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SDS SURFACTANT EFFECTS ON STABILITY AND THERMOPHYSICAL PROPERTIES OF Al_2O_3–WATER BASED NANOFLUIDS

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ABSTRACT: Nanofluids have been considered as new potential heat transfer fluids, but there are controversial results about the stability and thermophysical properties of nanofluids in literature. In this experimental study, nanofluids at different aluminium oxide (Al_2O_3) volume fractions (0.3–1.1%) and sodium dodecyl sulfate (SDS) surfactant weight fractions (0.2–0.8%) were prepared by utilizing the two-step method. Stability of the obtained nanofluids was determined according to the sedimentation method, zeta potential and average particle size analysis. Density, viscosity and thermal conductivity of the nanofluids were measured experimentally from 298 K to 338 K. According to the results, the nanofluids prepared with 0.2% SDS began to collapse within a few minutes. However, it was observed that the stability of nanofluids prepared with 0.4% SDS, 0.6% SDS, and 0.8% SDS changed with the particle concentration. Besides, relative density values of nanofluids were found to be independent of temperature for each particle concentration. While relative viscosity of nanofluids increased with temperature, the highest relative thermal conductivity values of nanofluids with different weights of SDS were achieved at different temperatures. In general, relative thermal properties tend to increase with an increase in particle concentration. It has been observed that the stability and dispersion of nanofluids have a high effect on thermophysical properties.

Keywords: *Nanofluid, Aluminium Oxide, SDS, Stability, Thermophysical Properties*

SDS Yüzey Aktif Maddesinin Al_2O_3-Su Bazlı Nanoakışkanların Kararlılığı ve Termofiziksel Özellikleri Üzerine Etkileri

ÖZ: Nanoakışkanlar, yeni potansiyel ısı transfer akışkanları olarak kabul görmektedir; ancak literatürde nanoakışkanların kararlılığı ve termofiziksel özellikleri hakkında tartışmalı sonuçlar bulunmaktadır. Bu deneysel çalışmada, farklı hacim oranlarında alüminyum oksit (Al_2O_3) (%0,3–1,1) ve farklı ağırlık oranlarında sodyum dodesil sülfat (SDS) yüzey aktif madde (%0,2−0,8) içeren nanoakışkanlar, iki adımlı metot kullanılarak hazırlanmıştır. Elde edilen nanoakışkanların kararlılıkları, sedimantasyon yöntemi, zeta potansiyel ve ortalama boyut analizlerine göre belirlenmiştir. Nanoakışkanların yoğunluğu, viskozitesi ve ısıl iletkenliği 298 K ile 338 K sıcaklık aralığında deneysel olarak ölçülmüştür. Elde edilen sonuçlara göre, %0,2 SDS ile hazırlanan nanoakışkanlar birkaç dakika içerisinde çökmeye başlamıştır. Bunun yanı sıra %0,4 SDS, %0,6 SDS ve %0,8 SDS ile hazırlanan nanoakışkanların partikül konsantrasyonu ile kararlılıklarının değiştiği gözlemlenmiştir. Nanoakışkanların temel akışkana göre bağıl yoğunluk değerlerinin her bir partikül konsantrasyonu için sıcaklıktan bağımsız olduğu bulunmuştur. Nanoakışkanların bağıl viskozitesi sıcaklıkla artarken, farklı SDS ağırlıkları ile hazırlanan nanoakışkanların en yüksek bağıl ısıl iletkenlik değerlerine farklı sıcaklıklarda ulaşılmıştır. Genel olarak, bağıl termal özellikler, partikül konsantrasyonundaki artışla artış eğilimi göstermektedir.

Nanoakışkanların kararlılığı ve dispersiyonunun termofiziksel özellikler üzerinde yüksek bir etkiye sahip olduğu gözlemlenmiştir.

Anahtar Kelimeler: *Nanoakışkan, Alüminyum Oksit, SDS, Kararlılık, Termofiziksel Özellikler*

1. INTRODUCTION

The advancement of nanofluids, which are prepared with nanoparticles and a base fluid, has become a significant topic in nanotechnology, microelectronic technology, and processes requiring high heat flux. Nanofluids present better thermophysical properties than conventional fluids, not including particles (Sezer et al., 2019). However, not providing the stability of nanofluids is a critical problem that prevents the development of this field. Having high surface areas and energies, nanoparticles tend to form clusters. Due to the forming of particle clusters, volume ratio, hydrodynamic properties, density, viscosity, and thermal conductivity of fluids can be changed (Ali and Salam, 2020). To obtain long term stable nanofluids, chemical and physical treatments are applied to suspensions. High energy applications to disperse agglomerated particles such as ultrasonication, homogenization and ball milling are among the physical processes, while pH change, surface modification of nanoparticles and addition of surfactants are identified as the chemical processes (Sezer et al., 2019). Surfactants are formed of hydrophilic and lipophilic parts, and according to their hydrophilic parts, they are separated into four groups: amphoteric surfactants, cationic surfactants, nonionic surfactants, and anionic surfactants. In solution, surfactants form self-forming molecules that belong to micelles and help decrease the surface tension between the two phases (Ali and Salam, 2020). Micellization is significant for colloid chemistry. Surfactants have been widely used for the preparing stage of nanofluids. Increased interparticle repulsive (electrostatic and steric) forces will improve particle dispersion stability in fluids. With the addition of nanoparticles, strong bonds are formed between the surfaces of nanoparticles and polar groups of surfactants, and the effects of electrostatic repulsion and steric barriers inhibit aggregation of particles (Nair et al., 2018). When an adequate quantity of surfactants is added, a surface film surrounding nanoparticles forms as a consequence of surface adsorption. If the thickness and intensity of the surface film are sufficient, the aggregation of nanoparticles can be prevented (Zareei et al., 2019).

