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A Comprehensive Review on the Effect of Various Ultrasonication Parameters on the Stability of Nanofluid

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***Abstract:* Nanofluids (Engineered colloidal suspension of nanoparticles) are the new and promising heat transfer fluids with exceptional properties. Low stability, high pressure drop, and viscosity are the important drawbacks limiting the industrial application of nanofluids. The aggregation and sedimentation of nanoparticles are related to the colloidal structure of nanofluids, which directly affects the stability and viscosity. Several studies have revealed that the thermophysical properties of nanofluid are influenced by the nanoparticle type, size, shape, and concentration, base fluid type, and operating conditions. Furthermore, the ultrasonication probe type, time, power, frequency, and intensity, as well as surfactant type and concentration, are the primary factors influencing nanofluid stability. Among them, ultrasonication treatment is the simplest and most effective technique with longer nanofluid stability period. It is expected that, the present review will provide guidance and contribute towards various considerable ultrasonication factors which can prolong the stability period of the nanofluid.**

***Keywords*: Nanofluid; stability; ultrasonication; transducer; ultrasonication time; amplitude**

I. INTRODUCTION

Nanofluids are formed from the dispersion of nanoparticles in a heat transfer base fluid like water, refrigerants, ethylene glycol, propylene glycol, oils, and alcohols [1]–[10]. At least one particle dimension should be in the nanometer range with the superior thermal, electrical, optical, physical, and rheological properties. Prominent results confirmed the increment of the thermal conductivity with the addition of distinct nanoparticles [11], [12]. From the past few years nanofluids have gathered more attention especially in the field of heat transfer, lubrication, drug delivery, solar, oil recovery, drilling fluid, anti-freeze, paint, and wastewater treatment applications [13], [14]. Generally, liquid samples with dispersed particles are susceptible to form unstable agglomerates from the various particle to particle attraction forces including, gravitational, van der waals force, friction, combustion, Brownian and electrostatic forces to compromise the stability of the nanofluids [15]–[24]. Also, compared to nanoparticles barely movement was seen in the micro size particles in a dispersion phase whereas, nanoparticles are continuously moving in a random molecular motion and do not clog the flow. As the mass of nanoparticle is so small, the effect of gravitational force becomes negligible, but in some cases due to high surface activity the nanoparticles are prone to form clusters. At the same time, the nanofluids major applicability is also based on the proposed stability mechanism to avoid the further issues while loading, pumping, and processing [25]–[34].

According to this prospective, the proposed correlations for predicting nanofluid thermophysical properties like thermal conductivity, electrical conductivity, density, and viscosity are based on the assumption of stable suspension of nanoparticles [35]–[44]. So, poor stability mechanism may reduce the performance of the nanofluid. Also, the aggregates may clog the flow with the increased viscosity and pressure drop and decrease the rate of heat transfer with reduced thermal conductivity [45]. Various studies revealed that, choosing proper nanoparticle and base fluid type, and operating conditions (pH, temperature, ultrasonication parameters and zeta potential are the main factors responsible for the nanofluid stability [46]–[51]. Among them, ultrasonication treatment is the simplest and most effective technique with longer nanofluid stability period. Instead of overstressing on the thermophysical properties of nanofluid, the current paper reviewed various ultrasonication treatment parameters on the colloidal suspension of nanoparticles in the base fluid.

II. MATERIALS AND METHODS

Effect of ultrasonication treatment on the nanofluid stability

Ultrasound is well known for its homogeneous dispersion of nanoparticles in the base fluid techniques. Generally, using the chaotic principle more than 20 kHz of ultrasonic frequencies are applied to the solution for attaining longer period of stability. leading to the commonly known process as ultrasonication. Studies revealed that, using different type of ultrasonic transducer at distinct sonication time, frequency, power, and amplitude unique dispersion behavior of nanoparticles can be achieved [52], [53]. Finally, 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), field emission scanning electron microscopy (FESEM), thermogravimetry analysis (TGA), transmission electron microscope (TEM) and UV–Vis spectrometer, etc.

