

Synergetic Effect of SDS/GA Mixture on Stability of Aqueous CNT Nanofluid

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Abstract The stability of nanofluid is the main challenge for their heat transfer applications. Stability means that dispersed solid nanoparticles in basefluid such as engine oil, ethylene glycol (EG), water do not aggregate at a significant rate. The addition of surfactant in basefluid is an excellent option to maintain the stability of nanofluid. This research's major emphasis is in order to make stable nanofluid for thermal applications using different surfactants. Carbon nanotubes (CNT) nanoparticles are dispersed in water (DDW) with the help of SDS, GA and mixed surfactant (mixture of SDS and GA in 50:50 ratio) using a modified-two step method. Results showed that dispersion of CNT in basefluid was better at 1:1 surfactant/CNT ratio, 0.3 wt% of CNT concentration and 180 minutes (SDS), 150 minutes (GA), 90 minutes (mixed surfactant) ultrasonication time. Nanofluid prepared with SDS, GA and mixed surfactant were found to be stable upto about ~90 days, ~150 days and ~200 days, respectively. CNT nanofluid prepared with SDS, GA and mixed surfactant showed 33.9%, 46.3% and 54.3% enhancement in thermal conductivity as compared to DDW, respectively. According to the results, all three nanofluids can be used as a heat transfer fluid, but nanofluid prepared with mixed surfactant is more suitable because it showed higher thermal conductivity enhancement and better stability which are essential for heat transfer application.

Keywords: stability, CNT nanofluid, surfactant, heat transfer, water, thermal conductivity

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1. Introduction

Energy in the form of heat plays major role in our everyday lives and various devices are used to transfer heat between two or more materials/objects. Such devices varies in range of sizes from those in a domestic setting (e.g. gas geyser) up to large industrial scale heat exchangers (HE) (e.g. Petroleum industries). Researchers have been continuously trying to improve the thermal performance of heat transfer devices in order to increase their overall energy efficiency or minimize their constructional size. Various options attempted by experts to accomplish this task are geometry modification (for example use of tubular HE, plate HE, regenerative HE, and extended surface HE) and/or the working fluid operational conditions (i.e., crossflow, parallel flow, etc.). In spite of these no further significant enhancements can be achieved without utilizing a working fluid of higher thermal properties than those conventionally employed [1].

Nanofluids due to their improved characteristics compared to conventional fluids are getting attention of scientific community to improve heat transfer devices efficiency [2-6]. Nanofluid is the suspension of solid nanoparticles (metallic, metal oxide, carbon allotropes) in

conventional fluid (water, ethylene glycol, kerosene, etc.). It is important to note that among various nanoparticles carbon nanotubes (CNT) have some unique properties such as elevated thermal conductivity [7], higher stability [8], lower density [9], lower corrosion and erosion surface effects [10], lower pressure drop and pumping power [10], larger aspect ratio [11] in comparison to other nanomaterials. Akash *et al.* [12] compared three nanofluid prepared using Cu, Al and CNT at 0.3 wt% each and reported that CNT nanofluid has higher thermal conductivity compared to Cu and Al nanofluid. Sivalingam *et al.* [13] reported 24.48% enhancement in thermal conductivity of solar glycol (SG)-based CNT nanofluid prepared at concentration 0.6 vol% compared to SG. Wang *et al.* [14] found 8.23% enhancement in thermal conductivity of water-based CNT nanofluid prepared at concentration 0.5 vol% in contrast to water. Singh *et al.* [15] observed 152% thermal conductivity enhancement of water-based CNT nanofluid prepared at concentration 0.05 wt% compared to water. Walvekar *et al.* [16] reported 70%-250% enhancement in thermal conductivity of water-based CNT nanofluid prepared at concentration in the range of 0.051 wt% to 0.085 wt% compared to water. Moradi *et al.* [17] found 25% thermal conductivity enhancement of water-based CNT nanofluid prepared at concentration 0.25 wt% compared to water.

Despite the promising soundness of nanofluid in terms of thermal conductivity, there are some important facts to be considered before its industrial applications. First, the viscosity of nanofluids is higher than their basefluids due to the presence of the dispersed particles in it [18]. Therefore, viscosity of nanofluid would increase with increase in particle concentration would lead to higher pumping power to drive the flow. Secondly, the physical stability of the dispersed particles directly affects the thermo-physical properties of the suspensions, especially its effective viscosity and effective thermal conductivity [19]. For instance, a homogeneously dispersed and physically stable nanofluid would generally have lower effective viscosity and higher effective thermal conductivity than a nanofluid in an unstable condition [1].