There are many studies about nanofluids prepared by using surfactants in the literature, and one of the most commonly used surfactants at the preparing stage of nanofluids is sodium dodecyl sulfate (SDS) surfactant (Sezer et al., 2019). Sing et al. prepared carbon nanotube (CNT) nanofluid with SDS surfactant, and investigated the stability of nanofluids by changing the surfactant/CNT concentration ratio from 1 to 3. They concluded that nanofluids with SDS surfactant were stable for long-duration, and the best dispersion was obtained when the surfactant/CNT ratio was 1 (Singh et al., 2020). Hwang et al. studied the dispersion stability of nanofluids. The nanofluids were obtained using carbon black (CB) and Ag, water, and SDS and oleic acid as nanoparticles, base fluid and surfactants, respectively. According to the results, adding SDS to CB nanofluids enhanced stability due to strong electrostatic repulsion (Hwang et al., 2008). Rao and Babu reported that the suspensions, including SDS and Al_2O_3 particles, were stable for a long time without settling (Rao and Babu, 2019). Even though the results of these studies are compatible with each other, Das et al. and Ma et al. noted controversial results with these papers. Al_2O_3-water nanofluid was prepared using different surfactants, cetyl trimethyl ammonium bromide (CTAB), sodium dodecylbenzenesulfonate (SDBS) and SDS by Das et al. Stability of obtained nanofluids was determined. They reported that Al_2O_3-water nanofluid with SDS did not show satisfactory stabilization (Das et al., 2017). Ma et al. investigated the effect of SDS on stability of Al_2O_3-CuO/Water and Al_2O_3-TiO_2/Water nanofluids by applying UV–Vis, TEM, and sedimentation methods. Results show that agglomeration and particle clusters occurred by adding SDS (Ma et al., 2021).

Surfactants affect not only the stability but also the thermophysical properties of nanofluids. Xia et al. investigated the thermal conductivity ratio of nanofluids with SDS and polyvinylpyrrolidone (PVP) individually. They observed that with the addition of surfactants, the thermal conductivity ratio of nanofluids first increased and then decreased (Xia et al., 2014). Jha et al. used SDS and Tween 20 surfactants for preparing water-alumina nanofluids and measured thermal conductivity and viscosity values of the obtained nanofluids. According to the results, the values of water alumina with SDS were higher than those of water alumina and water alumina with Tween 20 (Jha et al., 2015). Shah et al. carried out a study on the rheological properties and thermal conductivities of reduced graphene oxide (rGO)/ethylene glycol (EG) nanofluids with SDS. They discovered that when SDS concentration was varied, inconsistent trends for thermal conductivity ratios were observed. Also, the viscosity variation of nanofluids at constant particle concentration was dependent on temperature and SDS concentration. Both enhancement and reduction in viscosity compared to base fluid were observed (Shah et al., 2020). In contrast to these studies, it was reported by Assael et al. that significant variation in thermal conductivity of nanofluids, including carbon-multiwall nanotubes (C-MWNT) with SDS concentration was not obtained (Assael et al., 2004).

As mentioned above, there are conflicting and inconsistent results for nanofluids prepared by using SDS surfactant. Therefore, this study aims to analyze the stability and thermal properties of nanofluids. The density, viscosity, and thermal conductivity measurements of nanofluids prepared at different concentrations of SDS and nanoparticles are conducted in the range of 298 K to 338 K.

2. MATERIAL AND METHOD

2.1. Materials

Al_2O_3 has been preferred for preparing nanofluids because it is cheap and nontoxic. Al_2O_3 nanoparticles were procured from Nanografi Co. Inc. and their properties are given in Table 1. SDS, an anionic surfactant, was utilized as a stabilizer and it was purchased from Merck. Any further purification was not applied to the chemicals.

Table 1. Properties of used chemicals.

	Properties	Values
Al_2O_3 Nanoparticles	Molecular weight (g/mol)	101.96
	Phase	Gamma
	Morphology	Nearly spherical
	Purity (%)	99.5+
	Average particle size (nm)	18
	True density (g/cm^3)	3.9
	Specific heat capacity (J/g.K)	0.89
	Specific surface area (m^2/g)	140
SDS	CAS number	151-21-3
	Molecular weight (g/mol)	288.37
	Density (g/cm^3)	1.01
	Critical micelle concentration CMC (g/dm^3)	2.74

2.2. Preparation of Al_2O_3-Water Nanofluids with Surfactant

The two-step method was applied to prepare nanofluids. Firstly, different weight ratios of surfactants (0.2%, 0.4%, 0.6%, and 0.8%) and water were mixed with a magnetic stirrer at 500 rpm for one hour. A high precision electronic balance (Mettler Toledo) with an accuracy of 0.0001 g was utilised for weight measurements. Then, Al_2O_3 particles at 5 different volume ratios (0.3%, 0.5%, 0.7%, 0.9%, and 1.1%) were added to the solution directly. After mixing at 1000 rpm for 30 min (magnetic stirrer), ultrasonic agitation (NanoLinker NL400) with 300 W was applied to the solution for one hour to increase the dispersion rate.