The effect of type of ultrasonic transducer

The ultrasonication transducers scatters the acoustic energy into medium in the form of ultrasonic waves. These ultrasonic vibrations can be applied in an indirect and direct way. As shown in **Fig. 1**, ultrasonic bath is used for applying the indirect form of waves and whereas probe sonicator is used for delivering direct form of ultrasonic waves. In the bath ultrasonic transducer, the sample is taken in a conical flask and immersed in the water bath. As the wave does not pass directly through the sample the cavitation process distribution is non-uniform. The ultrasonic wave intensity is also very low. As a result, the repeatability and scalability of the process is difficult.

Whereas, in direct sonication the ultrasonication transducer probe/horn is directly immersed in the sample to create the high intensity mechanical vibrations. Later, these vibrations directly pass through the sample in the form of acoustic waves. As the acoustic power is higher in the transducer the local heating is created in the form of heat energy. Moreover, the acoustic power intensity of the probe is nearly 100 times higher than the bath type ultrasonication. So, the probe type sonicator can provide better dispersion of particles compared to bath type by reducing particle size distribution.

For example, Noroozi et al. [54] compared the Al_2O_3 particle size distribution (PSD) between bath and probe type sonicator. As shown in **Fig. 2(a)**, the PSD was narrow representing the proper dispersion of nanoparticles in case of probe type sonicator. Also, with the reduction in particle size there was a shift in the absorption spectra was noticed in case of sonication (**Fig. 2(b))**. Similarly, Pradhan et al. [55] also confirmed that, mono dispersion of particles are possible by using probe type compared to bath type ultrasonic transducer **Fig. 2(c)**.

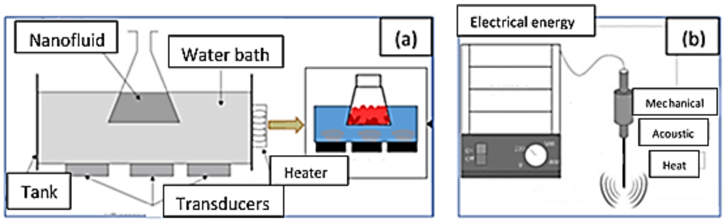

Figure 1 The ultrasonic transducers (a) bath type (b) probe or horn type

The effect of ultrasonication time

Even today, there is no proper approach on how much ultrasonication time is required to maintain/prolong the stability period of nanofluid. In most of the studies homogenization of the nanofluid was achieved at longer period of ultrasonic duration [56], [57]. In contrary, some of the studies also mentioned the creation of local heating from the prolonged ultrasonication time [58], [59]. In many studies researchers reported the effect of ultrasonication time on the particle size distribution and the thermophysical properties of the nanofluid [31], [47], [50]. In this regard, Amrollahi et al. [60] investigated the effect of ultrasonication time on the stability of a carbon nanotube-based nanofluid. They investigated the stability period of nanofluids in various nanoparticle compositions with varying ultrasonication times. They discovered that during ultrasonication times of up to 10 hours, the sedimentation time of elevated nanofluid concentrations is longer than that of lower concentrations. Nonetheless, at sonication times greater than 10 h, the tendency is vastly different; at higher concentrations, longer sediment time was achieved at longer ultrasonication time. According to their findings, increasing the ultrasonic irradiation time results in a much higher concentration of colloidal particles rather than cluster centres; the ultrasonic process breaks down large clumps of particles into relatively small subsets or even separates them into suspended particles. They also explained that at higher particle densities, Brownian motion between particles is greater than at lower concentrations, resulting in a longer sedimentation time. Sonawane et al. [16] studied the effect of ultrasonication time on the thermal conductivity enhancement (TCE Fig. 3(a)) of the TiO2/water nanofluid. Their results confirmed the generation of the local heat after 60 min of ultrasonication time and from the clustering the TCE was decreased. The local heat generated by ultrasound iss proportional to the acoustic energy dissipated (Equation 1) and intensity of ultrasound waves can be represented as the power dissipated per unit area (Equation 2). Here, P, m, Cp and Ap are denoting power (W), mass (kg), specific heat and cross-sectional area, respectively. Further, Chakraborty et al. [61] stated that the settling time of 0.2 wt % Ag/water nanofluid was decreased with increasing ultrasonication time as shown in **Fig. 3(b)**.

