
SWCNT–W, DWCNT–W, FWCNT–W, MWCNT–W'	45 min (bath sonicator)	Temperature: 20–40 °C	SDS	SEM, TEM, Fourier transformed infrared spectroscopy, ZS Nano S analyzer	Thermal conductivity, stability	Functionalized CNT structure had best dispersion and didn't tend to agglomerate due to the fineness of particles. In comparison, functionalized particles agglomerated lately than nanofluid obtained from other two methods. Ultrasonication duration does not provide much effect on functionalized nanofluids	[90]
MWCNT–EG	0, 5, 40, 140, 520, 1355 min (pulsed and continuous)	Gum arabic concentration: 0.1–3%	Gum arabic	SEM, TEM	Thermal conductivity, viscosity	Nanofluid behaved as a non-Newtonian fluid. Maximum viscosity achieved for the ultrasonication of specific energy input 1.44×10^5 kJ m^{-3}. Prolonged ultrasonication duration is best for stability and viscosity as observed from the results	[92]
SWCNT–W	0, 20, 40, 60, 80, 100, 120 min Tip sonicator	Wavelength, sonication time, sonication power, diameter and length of SWCNT	Sodium deoxycholate (DOC)	UV–vis–NIR absorption spectra, AFM	Absorption, I_{max}-to-FWHM ratio, resonance area, SWCNT count	The ultrasonication conditions strongly affect the UV–vis–NIR absorption and the resonant and non-resonant background of SWCNT Intense ultrasonication duration is required for smaller diameter SWCNT which reduces the length of the SWCNT Ultrasonication tip of larger diameter was found to be more effective in dispersing the SWCNT	[91]
MWCNT–W	5 min–18 h (Horn)	Temperature: 700–850 °C		TEM	Thermo electric properties	Seebeck coefficient was -2.5 µV K^{-1} afore ultrasonication and 12 µV K^{-1} for ultrasonication thereafter 12 h	[48]
MWCNT– Epoxy resin (10–20 nm)	15, 45, 135 min	Sonication time, power, temperature		SEM	Tensile strength, tensile modulus, peak factor, storage modulus	Highest young's modulus obtained at ultrasonication power of 50 w and duration of 45 min. Highest tensile strength obtained at 25 w and 45-min ultrasonication duration At 50 w and 15-min highest glass transition temperature	[93]
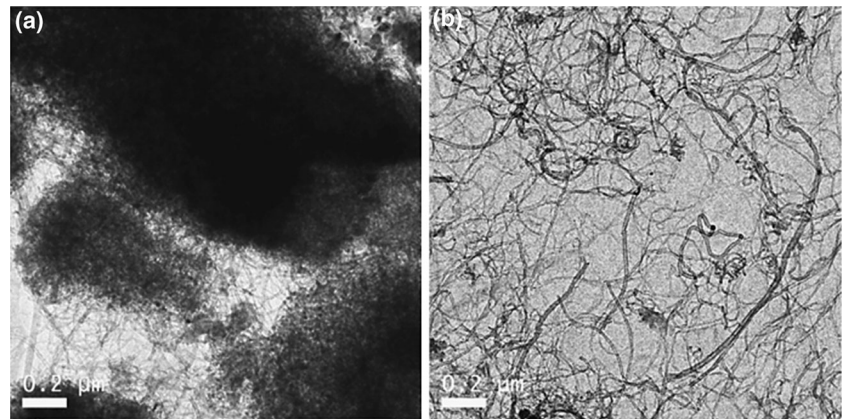
ultrasonication process and was highly dependent on many of the parameters of the base fluid, including the vapor pressure, viscosity, surface tension, density and molecular weight. This process is mainly guided by minimization of sonication requirements. Effect of ultrasonication on aggregation factors was also studied in [89] as shown in Fig. 27.

Meibodi et al. [47] studied the prominence of various parameters on thermal conductivity and stability of carbon nanotubes. They found that the more stable solution might not have higher thermal conductivity value and thermal conductivity of nanofluid is dependent on time soon after sonication, whereas independent of time at longer durations [47].