2.3. Stability Analysis

Sedimentation method, particle size and distribution analysis and zeta potential measurement were utilised to evaluate the stability of the nanofluids. The sedimentation method is easy and economical, and it is based on observing the precipitation of suspensions by taking photographs at regular intervals. Malvern Nano ZS90 was used for particle size and distribution analysis. Zeta potential and particle size analyses were carried out at Çankırı Karatekin University.

2.4. Measurements of Density, Viscosity, and Thermal Conductivity

For density measurements, a calibrated pycnometer with a volume of 25 ml was utilized. Viscosity measurements were carried out by a rheometer (Anton Paar). The thermal conductivity of fluids was determined based on the transient hot-wire method. This method is based on the measurement of the metallic wire's temperature/time response to an immediate electrical signal. The wire is both a thermometer and a heater. The wire is submerged in tested liquid and heated as the current passes through it. The thermal conductivity of the fluid influences the temperature increase of the metallic wire. The device (Thermtest THW-L2) uses Fourier heat conduction equation to calculate the thermal conductivity coefficient (Altun and Şara, 2021). The temperature was adjusted with a sensitivity of 0.1 °C. Before the measurements of the thermal properties of nanofluids, those of pure water were executed. Maximum deviations for water were calculated as 0.3%, 2.1% and 1.2% for density, viscosity and thermal conductivity measurements, respectively.

3. RESULTS AND DISCUSSION

Nanofluids were prepared as described in the method. Precipitation of nanoparticles was observed for analyzing the stability of nanofluids. The density, viscosity, and thermal conductivity of the nanofluids with 0.2%, 0.4%, 0.6%, and 0.8% by weight of SDS were measured experimentally for 298 K, 308 K, 318 K, 328 K, and 338 K. The SDS weight percent of 0.2 is below the CMC point, which is defined as the surfactant concentration at which micelles begin to form (Singh and Tyagi, 2014). However, the other concentrations are above the CMC value, but it is also reported that temperature has an effect on the CMC point (Mohajeri and Noudeh, 2012). In this study, the base fluid term is referred to as water-surfactant solutions. The thermal properties of base fluids were obtained from our previous study (Altun and Şara, 2021).

3.1 Stability of nanofluids

Figure 1 shows pictures of nanofluids using 0.3% Al_2O_3 and SDS in different concentrations immediately after preparation, 30 minutes after preparation and 24 hours after preparation. According to Figure 1, nanofluids prepared with 0.2 SDS settled in 30 minutes. The highest stability was achieved with nanofluids prepared at a weight percentage of 0.8 SDS.

Pictures of nanofluids with 1.1% Al_2O_3 and SDS in different concentrations immediately after preparation and 4 hours after preparation are given in Figure 2. It has been observed that the higher the particle concentration of the nanofluid, the shorter the precipitation time. When SDS concentration was increased, the stability of nanofluids enhanced. However, nanofluids at the Al_2O_3 particle concentration of 1.1% remained stable for a maximum of 4 hours. After 4 hours, transparent solutions occurred. This behavior is thought to be due to the hydrophile–lipophile balance (HLB) value. The HLB value gives information about the functionality and usage areas of surfactants (Galioğlu Atıcı, 2016). The HLB value of SDS is 40 (Schramm et al., 2003), and a clear solution can be obtained at this HLB value. Ma et al. investigated the stability of Al_2O_3-TiO_2/water nanofluids with SDS by TEM, particle size, and sedimentation analysis. TEM images show that nanofluids with SDS have large agglomerates and clusters. Besides, the average nanoparticle sizes of nanofluids with and without SDS are quite close to each other. It can be seen from sedimentation photographs that the nanofluid with SDS sediment in one day (Ma et al., 2021). In a study by Shah, the stability of rGO/EG based nanofluids with different SDS concentrations was analyzed. According to the visual inspections of nanofluids, 0.04 vol% nanofluid without SDS surfactant is the most stable, and it was seen that nanofluids sediment 24 hours later (Shah et al., 2020). Zhai et al. investigated the stability of Al_2O_3-EG based nanofluids with SDS. They observed phase separation in nanofluids with SDS after three days, and pure Al_2O_3-EG nanofluid is more stable than the nanofluid with SDS (Zhai et al., 2019).