$$\text{Power dissipated } (P) = mC_p\left(\frac{dT}{dt}\right) \qquad \ldots\ldots(1)$$

$$\text{Intensity} = \frac{P}{A_P} \qquad \ldots\ldots(2)$$

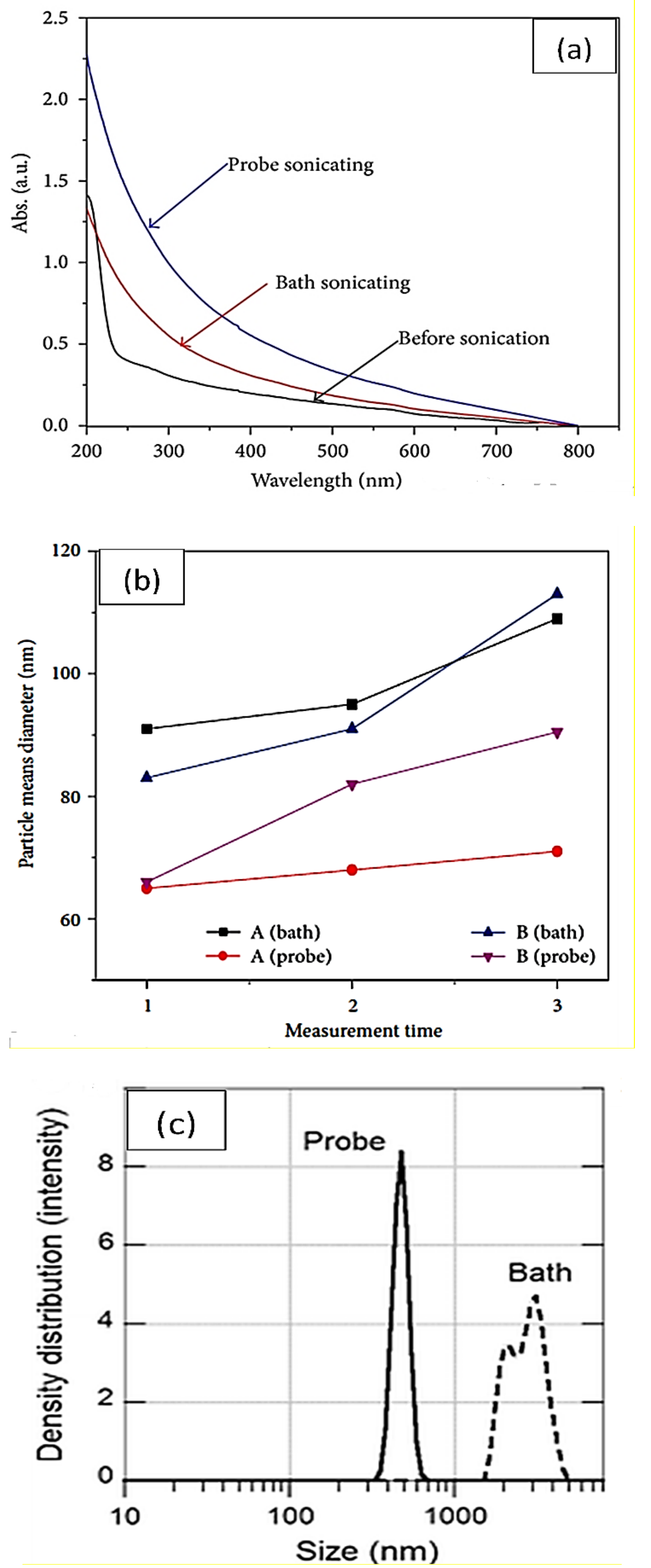

Figure 2: (a) The UV-vis absorption spectra of the Al_2O_3 nanoparticles without and with the bath and probe-type sonicators **(b)** The particle size distribution of the Al_2O_3 [54] **(c)** aluminum [55] nanoparticle with the bath and probe-type sonicators.