Preparation of stable dispersion of CNT in polar basefluid like water is a challenging task due to its hydrophobic nature. Investigators have tried various surfactants/additives such as cetyl trimethyl ammonium bromide (CTAB) [14,17], sodium dodecylbenzene sulfonate (SDBS) [20,21], polyvinyl pyrrolidone (PVP) [22,23], gum arabic (GA) [24,25,26], sodium octanoate (SOCT) [14,27], sodium dodecyl sulfate (SDS) [28,29], etc. to stabilize the CNT nanoparticles dispersion in basefluid. GA is anionic in nature and a mixture of arabinogalactan, oligosaccharide, polysaccharide and glycoprotein, and its molecular weight reaches $(2-3) \times 10^5$. For its excellent amphiphilicity, GA is usually used as the stabilizing and suspending agent for oil-water interface emulsification and has been used as the stabilizing agent for ink pigments from ancient times. Additionally, GA can make the hydrophobic CNT have a good dispersibility and stability in GA colloidal solution for its low viscosity [30]. Seong *et al.* [31] compared SDBS and SDS as surfactants for preparation of Graphene nanofluid and concluded graphene nanofluid with added SDS showed higher thermal conductivity compared to graphene nanofluid with added SDBS.

Few studies are available on mixed surfactant systems for the dispersion of CNT in basefluids. Madni *et al.* [27] investigated the CNT dispersion in basefluid (Dimethyl formamide, DMF) using DTAB, SOCT and mixed surfactant (mixture of SOCT and DTAB). They found mixed surfactant system at low concentration (20 Dmb%) has better CNT dispersion ability than DTAB and SOCT alone used at high concentration (40 Dmb%). Javadian *et al.* [32] reported that mixed surfactant (mixture of SDS and DTAB) have superior properties than both single surfactants for CNT dispersion in basefluid. Mixed surfactant system at lower concentration of 0.9 mM showed a higher dispersive action as compared to individually used at high concentration SDS 10 mM and CTAB 25 mM, respectively. Babita *et al.* [33] investigated CNT dispersion in water using GA, SDBS and mixed surfactant (mixture of GA and SDBS). They found CNT dispersion with mixed surfactant was enhanced 54% and 58% in comparison to SDBS and GA individually used for the dispersion of CNT in water, respectively. Thus, it can be concluded that mixed surfactant system is superior to the use of a single surfactant to disperse nanoparticles in basefluid due to synergetic effect. According to the authors' knowledge, there is no data on the CNT dispersion in water as a basefluid utilizing a surfactant mixture (mixture of SDS and GA) hitherto.

In this research, stable CNT nanofluid were made utilizing three different surfactants SDS, GA and mixed surfactant (mixture of SDS and GA). The novelty of this work is that first time mixed surfactant system i.e., mixture of SDS and GA has been used for the preparation of stable CNT nanofluid, according to the author's knowledge, which shows better dispersion of CNT in basefluid and thus increased stability period of nanofluid. The present work demonstrates that prepared CNT nanofluid using mixed surfactant can be used as a coolant in thermal applications due to elevated thermal conductivity and lower viscosity which are the basic requirement parameters of heat transfer fluids.

2. Materials and Methodology

2.1. Materials

In this study, industrial-grade carboxylic acid functionalized multi-walled carbon nanotube was used as a nanomaterial. SDS and GA were used as a surfactant. Double distilled water (DDW) was employed as a basefluid prepared in laboratory using a glass double distillation unit. Specifications of CNT and surfactants are given in Table 1 and Table 2, respectively. These reagents/chemicals were used without further purification and treatment.

Table 1. CNT specifications

Length (μm)	10-20
Inner Diameter (nm)	5-15
Outer Diameter (nm)	50-80
Density (gm/cm^3)	2.1
Purity (%)	>90
Supplier	Nanostructured and Amorphous Materials, Inc. USA

Table 2. Details of surfactants

Surfactant	Structure formula	Molecular weight, gm/mol	Purity	Supplier
SDS	$\text{C}_{12}\text{H}_{25}\text{NaO}_4\text{S}$	288.38	99%	Central Drug House Pvt. Ltd.
GA	$\text{C}_{26}\text{H}_{34}\text{N}_2\text{O}_{13}$	---	99%	Qualikems Fine Chem Pvt. Ltd.