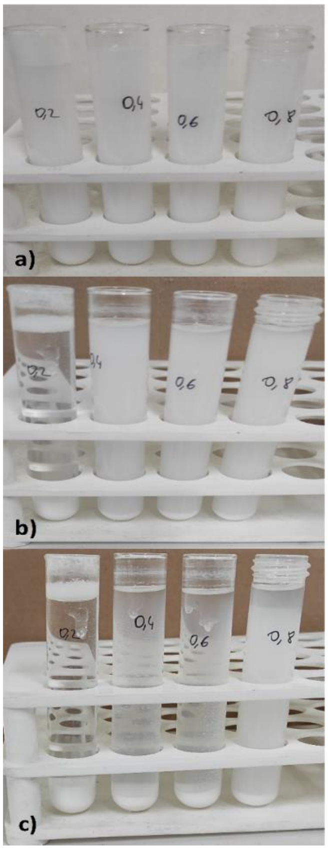

Figure 1. Visual inspection of nanofluids prepared using 0.3% Al_2O_3 and SDS in different concentrations a) immediately after preparation b) 30 min after preparation c) 24 hours after preparation.

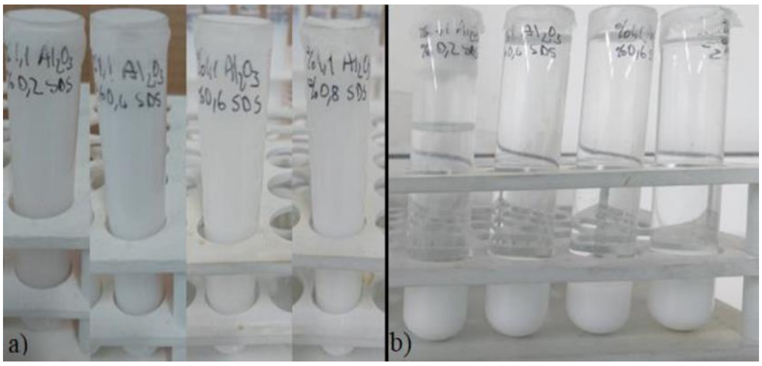

Figure 2. Visual inspection of nanofluids prepared using 1.1% Al_2O_3 and SDS in different concentrations a) immediately after preparation b) 4 hours after preparation.

Zeta potential and average particle size of nanofluids prepared with SDS are given in Table 2. It is known that if the zeta potential is close to ±30 mV, nanofluids can be reasonably stable, and collapse with little stability when it is around ±15 mV (Choudhary et al., 2017). Around the isoelectric point, interparticle repulsive interactions diminish, and when the attractive forces between particles surpass the repulsive forces, unstable highly agglomerated particles occur. If the zeta potential is distant from this point, the attractive force is decreased, and as a result, the average particle size is reduced (Sayan et al., 2009). When the zeta potential values measured 0.30 h after preparation were examined, the minimum and maximum zeta potential values of nanofluids were obtained using 0.2 wt% and 0.8 wt% surfactant ratio, respectively. Obtained nanofluids have little stability but settle lightly according to the zeta potential. Nanofluids with low Al_2O_3 particle concentrations have greater zeta potential values than nanofluids with high Al_2O_3 particle concentrations. These results are also compatible with visual analysis. Because of agglomeration, bigger particle clusters accumulate over time and precipitate, while smaller particles stay suspended in solution. As a result, particle size changes with time (Altun et al., 2021). Zeta potential and average particle size measurements of the nanofluids that settled down were not performed.

Table 2. Zeta potential and average particle size of nanofluids with SDS.

Al_2O_3 volume fraction (%)	SDS weight fraction (%)	Zeta potential (mV)			Average particle size (nm)		
		0.30 h	4 h	48 h	0.30 h	4 h	48 h
0.3	0.0	17.2	-2.4	33.6	355	1887	227
	0.2	-3.5	–	–	1659	–	–
	0.4	-18.0	-37.1	-34.8	429	563	531
	0.8	-27.8	1.9	–	2971	1517	–
1.1	0.0	5.9	–	–	877	–	–
	0.2	-3.6	–	–	825	–	–

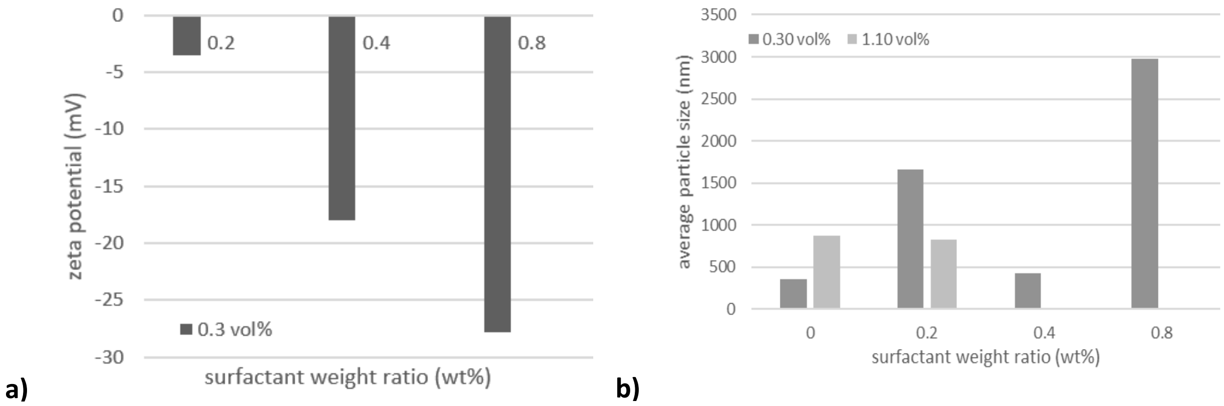

Figure 3. The graphs of a) zeta potential and b) particle size values of nanofluids prepared after 0.30 h versus surfactant concentrations at 298 K.