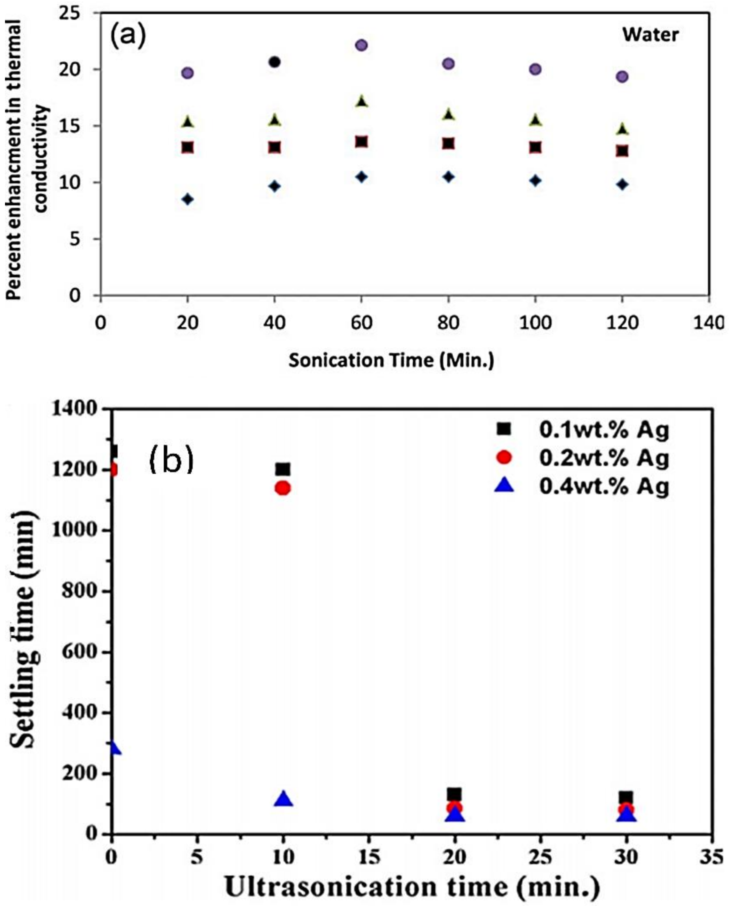

Figure 3 (a) The effect of ultrasonication time on the TCE of TiO_2/water nanofluid [16] **(b)** Effect of ultrasonication time on the settling time of the Ag /water nanofluid [61]

The effect of ultrasonication frequency and amplitude

Based on frequency, ultrasound is categorized into low (20–100 kHz), high frequency (100 kHz–1 MHz) and diagnostic (1–500 MHz) [62]–[64]. Ultrasonic frequencies in the range of 20–100 kHz is commonly used for the dispersion of nanofluid in the base fluid [65], [66]. Ultrasound within this range can produce acoustic shock waves which are used to maintain the stability of the nanofluid [67]. Asadi et al. [15] also emphasized the significance of ultrasonication parameters such as irradiation time, power, frequency, and amplitude on the stability and thermophysical properties of nanofluid. They concluded that by maintaining optimal ultrasonication parameters, we can achieve greater dispersion of the nanoparticles as well as improved heat transfer properties of the nanofluid.

In this regard, Santos et al. [68] experimented on the bath type ultrasonicator to identify the high intensity zones. Based on results, the maximum perforations appeared at maximum intensity which confirmed the non-homogeneous intensity distribution of bath type ultrasonicator. In other study, Mahbubul et al. [69] and Nguyen et al., [70] studied the effect of ultrasonication amplitude on the PSD of the Al_2O_3 nanoparticles in the water based nanofluid. They observed that, higher the amplitudes, lower the aggregate size from the enhanced rate of bubble collapse at higher vibration amplitude (Fig 4 and 5). Al-Waeli et al. [71] investigates the effect of nanofluid stability with variations in ultrasonication parameters. Their research concluded that the longer the ultrasonication period, the less settling of nanoparticles without further mixing.