2.2. Methodology

2.2.1. Preparation of CNT Nanofluid

Modified two-step procedure was used for the preparation of CNT nanofluid. Initially, surfactant-water solutions had been made by the addition of 0.05 wt%, 0.1 wt%, 0.15 wt%, 0.2 wt%, 0.25 wt% and 0.3 wt% concentrations of surfactants in 100 ml of DDW (basefluid) with the help of a magnetic stirrer provided by Labman Scientific Instruments Pvt. Ltd. India. SDS, GA and mixed surfactant (50:50 ratio) were used to prepare surfactant-water solution. Then, 0.05 wt%, 0.1 wt%, 0.15 wt%, 0.2 wt%, 0.25 wt% and 0.3 wt% concentration of CNT nanoparticles were dispersed in each of the prepared surfactant-water solution and sonicated for 60 minutes utilizing an ultrasonication bath provided by Aczet Pvt. Ltd. India at a frequency of 40 ± 3 kHz. Surfactant/CNT ratio

was thus maintained 1:1. During the sonication process, temperature of ultrasonicator bath was maintained at around 30 °C. After the sonication process, resultant nanofluid was centrifuged at 2000 revolutions per minute (RPM) for 1 hour provided by Elektrocraft Pvt. Ltd. India. The modified technique consists of separation of coarse agglomerates of CNT nanoparticles from the CNT nanofluid by applying centrifugal force after its preparation [34]. After centrifugation, suspension above the sediment was poured out very carefully in a glass tube. Then, all the experiments were performed with this suspension.

3. Characterization

Table 3 shows the details of instruments/equipments used in this study.

4. Results and Discussion

4.1. Effect of Surfactant

DDW is a polar fluid and CNT has hydrophobic nature due to which dispersion of CNT in DDW is a challenging task. Addition of surfactants is required to disperse CNT particles in DDW. Surfactants have a hydrophilic polar

head group and a hydrophobic lengthy tail due to which it create a linkage between polar basefluid and nanoparticles [35,36]. Surfactants SDS, GA and mixed surfactant system were selected to disperse the CNT nanoparticles in DDW. Absorbance of prepared nanofluid was measured to investigate the influence of all three types of surfactants on the dispersion of CNT nanoparticles in DDW. Absorbance of nanofluid was measured just after the preparation at wavelength 800 nm because, at 800 nm, surfactant does not show any effect in the DDW and measured absorbance is due to only CNT nanoparticles [37,38]. Measured absorbance has been converted into concentration by Lambert Law as described in experimental papers Singh *et al.* [37] and Babita *et al.* [33]. From the results, it had been found that when individual GA and SDS was used to prepare CNT nanofluid, nanofluid prepared with GA showed high CNT dispersion in DDW in comparison to nanofluid prepared with SDS. Surfactant GA was also found to be better than other surfactants SDS and CTAC [39]. When mixed surfactant system was used to prepare nanofluid, CNT dispersion in DDW was improved in comparison to SDS and GA under same condition as shown in Figure 1. This may be due to synergetic behavior of mixed surfactant. Mixed surfactant system (mixture of SDBS and GA) showed higher dispersion in comparison to individually used surfactants SDBS and GA, respectively due to its synergetic effect [33].

Table 3. Details of instruments/equipments used in this study

Instruments/Equipments	Name of Measurements	Company with model no.	Accuracy	Error in measurement
For stability				
Camera	Images/photographs	---	---	---
UV-Vis spectrophotometer	Absorbance	Hitachi; model no U-2190	98%	2%
Zeta size analyzer	Zeta Potential	Anton Paar GmbH; model no: Litesizer 500	---	---
For Thermo-physical properties				
Specific gravity (SG) bottle	Density	Borosilicate, Delhi, India	---	±2%
Ostwald viscometer	Viscosity	Borosilicate, Delhi, India	---	±0.4%
KD2 pro thermal property analyzer	Thermal conductivity	Decagon Devices Inc., USA, model no. DB1551,	98%	±2%