3.2 Density

The ratio of the nanofluid density to the base fluid density, ϱ_r, is referred to as the relative density in this paper. In Figure 4, ϱ_r values for nanofluids prepared with different SDS surfactant ratios are plotted against solid particle volume percentages. It is seen that density ratios increase with particle concentration and do not have an important change with temperature for all SDS concentrations. The relative densities of nanofluids prepared with 0.7% Al_2O_3 and different surfactant concentrations at 298 K and 338 K are graphically given in Figure 5. The maximum difference between the relative density values is around 0.17%. Besides, it is observed that relative density tends to increase slightly with surfactant concentration.

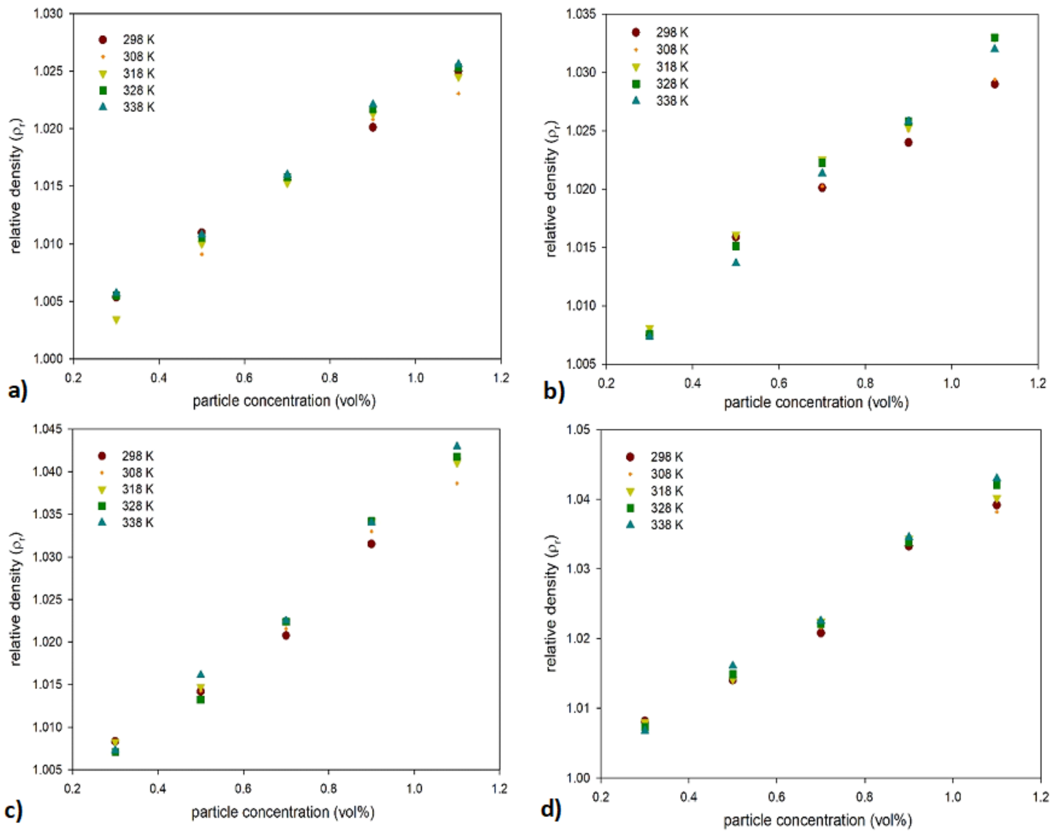

Figure 4. Effects of particle concentration on relative densities of nanofluids at different temperatures a) 0.2% SDS, b) 0.4% SDS c) 0.6% SDS, d) 0.8% SDS.

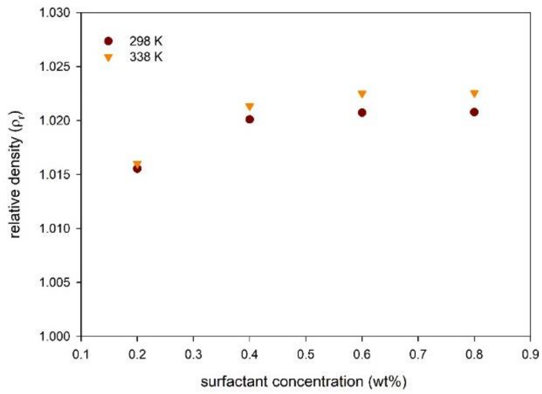

Figure 5. Effects of surfactant concentration on relative densities of nanofluids prepared with 0.7% Al_2O_3 at 298 K and 338 K.

