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Influence of different parameters and their coupled effects on the stability of alumina nanofluids by a fractional factorial design approach

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ABSTRACT

Nanofluids have been introduced as new-generation fluids able to improve energy efficiency in heat exchangers. However, stability problems related to both agglomeration and sedimentation of nanoparticles have limited industrial-level scaling. A fractional factorial experimental 2^{k-1} design was applied in order to evaluate the effects of nanoparticle concentration, surfactant type and concentration, ultrasonic amplitude as well as ultrasonic time on the stability of alumina (Al_2O_3) nanofluids. Commercial alumina nanoparticles (particle diameter <50 nm) were dispersed in deionized water using ultrasonic probe dispersion equipment. Sodium dodecylbenzenesulfonate (SDBS) and cetyltrimethylammonium bromide (CTAB) were used as surfactants. The stability of the nanofluids in static mode was monitored by visual inspection and UV visible spectroscopy. The results of the experimental design showed that the coupled effects between surfactant type and surfactant concentration and between ultrasonication tip amplitude and ultrasonication time had the most pronounced effects on nanofluid stability. The experimental conditions providing the best stability were 0.5 wt% of Al_2O_3, CTAB, critical micelle surfactant concentration, 30% ultrasonic amplitude and 30 min of ultrasonication.

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1. Introduction

Nanofluids are considered to have high potential in improving energy efficiency in heat transfer systems [1]. Nanofluids were presented by Choi and Eastman in 1995 [2]. They are suspensions obtained by dispersion of nanoparticles (<100 nm) in conventional fluids (water, fuel oil, ethylene-glycol, etc.). These kind of fluids are used in heat transfer systems [3–7], such as, thermosyphons [8–12], heat pipes [13–15], direct solar absorption [16,17] and micro-channels [18,19], among others. Since the introduction of nanofluids, big efforts have been made in order to enhance the principal thermophysical properties of conventional fluids involved in heat transfer processes [6,20,21].

Nonetheless, the application of nanofluids at industrial level has been limited by their poor stability. Such instability is generally associated with the agglomeration and sedimentation of nanoparticles caused by their high surface energy [22] and it is the cause of differences in thermo-physical properties for similar nanofluids found in the literature [23,24]. Aggregate size has a significant effect on thermal conductivity, heat transfer efficiency, optical properties as well as rheological properties of nanofluids [22].

Dispersion of nanoparticle powders involves the fragmentation of larger secondary agglomerates into their constituent primary particles while avoiding subsequent aggregation or agglomeration. This physical dispersion can be achieved by ultrasonication technique [25–27]. Additionally, electrostatic and steric stabilization are the most common methods used to stabilize the nanoparticles dispersed in a fluid. In electrostatic stabilization, surfactants or pH modifications are commonly used to provide surface charge to nanoparticles thus, generating strong repulsive forces among them [1,28–30]. In steric stabilization, functional groups are attached to the nanoparticles surface as a physical barrier between nanoparticles [31–33]. Combination of ultrasonication and surfactant used for electrostatic stabilization, are commonly utilized to prepare nanofluids [34–36].

Nanofluid stability is determined by the sum of the attraction and repulsion forces between nanoparticles [32] and it is still one of the main challenges in the world of research for nanofluid applications [6,31,37–44]. The most important attraction forces

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among nanoparticles are Van der Waals-type, [6,37,38,45–47]. Accordingly, if there is no energy barrier preventing the transition to a lower-energy state, those forces will prevail and hence the nanofluid will become unstable [32,49,28].

Factors like preparation method [39], nanoparticle concentration [49], nanoparticle type [45], nanoparticle shape [50], surfactant type [35,40,44,48,49,51–53] surfactant concentration [30,35,44,48,51–54], pH [51,52], ultrasonication type and time [51,55] as well as power of ultrasonication [56,57] have direct effects on the stability of nanofluids and their effects depend on both the nature of the nanoparticles and the base fluid [38,51].

In a recent work, Anushree et al. [45] studied the stability of metal oxide/water nanofluids: α-Al$_2$O$_3$, TiO$_2$, and γ-Al$_2$O$_3$ using time-dependent changes in UV–vis absorbance, hydrodynamic diameter, and zeta potential. They reported that stability was increased in γ-Al$_2$O$_3$ compared to α-Al$_2$O$_3$ and TiO$_2$ nanofluids. They also found that nanofluid instability increased as nanoparticle concentration was higher. Menbari et al. [51] researched the effects of stability parameters such as pH value, surfactant (sodium hexametaphosphate) concentration, and sonication time on nanofluids of CuO/water, γ-Al$_2$O$_3$/water and a mixture. They found optimal pH values in the range of 7–8.2, 8–9 and 7.6–8.5, respectively, and optimal surfactant mass concentration (weight ratio of the surfactant to nanoparticles) in the range of 1–1.5 for CuO/water and Al$_2$O$_3$-CuO/water. The authors also reported an optimal sonication time of 45 min for Al$_2$O$_3$/water and more than 100 min for CuO/water and Al$_2$O$_3$-CuO/water.