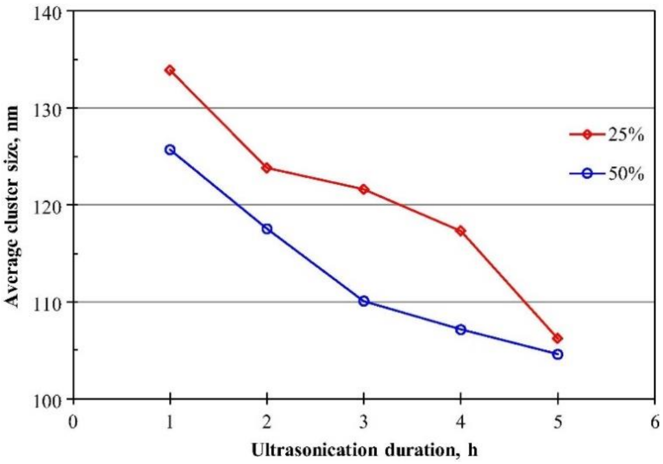

Figure 4. Al_2O_3 nanoparticles PSD at 25% and 50% amplitudes [52]

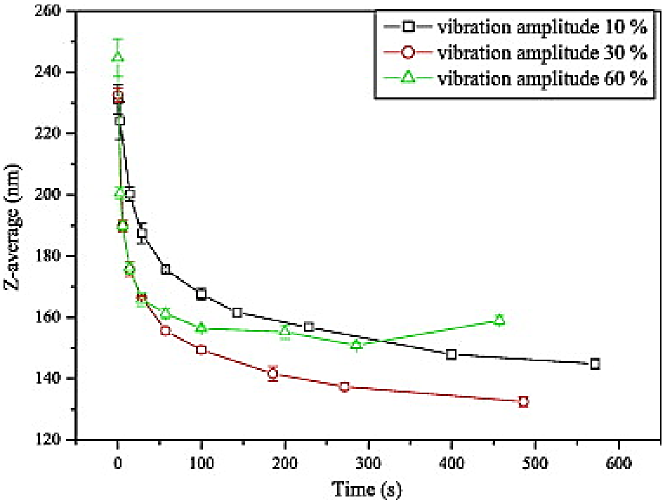

Figure 5 Al_2O_3 nanoparticles PSD at 10%, 30%, 60% amplitudes [70]

Amato et al. [72] investigated the effect of ultrasonication time and amplitude (%) on the particle size distribution of nanoparticles. According to their findings, ultrasonication of the can cause local heating due to cavitation of the sample. This heat can cause nanoparticles to re-agglomerate and form larger clusters. Furthermore, increasing the ultrasonication amplitude % can reduce the ultrasonic irradiation time, thereby improving stability. Noroozi et al. [54] investigated the impact of ultrasonic transducer type and intensity on the stability and thermophysical properties of an alumina-based nanofluid. Their comparative study concluded that higher and more focused ultrasonication from a probe type transducer at a higher intensity can effectively increase the stability and dispersion of the nanofluid.

III. CONCLUSION

Achieving well dispersed and stable suspensions have been one of the important drawbacks in nanofluid investigations. All favorable morphological, thermal, electrical and physical properties of nanofluid can be tuned as required by maintaining the stability of the nanofluid. In this current review, a special attention was given to the ultrasonication technique of deagglomeration of the nanoparticles because of its simplicity. In this regard, the effect of various parameters including ultrasonication transducer type, ultrasonication time, and ultrasonication frequency and amplitude on the stability of the nanofluid was reviewed. The study concluded that, the probe type ultrasonic transducer with high ultrasonication time and ultrasonication amplitude can result a well dispersed nanofluid with prolonged stability period. Moreover, based on the quantity of the nanofluid optimum ultrasonication time and frequency can be tuned to avoid the local heating while processing.

IV. ACKNOWLEDGEMENT

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