Nasiri et al. [90] researched on the outcome of ultra-sonication dispersion method on thermal conductivity and stability of SWCNT, Double Wall CNT (DWCNT), Few Wall CNT (FWCNT) and two different MWCNT nano-fluid. The experiment showed that the functionalized nanofluid has best stability and thermal conductivity compared to nanofluid prepared by ultrasonic bath and probe method (refer Fig. 28). After 50 h, the functionalized profile began to level due to stability, while other two profiles declined [90]. Colloidal dispersion of SWCNT in water using sodium deoxycholate as a surfactant for different sonicator parameters was studied by Yu et al. [91]. Sonication power was found to largely influence dispersion of SWCNT than sonication time on the resonance ratio. Ultrasonication was found to be more effective in

Fig. 26 Effect of different parameters on properties of MWCNT–W nanofluid when ultrasonicated for different time, at different temperature, GA surfactant and DI water. **a** Viscosity vs shear rate at 15 °C, **b** viscosity vs shear rate at 30 °C. At different ultrasonication time **c** flow consistency index and **d** flow behavior index. (Reprinted from [88], copyright (2009) with permission from Elsevier)
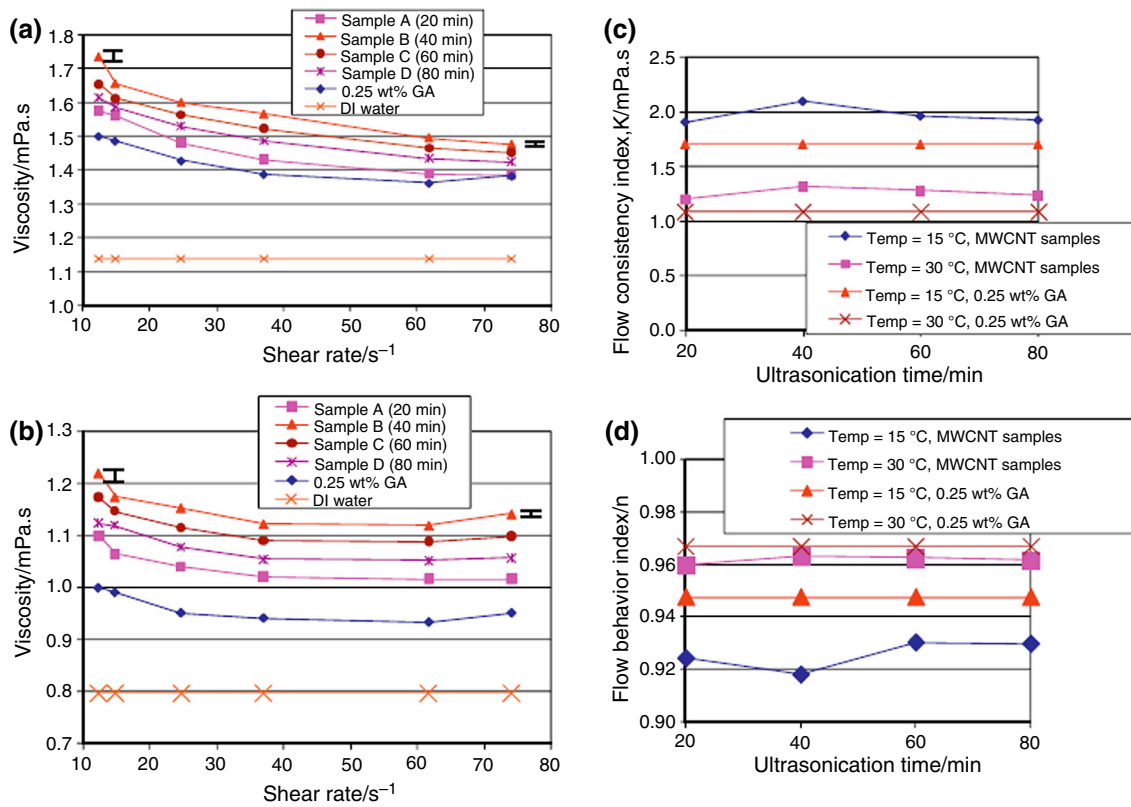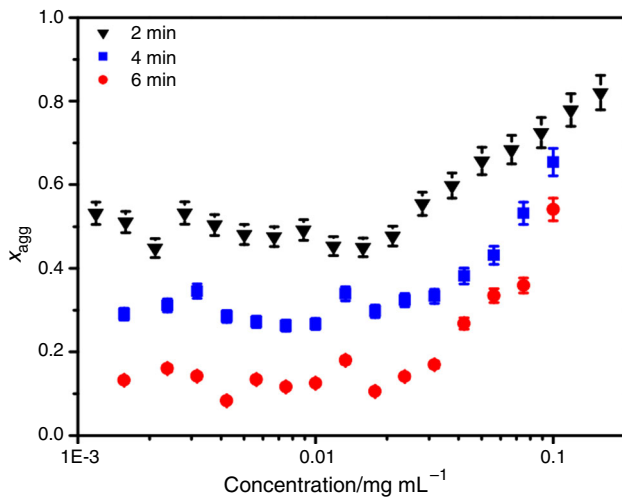