3.3 Viscosity

The ratio of the nanofluid viscosity to the base fluid viscosity, μ_r, is referred to as the relative viscosity in this paper. In Figure 6, the effects of nanoparticle volume percentages on μ_r values of nanofluids prepared with different SDS surfactant ratios are given.

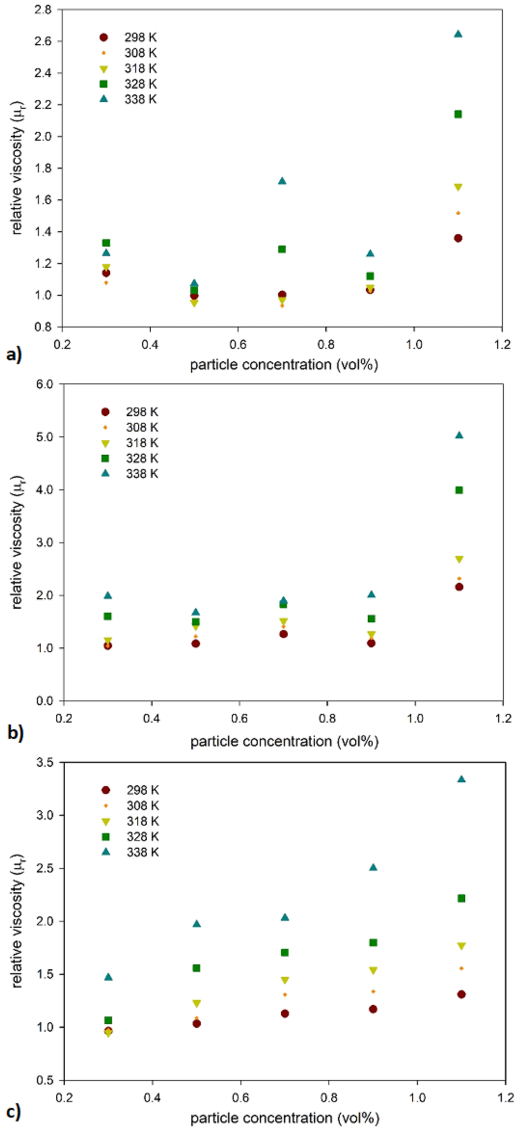

Figure 6. Effects of particle concentration on viscosity of nanofluids at different temperatures a) 0.2% SDS, b) 0.4% SDS, c) 0.8% SDS.

In this section, the effects of surfactant amount, temperature and particle concentration on the relative viscosities of nanofluids have been investigated. It was observed that viscosity values changed nonlinearly with the amount of surfactant. Similar results were found in a study by Khairul et al. Accordingly, it was reported that the viscosity values of the nanofluids depend on the weight fraction of the SDBS surfactant in the suspensions, and the viscosities of the nanofluids change with SDBS irregularly. Zhai et al. analyzed the stability of Al_2O_3-EG nanofluids prepared with SDS and PVP surfactants. According to the study, it was determined that the nanofluids prepared with SDS are less stable and have a higher viscosity than those with PVP (Zhai et al., 2019).

There are different results regarding the rheological behavior of nanofluids in the literature. The reason for this is that various factors, such as concentration, temperature, surface charge, nanoparticle and base fluid properties, dispersants, aggregation degree and ultrasonication time have an effect on the rheological behavior of nanofluids (Sharma et al., 2016; Wang et al., 2013). It is believed that the aggregation of nanoparticles and Brownian motion are probably mechanisms that affect the rheological properties (Wang et al., 2013). The addition of surfactant affects parameters such as pH, conductivity, zeta potential, suspension stability, and particle aggregation. It has been reported that the relative viscosity is independent of temperature for low particle ratios but is dependent on temperature for higher particle ratios (Meyer et al., 2012; Meyer et al., 2016). Temperature and particle concentration are significant factors that affect the viscosity of the nanofluid. In this study, the relative viscosity values of nanofluids increased with temperature. Zhai et al. stated that higher relative viscosity was obtained at high temperatures since when the temperature increases, the contribution of the hydrogen bonding network to the viscosity decreases, but the viscous dispersion is dominant (Zhai et al., 2019). Besides, surfactants may not prevent the formation of agglomeration at high temperatures in nanofluids prepared using surfactants. This can cause an increase in viscosity at high temperatures (Suganthi and Rajan, 2017). However, there are controversial results in the literature about the effect of temperature on the viscosity of nanofluids. Many researchers have asserted that the relative viscosity is independent of temperature (Jarahnejad et al., 2015; Longo and Zilio, 2011; Vajjha et al., 2010). On the other hand, there are also studies including that relative viscosity decreases as the temperature increases (Lee et al., 2011; Sundar et al., 2014). In this study, the relative viscosity of nanofluids changes nonlinearly with particle concentration. Although many researchers have claimed that viscosity values increase systematically with particle concentration (Batchelor, 1977; Wang et al., 1999), it was asserted in a study that since the increase in viscosity ratio with the concentration is usually found for nanometric size distributions, it does not follow the classical dependence on the volume fraction (Pastoriza-Gallego et al., 2011).