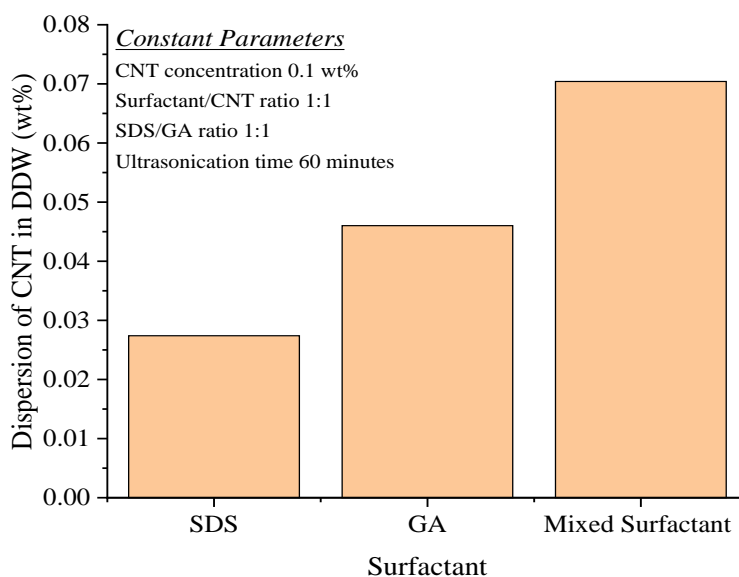


Figure 1. Effect of surfactant on CNT dispersion in DDW

4.2. Effect of Surfactant/CNT Ratio

An optimum concentration of surfactant added shows better dispersion of nanoparticles in basefluid. When used beyond the optimum concentration, surfactant deteriorates the thermo-physical properties of nanofluid including thermal conductivity and also degrades the chemical stability [40]. It is necessary to find out the optimum surfactant concentration for the preparation of stable nanofluid. Therefore, in this section, CNT dispersion in DDW as a function of surfactant/CNT ratio has been investigated. For this investigation, the ratio of surfactant to CNT was changed from 0.5:1 to 3:1 with a constant CNT concentration of 0.1 wt% and ultrasonication time of 60 minutes. To study the effect of surfactant/CNT ratio on the CNT dispersion in DDW, a graph has been plotted between dispersion of CNT concentration in DDW vs. surfactant/CNT ratio, as shown in Figure 2. It has been observed that dispersion of CNT in DDW was increased with all types of surfactants as the surfactant/CNT ratio was increased from 0.5:1 to 1:1. This result may be due to an insufficient amount of surfactant in DDW. That is why, surfactant has not covered the CNT' surface totally to offer steric hindrance between CNT nanoparticles surfaces. The uncovered CNT nanoparticles aggregated and then clusters formed due to Van der Waals forces, after that settled down rapidly, giving less CNT dispersion in DDW. At 1:1 ratio of surfactant to CNT, amount of surfactant was enough that covered the surface of CNT particles entirely due to which higher dispersion of CNT was observed [33]. As surfactant/CNT ratio was increased from 1:1 to 3:1, CNT dispersion in DDW was decreased. As the surfactant concentration increased over the optimum concentration, a reduction in the dispersion of

CNT in DDW was observed due to the self-aggregation effect of surfactant molecules [41]. The same type of observation was observed in 2018 by Babita *et al.* [33]. They found that surfactant/CNT ratio 1:1 showed better CNT dispersion in DDW.

4.3. Effect of CNT Concentration

Based on the above results, surfactant/CNT ratio 1:1 gives better CNT dispersion in DDW as compared to other ratios. So, subsequent studies were carried out with ratio 1:1. In the literature, it has been found that with increasing the particle concentration in basefluid, average particle separation distance reduces due to which potential of Van der Waals forces increases. If Van der Waals forces will dominate over the electrostatic repulsive forces; particles agglomeration will take place [42]. Therefore it had essential to find out the influence of CNT concentration in DDW on the dispersion of CNT in DDW. For this study, nanofluid at a constant ultrasonication time 60 minutes were prepared with varying CNT concentrations from 0.05 wt% to 0.3 wt%. Researchers have reported poor stability of nanofluid at high particle concentrations [42,43]. To look into the effect of CNT concentration on the CNT dispersion in DDW, a graph has been plotted between dispersion of CNT concentration in DDW vs. initial CNT concentration, as shown in Figure 3. This was found that as CNT concentration increased, dispersion of CNT in DDW increased with all three surfactants. Also, at each CNT concentration, nanofluid prepared with mixed surfactant showed higher dispersion of CNT nanoparticles in DDW whereas nanofluid prepared with SDS showed least dispersion of CNT nanoparticles in DDW.