Fig. 27 At different ultrasonication time, effect of concentration on aggregation fractions (X_{agg}) of SWCNTs. (Reprinted with permission from [89]. Copyright (2009) American Chemical Society)

removing bundles of SWCNT to obtain homogeneous solution. Figure 29 shows variation in count (%) for change in nanoparticle length and diameter for different ultrasonication time [91].

Ruan and Jacobi [92] experimented the ultrasonication effects on rheological and thermal properties of MWCNT nanofluid. They investigated the effects macroscopically and microscopically. With sonication specific energy input, thermal conductivity increased non-linearly. Viscosity of nanofluid decreased with increase in shear rate. Using GA as a surfactant and sonicating for 120 min was found to be more stabilizing than without sonication [92]. Another study [48] was performed on the investigation of high energy probe sonication effect on thermoelectric power of MWCNT having larger diameter obtained by chemical vapor deposition with hydrogen/argon mixture carrier gas, liquid carbon precursor, and iron catalyst particles. The size of the nanotubes shortened, thus reducing electrical conductivity (Fig. 30) due to over sonication time [48]. In [59], the effect of sonication time on MWCNT–Epoxy resin was studied. It was observed that increasing the sonication time from 20 to 30 min showed improved electrical conductivity and strength of the nanocomposite [59]. Montazeri and Chitsazzadeh [93] studied the effect of sonication parameter on mechanical properties of MWCNT–Epoxy resin nanocomposite. Dynamic mechanical thermal analysis (DMTA) and tensile test were conducted under different dispersion state. The result showed