Mondragon et al. [58] analyzed the influence of solid content, pH, and salt concentration on the stability of silica/water nanofluids, obtaining stable nanofluids for at least 48 h with high solid content, using pH values greater than 7. In addition, Khairul et al. [30] evaluated the effects of nanoparticles and surfactant concentration on the stability of water-based alumina and copper oxide nanofluids. They found an optimal concentration of surfactant (SDBS) at 0.1 wt% for Al$_2$O$_3$/water and 0.15 wt% for CuO/water. Furthermore, Mahbubul et al. [59] assessed the effect of ultrasonication time on the colloidal dispersion and thermophysical properties of 0.5 vol% Al$_2$O$_3$/water nanofluid. They concluded that longer ultrasonication time is more effective and at least 2 h of ultrasonication are needed for a nanofluid to perform adequately.

In another work, Hwang et al. [60] implemented different techniques such as stirrer, ultrasonic bath, ultrasonic disruptor, and high-pressure homogenizer to disperse highly-agglomerated carbon black and silver nanoparticles in deionized water and silicon oil, respectively. Their results showed that the high-pressure homogenizer was the most successful method in breaking down the agglomerated nanoparticles suspended in base fluids. Chung et al. [26] assessed different ultrasonic techniques on a ZnO nanoparticle suspension in water, finding later that dispersion by ultrasonic horn was more adequate in terms of size reduction rate, minimum achievable size, and sedimentation rates, compared to different ultrasonic baths.

Experimental designs, such as the fractional factorial type, have also been applied to the study of nanofluids. This type of design is a kind of screening experiment in which many factors are considered. Its main goal is to identify the factors or coupled effects that have significant influence on a response variable [61]. Such factors or coupled effects are then further researched to find optimal values according to the requirements of the response variable [62,63]. Meibodi et al. [64] studied the role of eight parameters in both the stability and thermal conductivity of carbon nanotubes/water nanofluids, by using a fractional factorial 2^{8-4} resolution IV design. In their work, they also studied the effects of changes in nanoparticle size, nanoparticle weight percentage, surfactant type, surfactant weight percentage, temperature, pH, ultrasonic power, as well as elapsed time after preparation. Their results showed that

the main factor affecting the thermal conductivity of nanofluids is the elapsed time after preparation. They also reported that the effects caused by different interactions altering the stability of nanofluids are aliased. Such results are inconclusive due to the resolution of the experimental design and errors reported by the authors, attributed to nanofluid stability variations.

In the studies mentioned above, it can be identified that the stability analysis is commonly focused on the effect of one or two factors. Nonetheless, studies encompassing the effect of more than three factors, and their interactions, in the assessment are not common. Therefore, studying more factors and their coupled effects on nanofluid stability is essential to both identify those that have considerable influence and to optimize values, in order to achieve real-life nanofluid usage.

In this work, a fractional factorial 2^{5-1} resolution V design was applied to study the effects of nanoparticle concentration, surfactant type, surfactant concentration, ultrasonic amplitude, and ultrasonic time, as well as their coupled effects, on the stability of alumina nanofluids. Variation of UV–vis absorbance, and visual inspection over time were used to evaluate variations in nanofluid stability.

2. Methodology

2.1. Materials and methods

Alumina nanoparticles (<50 nm, from Sigma-Aldrich) were used in the nanofluids preparation. The morphology and particle size distribution of commercial Al$_2$O$_3$ were characterized by scanning electron microscopy (FE-SEM) in a JEOL JSM7100F at Instituto Tecnológico Metropolitano - ITM.

The nanofluids were obtained by the two-step method [65], to this Al$_2$O$_3$ and deionized (DI, <0.1 MΩ cm resistivity) water were combined in the right amount to obtain 20 ml of nanofluids with concentrations of 0.1 and 0.5 wt%.

Anionic sodium dodecylbenzenesulfonate (SDBS) and cationic cetyltrimethylammonium bromide (CTAB) were used as surfactants in the preparation of the nanofluid. Two levels of surfactant concentration were used, Critical Micelle Concentration (CMC) and five times the CMC. Previously, the CMC of each surfactant was determined through the electrical conductivity method. In this method, the variation of solution conductivity with the change of surfactant concentration in a solution of DI water and ionic surfactant was measured. Due to the dependence of the conductivity with the surfactant ionization, a sharp drop at the point of CMC (amphiphilic self-aggregation) can be observed and with this the CMC could be determined [66,67].

Alumina nanoparticles were used for nanofluid preparation. The particles were weighted using an analytical balance (Precisa, EP225 SM-DR) in a 25 ml beaker. The right amount of surfactant needed to obtain the desired concentration of surfactant was dissolved with a magnetic stirrer (1000 rpm by 20 min) in 20 ml of DI water at room temperature. The surfactant solution was carefully added to the nanoparticles and the dispersion was carried out by direct sonication, which is the *National Institute of Standards and Technology (NIST)'s* recommended method for this type of dispersions [68]. Qsonica Q500 Sonicator was operated at a 20 kHz frequency to disperse the particles. The ultrasonication probe tip was immersed directly in the suspension and the supplied energy (regulated by adjusting the vibration amplitude) was ranged between 30 and 50%, with ultrasonication times of 15 and 30 min. In order to avoid heating problems, ultrasonication processes were conducted in pulse mode (2 s ON and 2 s OFF). The temperature of dispersion was controlled by a LAUDA Alpha RA24 thermostat bath, in order