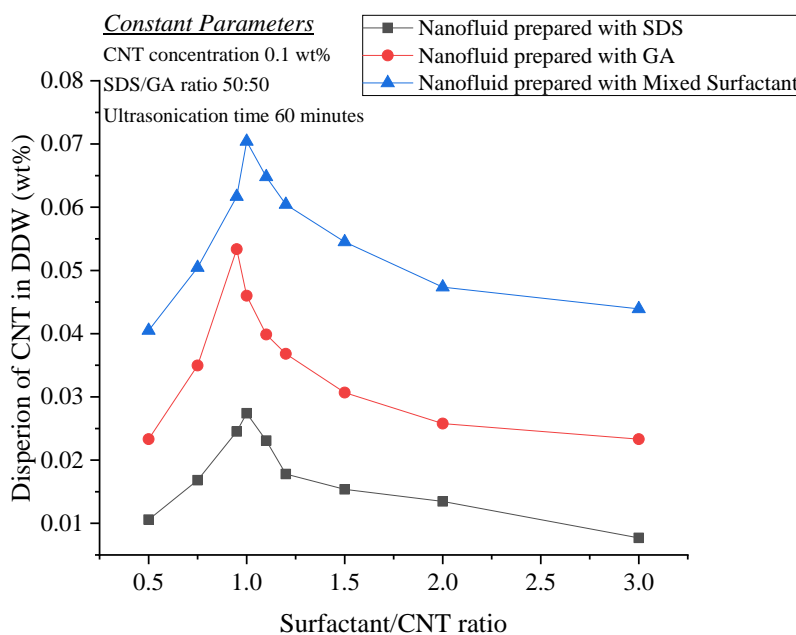


Figure 2. Effect of surfactant/CNT ratio on CNT dispersion in DDW

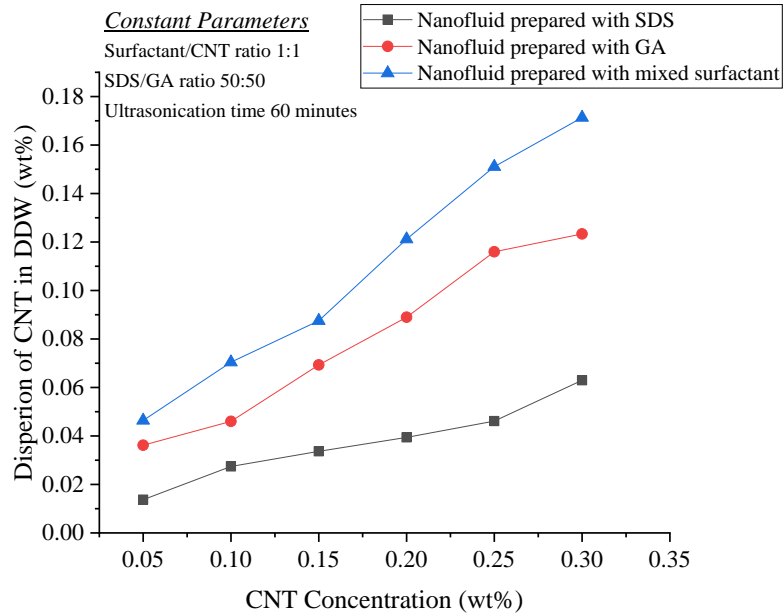


Figure 3. Effect of CNT concentration on the CNT dispersion in DDW

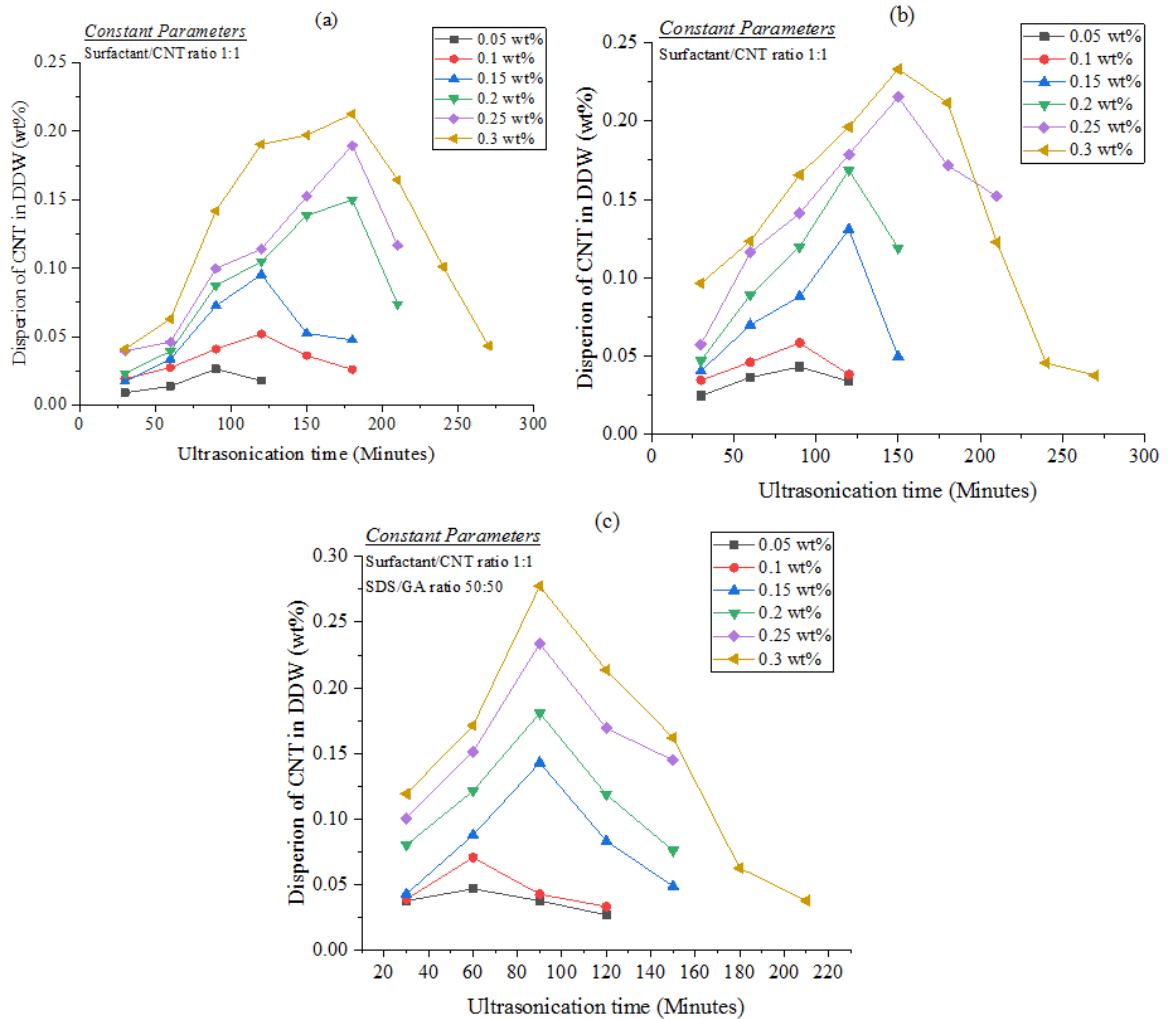


Figure 4. Effect of ultrasonication time on CNT dispersion in DDW with (a) SDS, (b) GA and (c) mixed surfactant

4.4. Effect of Ultrasonication Time

Ultrasonication is a physical approach for the dispersion of highly agglomerated nanoparticles in basefluid [36,37]. As a result, single nanoparticles distinct

from the bundle. This technique also give negative impact on the dispersion of nanoparticles in basefluid such as short ultrasonication time causes low dispersion of nanoparticles in basefluid and long ultrasonication time breakages/damages the structure of nanoparticles causes

low dispersion of nanoparticles in basefluid is observed [36]. Therefore, it is very necessary to find an optimum ultrasonication time for the preparation of nanofluid. In this section, effect of ultrasonication time has been investigated at all CNT concentrations. For determining the effect of ultrasonication time on the CNT dispersion in DDW, graphs have been plotted between dispersion of CNT concentration in DDW vs. ultrasonication time for all CNT concentrations, when nanofluid was prepared with all three surfactant as shown in Figure 4 (a), 4 (b), 4 (c), respectively. It was observed that dispersion of CNT in DDW increased with increasing ultrasonication time. Longer ultrasonication time breaks the agglomerate of CNT nanoparticles into minor structures that enhances the better CNT dispersion in DDW [33,44]. However, when ultrasonication time was increased beyond the optimum time; CNT dispersion in DDW followed a decremental tendency for all the surfactants. This might be due to prolonged ultrasonication of nanofluid which broken the structure of CNT nanoparticles. The surplus ultrasonication time may increase the breakage rate of CNT nanoparticles, leading to the carbon formation, which settles down at the bottom of CNT nanofluid. Hence, damage to CNT nanoparticles would not enhance the CNT dispersion in DDW [33].

Obtained optimum ultrasonication time for all CNT concentrations are given in Table 4. Table shows that nanofluid prepared with mixed surfactant required minimum ultrasonication times of 60 minutes for 0.05 wt% to 0.1 wt% of CNT and 90 minutes for 0.15 wt% to 0.3 wt% of CNT for best dispersion in comparison to nanofluid prepared with GA and SDS which required higher ultrasonication time at each CNT concentrations. The use of mixed surfactant reduces both the preparation time and energy requirement for preparation making the procedure cost effective.