Fig. 28 Variation of effective thermal conductivity (K_{eff}) for change in temperature of functionalized nanofluid and nanofluid prepared by ultrasonic bath and probe **a** SWNTs, **b** DWNTs, **c** MWNTs1 and **d** MWNTs2. (Reprinted from [90], copyright (2009) with permission from Elsevier)
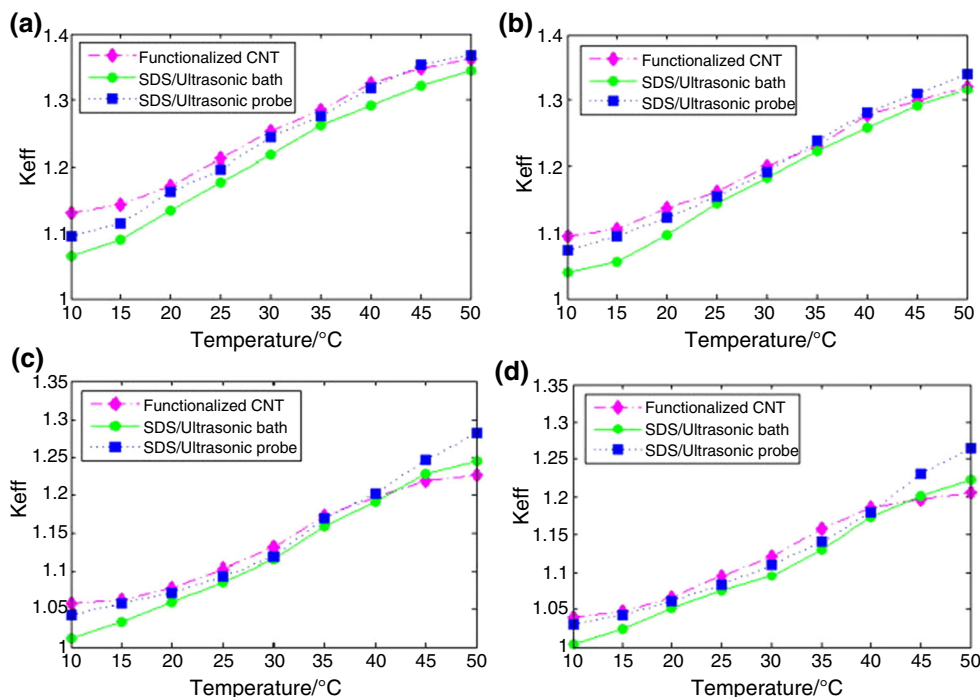
Fig. 29 a Diameter and **b** length statistics of SWCNTs analyzed using histogram for different ultrasonication duration in minutes. (Reprinted from [91], copyright (2012) with permission from Elsevier)
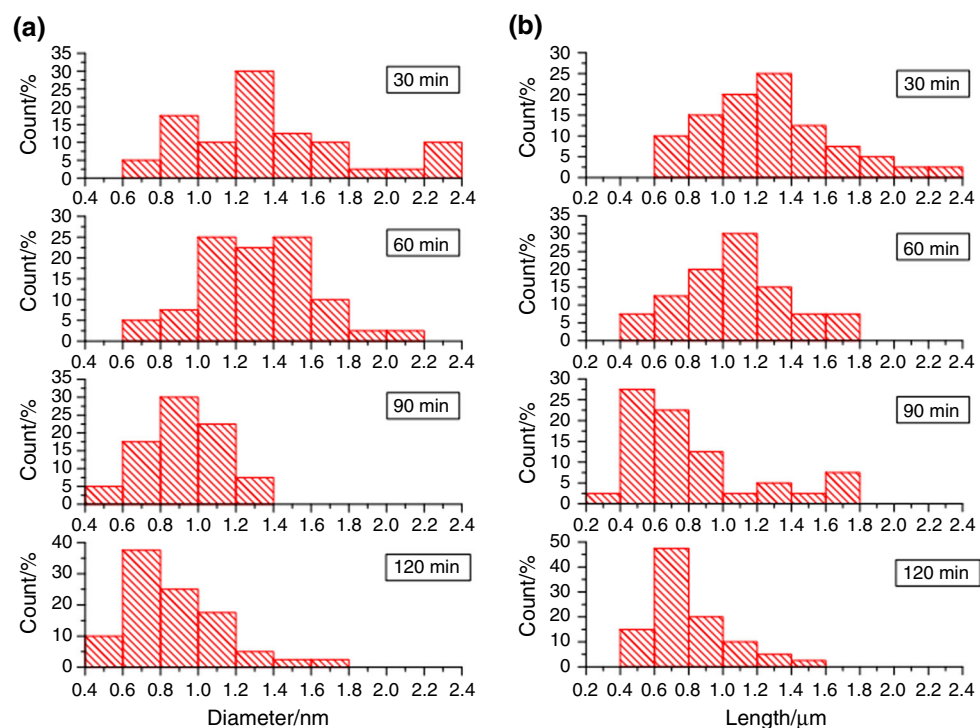
that the increase in the sonication time increased the Young's modulus of MWCNT [93]. Investigations pertinent to CNT nanofluids mentioned in this section are also mentioned in Table 5, which provides minor details of the studies.

Conclusions and future remarks

- Ultrasonication time has twofold effect on the nanofluids. At the optimum processing time, the ultrasonication aids in forming better dispersions, however, once the optimum time has been reached further ultrasonication results in an re-agglomeration.