3.4 Thermal conductivity

The ratio of the thermal conductivity of the nanofluid to the base fluid thermal conductivity, k_r, means the relative thermal conductivity. Figure 7 and Figure 8 show the change of relative thermal conductivity with the particle concentration for different temperatures. In Figure 7a and Figure 7b, the lowest value is obtained at 338 K, while the highest value is obtained at 298 K. However, the relative thermal conductivity values of nanofluids prepared by using weight surfactant concentration of 0.6% SDS and 0.8% SDS change with temperature, independently in Figure 8a and Figure 8b. Besides, to understand the effect of surfactant addition on relative thermal conductivity, the change of relative thermal conductivity values of nanofluids containing different particle concentrations against surfactant concentration at 308 K is shown in Figure 9. According to the figure, relative thermal conductivity values first improve to a certain point and then decrease with an increase in surfactant concentration.

Instead of a single mechanism related to the mechanisms for improving the thermal conductivity of nanofluids, a combination of many effects such as high conductivity paths formation with a higher thermal conductivity as a consequence of the aggregation of particles, the alteration in the thermodynamic properties of the fluid at the solid-fluid interface, the electric charge at the surface, Brownian motion of the particles (Michaelides, 2013), "nano-convection" caused by particle motion (Azizian et al., 2009) are considered. When using different concentrations of surfactant, the rate of thermal conductivity was found to be different for each temperature in a study conducted by Zhai et al. (Zhai et al., 2019). In the literature, it has been stated that with the contribution of Brownian movements and the increase in temperature, molecules and particles become more active and energy transfers from one point to another. Therefore, thermal conductivity values generally increase with temperature linearly or non-linearly. However, there are also studies involving the fact that the relative thermal conductivity decreases as the temperature increases (Kleinstreuer and Feng, 2011; Suganthi and Rajan, 2017). In another study, it was stated that relative thermal conductivity is almost independent of temperature, and the liquid phase is more dominant than the solid phase in the temperature-dependent feature of the nanofluid (Zhang et al., 2006).

The highest relative thermal conductivity value was obtained to be approximately 1.058 at 318 K with nanofluid prepared with the weight surfactant concentration of 0.6% SDS and Al_2O_3 nanoparticle concentration of 0.9%. A similar study was carried out by Xia et al. In this study, the relative thermal conductivities of nanofluids prepared with different particle and surfactant concentrations were investigated. It was reported that the relative thermal conductivity of nanofluid changes depending on surfactant ratio, and optimum values for each particle concentration are achieved with different surfactant ratios (Xia et al., 2014). It has been suggested by Li et al. that the use of the optimized amount of surfactant to the nanofluid is an important method among the enhancement techniques considered in terms of dispersion behavior and thermal conductivity efficiency (Li et al., 2008). When the amount of surfactant is insufficient, the surfactant cannot completely cover the surfaces of particles, causing the electrostatic repulsion between the particles to be weakened and flocculated. On the other hand, if the amount of surfactant is excessive, supersaturated adsorption occurs and plays a significant role in the formation of flocculations that will weaken the heat transfer between the particles. The narrowing of the heat transfer area because of the high surfactant concentrations may also be a reason for poor thermal conductivity (Wang et al., 2009).

There are controversial results in the literature about the effect of the stability of nanofluids on thermal conductivity. It has been suggested that stability is related to the increase in thermal conductivity of nanofluids. By increasing the distance between particles, the possibility of aggregation decreases, and the dynamism of nanoparticles increases. Thus, the heat transport process is improved (Khairul et al., 2016). On the other hand, Meibodi et al. (Meibodi et al., 2010) claimed that more stable nanofluids do not have higher thermal conductivity values.

As seen in the figures 7 and 8, relative thermal conductivity tends to increase with the particle concentration, but nonlinear change has been observed. In many studies, it has been concluded that the thermal conductivity of nanofluids increases approximately nonlinearly with the nanoparticle weight ratio, the values are close, and the thermal conductivity ratios of nanofluids prepared with higher particle volumes are less than the predicted values. One of the reasons may be that particles in nanofluids with high volume concentrations form agglomerates more quickly than low volume concentrations (Khairul et al., 2016; Wang et al., 2009; Xia et al., 2014; Zhang et al., 2006).