Table 4. Optimum ultrasonication time for CNT concentration

CNT Concentration, wt%	Surfactant		
	SDS	GA	Mixed Surfactant
0.05	90 minutes	90 minutes	60 minutes
0.1	120 minutes	90 minutes	60 minutes
0.15	120 minutes	120 minutes	90 minutes
0.2	180 minutes	120 minutes	90 minutes
0.25	180 minutes	150 minutes	90 minutes
0.3	180 minutes	150 minutes	90 minutes

5. Stability Evaluation of Prepared CNT Nanofluid

5.1. Visual Observation

Stability of nanofluid was examined by evaluating the sedimentation of CNT particles in suspension. In this method, sedimentation of solid nanoparticles in basefluid is observed with time by taking real photographs of nanofluid. It is the easiest and the cheapest method to evaluate the dispersion stability of solid nanoparticles in basefluid because there is no equipment required for this study [10,45].

For evaluating the sedimentation of CNT nanoparticles in the nanofluid, nanofluid prepared using SDS, GA and mixed surfactant were transferred/stored in a glass vial tube with a cap at room temperature. After that, photographs/images of prepared nanofluid were captured from time to time using a camera and after obtaining the pictures of nanofluid, compared with each other in terms of sedimentation of CNT nanoparticles at the bottom of the glass tube. It has been found that there was no CNT settlement observed at the bottom of the glass tube as shown in Figure 5 (a), 5 (b) and 5 (c). Nanofluid prepared with SDS, GA and mixed surfactant showed stability upto ~90 days, ~150 days and ~200 days, respectively. Various investigators examined the stability of CNT nanofluid using visual observation method [41,46,47,48]. Teng *et al.* [49] found the stability of DDW-based CNT nanofluid prepared by using SDS for upto 30 days. Asadi *et al.* [48] as reported by prepared CNT nanofluid was stable upto 30 days without any settlement of CNT nanoparticles at the bottom of the glass tube. Wang *et al.* [14] reported the stability of DDW-based CNT nanofluid prepared with SDS upto 14 days.

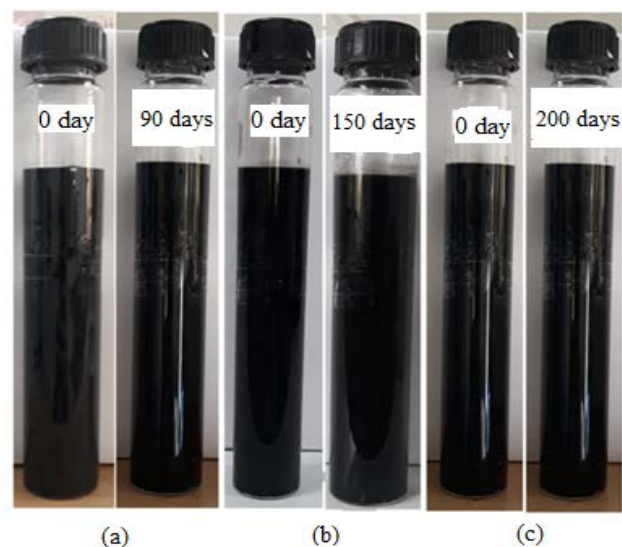


Figure 5. Photographs of CNT nanofluid prepared with (a) SDS, (b) GA and (c) mixed surfactant

5.2. Zeta Potential

This is another method to evaluate the dispersive behavior of nanoparticles in basefluid. It gives information on the magnitude of electrostatic interaction between colloidal particles and is thus a quantify of the solution' colloidal stability [6,38]. If the repulsive forces between nanoparticles are more significant than attractive forces, nanofluid stability is enhanced. In the literature, it is reported that a colloidal solution having a zeta potential of less than -15 mV or greater than +15 mV is likely to be stable due to electrostatic repulsion between nanoparticles [34,36]. A greater zeta potential value presents strong repulsion between nanoparticles in basefluid as well as shows better stability. The zeta potential sign value represents the nanoparticles' net charge. If the nanoparticles' surfaces have a net positive charge, the value of zeta potential will be positive and vice versa [38]. Zeta potential values of nanofluid prepared using different surfactants

are given in Table 5. This table represents that all the prepared nanofluid have a value of zeta potential less than -15 mV. As a result, it can be deduced that nanofluid prepared with all three surfactants are stable and could be used as a heat transfer fluid in thermal systems.