Fig. 30 Electrical conductivity (σ) of MWCNTs dispersed in Deionized water (DI H$_2$O) for different ultrasonication time **a** MWCNT synthesized, **b** MWCNT raw, **c** Seebeck coefficient of MWCNT synthesized and **d** Seebeck coefficient of MWCNT raw. (Reprinted from [48], copyright (2012) with permission from Elsevier)
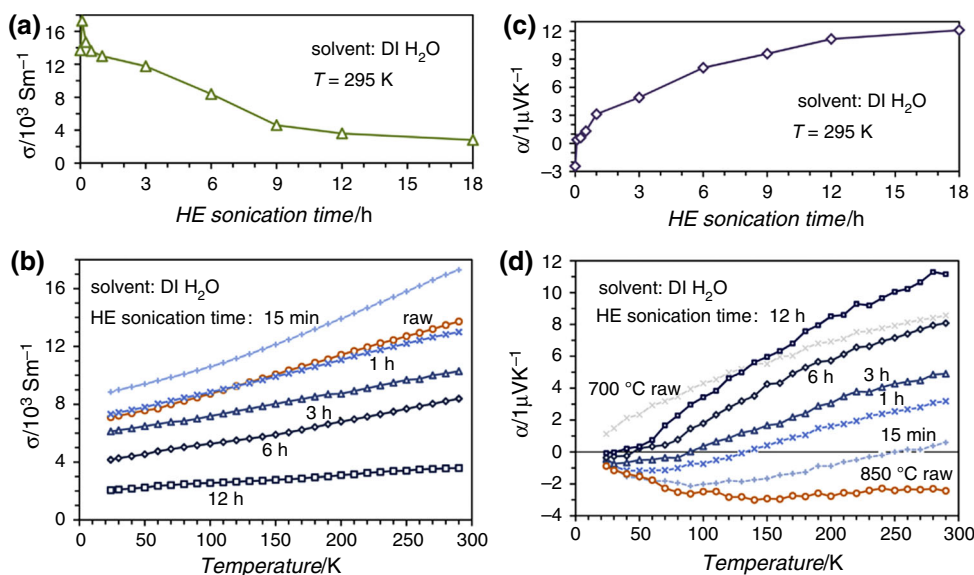
Table 5 Studies available about effect of ultrasonication on other nanoparticles based nanofluids

Nanofluid type	Time period	Variable parameter	Surfactant	Imaging type	Analyzed parameter	Remarks and observations	References
CuO–EG (10–30 nm)	1–30 h	Shear rate range: 0.01–100 S^{-1}		TEM, Dynamic light scattering	Thermal conductivity, viscosity, rheological property, zeta potential	Ultrasonicating for 9 h of duration provides best results in terms of stability and viscoelastic behavior	[83]
Silica–W + NaCl salt (12 nm)	3, 5, 7 min (probe)	Salt concentration: 0, 0.01, 0.05 M; pH: 1, 2, 5, 7, 10; Solid content: 0.10–0.20 W/W		Dynamic light scattering	Zeta potential, electrical double layer, viscosity, elastic and viscous moduli, particle size, Debye length and light backscattering	At pH = 2 isoelectric point was obtained. Solid content of 20 w/w delivered low viscosity and stability up to 48 h. Ultrasonication by probe method provides the best dispersion of nanofluids	[56]
Mg(OH)$_2$–W (20 nm)	10, 30, 50, 80, and 160 min	0.1, 0.2, 0.4, 0.8, 1, 1.5, and 2 vol%; Temperature: 25, 30, 35, 40, 45, 50 °C	CTAB, SDS, oleic acid	TEM	Stability, thermal conductivity, zeta potential	30 min of ultrasonication was the optimum time for the studied nanofluid in the presence of surfactant to obtain most nanofluid	[84]

- The optimum ultrasonication time is dependent on sonicator power, frequency used, volume concentration, nanomaterial type, base fluid, ultrasonicator type, etc.
- It is also observed that the sonication process not only reduces the agglomerate sizes but also decreases the size of the nanoparticle.
- Initially, at the beginning of ultrasonication, thermal conductivity of nanofluids were found to be decreased and further ultrasonication, the thermal conductivity of

the nanofluids increases for a certain optimum time depending on nanofluid.
- In the case of viscosity two types of trends were observed where one trend is that viscosity of nanofluid was decreased with increasing ultrasonication and other trend is the viscosity of nanofluids increases to the maximum for certain ultrasonication time then decreases, finally approaching the viscosity of the pure base fluid.
- Density of nanofluids was found to be increased with increasing ultrasonication durations.

- The stability of the nanofluid also depends on type of surfactant used. Surfactant used are usually nanomaterial specific. The concentration of surfactant used is also of concern. Using lesser concentration may lead to lower stability and over use may increase viscosity and thus increasing pressure drop. The stability of the nanofluid with surfactant is very much enhanced in comparison with the nanofluid without surfactants. With surfactant the nanofluids achieved stability for over months.

Following are some remarks for future work:

- It is necessary to consider as many sonication parameters as possible like durations, amplitudes, pulses, probe tip diameter, and sonication types.
- Effect of ultrasonication is needed to be considered with the change of the size, type, and concentration of particles in different base fluids.
- Surfactants also play some role in preparation and properties of nanofluids. Therefore, the effect of surfactant and temperature could be another review topic.
- Change of pH with and without using surfactants is another important research area.

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