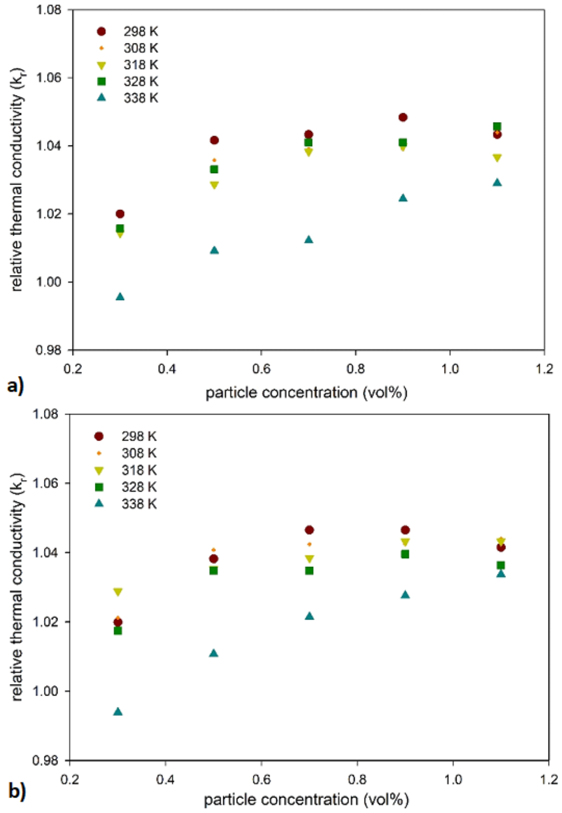

Figure 7. Variation of relative thermal conductivity with nanoparticle amount for nanofluids prepared using SDS a) 0.2% and b) 0.4%.

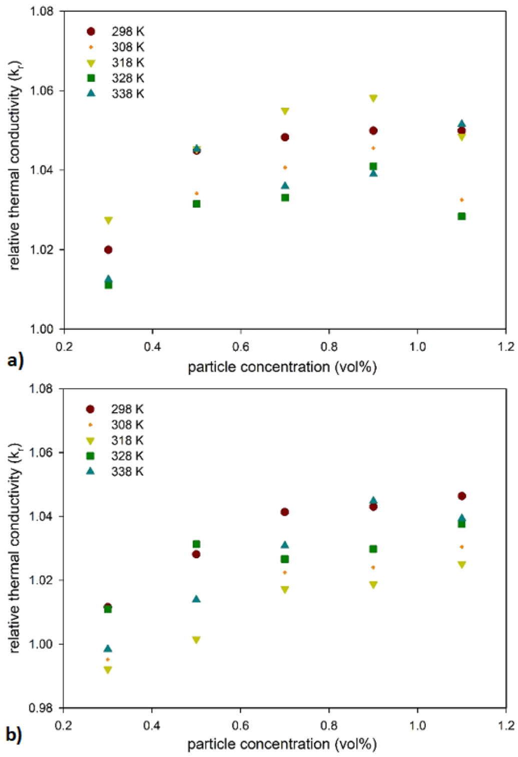

Figure 8. Variation of relative thermal conductivity with nanoparticle amount for nanofluids prepared using SDS a) 0.6% and b) 0.8%.

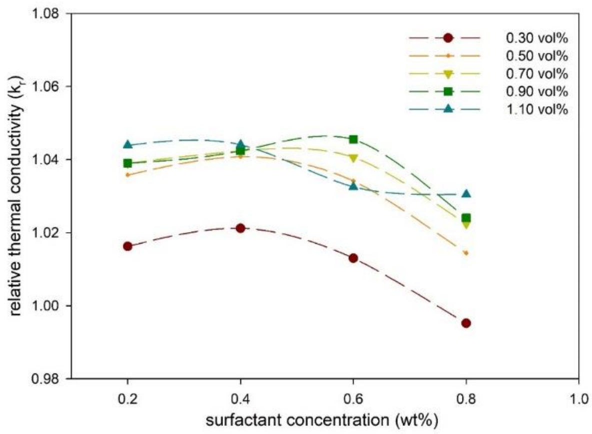

Figure 9. Variation of relative thermal conductivity with surfactant concentration for nanofluids prepared with different particle concentration at 308 K.

4. CONCLUSIONS

Investigations about nanofluids have been continued for nearly three decades. However, there are contradictory results about nanofluids using SDS surfactant as a dispersant agent. In this paper, Al_2O_3-water nanofluids by SDS addition were obtained by using a two-step method. While Al_2O_3 volume fractions were changed from 0.3% to 1.1%, surfactant weight concentration was changed in the range of 0.2% to 0.8%. The sedimentation method, zeta potential and average particle size analyses were used for evaluating the stability of nanofluids. Moreover, the effects of SDS surfactant concentration and temperature on the thermophysical properties of nanofluids were evaluated. According to the results, nanofluids using SDS surfactants remained stable for a few hours. The relative densities of nanofluids at all studied Al_2O_3 particle concentrations varied with particle concentration but not with temperature. Besides, the relative viscosity values of nanofluids are enhanced as temperature increases. At different temperatures, the optimal relative thermal conductivity values of nanofluids with different weights of SDS were obtained. It has been observed that relative thermal properties generally tend to increase with particle concentrations, and the stability and dispersion of nanofluids affect the thermophysical properties substantially.

NOMENCLATURE

Al_2O_3	Aluminum Oxide
SDS	Sodium Dodecyl Sulfate
CNT	Carbon Nanotube
CB	Carbon Black
CTAB	Cetyl Trimethyl Ammonium Bromide
SDBS	Sodium Dodecylbenzenesulfonate
PVP	Polyvinylpyrrolidone
rGO	Reduced Graphene Oxide
EG	Ethylene Glycol
C-MWNT	Carbon-Multiwall Nanotubes
CMC	Critical Micelle Concentration
HLB	Hydrophile–Lipophile Balance
ϱ_r	Relative Density
μ_r	Relative Viscosity
k_r	Relative Thermal Conductivity

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