Table 5. Zeta potential value of CNT nanofluid prepared using different surfactant

Zeta potential value (mV)	CNT nanofluid prepared with different surfactant
-27.8	SDS
-29.8	GA
-31.9	Mixed surfactant

5.3. UV-Vis Spectrophotometer

It is an effective method to examine the nanofluid stability. UV-Vis spectrophotometer is working on the principle of Beer-Lambert law as given below in Eq. (1).

$$A = \epsilon cl \quad (1)$$

where ϵ is absorptivity coefficient; c is concentration; l is a path length; A is the absorbance of the solution.

According to law, concentration of the particles in solution is directly proportional to its absorbance. For taking the absorbance of nanofluid, dilution was done because UV-Vis spectrophotometer only works on the

light/colorless samples [38,50]. Chen and Xie [50] reported that nanofluid might be diluted to get the quantifiable absorbance value from the UV-Vis spectrophotometer.

Sedimentation process in nanofluid begins just after the preparation of nanofluid. According to Gupta *et al.* [38] and Babita *et al.* [35] by measuring the absorbance of nanofluid from time to time from the top layer of prepared nanofluid, stability of nanofluid can be examined. If measured values from the UV-Vis spectrophotometer of the same nanofluid sample remain the same with time, it means that nanofluid sample is stable. However, if a decrement in measured values is observed, then nanofluid is instable. The decrement in values shows sedimentation of solid particles in basefluid.

Absorbance of nanofluid was measured by UV-Vis spectrophotometer with time. For this measurement, dilution of CNT nanofluid was done as described by author Gupta *et al.* [38]. Figure 6 depicts the measured absorbance of prepared nanofluid using SDS, GA and mixed surfactant. Nanofluid prepared with surfactant SDS, GA and mixed surfactant were found to be stable upto ~90 days, ~150 days and ~200 days in static condition. Babita *et al.* [33] also found mixed surfactant had better dispersion capability than single surfactant used for the preparation of CNT nanofluid.

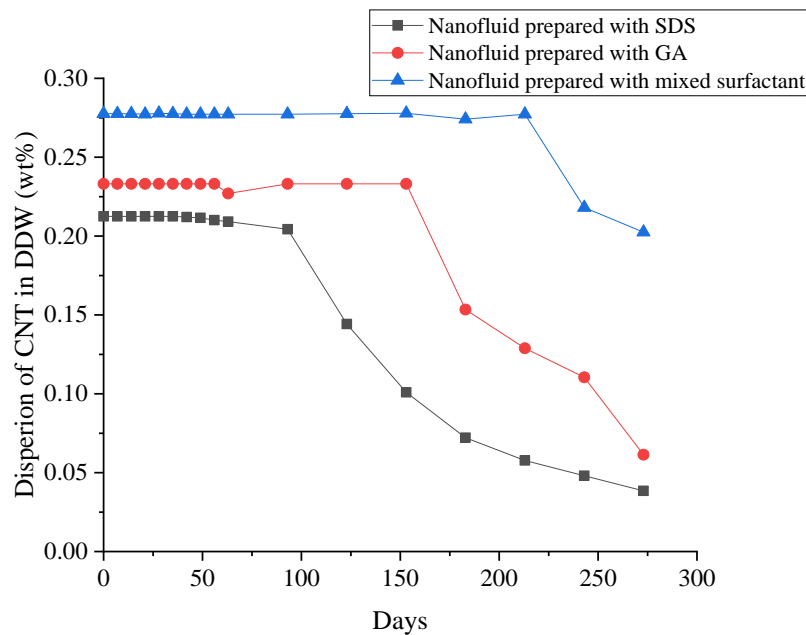


Figure 6. Stability evolution of CNT nanofluid samples using UV-Vis spectrophotometer

6. Thermo-physical Properties of Prepared CNT Nanofluid

6.1. Density

Density of a material is defined as mass per unit volume. To find the density of fluid, it is very necessary because it has an impact on the amount of pumping power needed to pump the fluid [38]. For determining the density of nanofluid at room temperature, specific gravity method was used. Table 6 shows measured density and percentage enhancement in density of nanofluid prepared with all

three surfactants with respect to DDW. Density of nanofluid was also calculated using basic mixture theory (Eq. (2)), as shown in Table 6. When compared the calculated values of density with measured values of density, it had been found that these values had maximum 1.5% deviation with good agreement.

$$\rho_{nanofluid} = (1 - (\phi_p + \phi_{surf1} + \phi_{surf2})) \rho_{bf} + \phi_p \rho_p + \phi_{surf1} \rho_{surf1} + \phi_{surf2} \rho_{surf2} \quad (2)$$

Where ρ is density; p is particle; ϕ is volume fraction; bf is basefluid; $surf1$ is surfactant 1; $surf2$ is surfactant 2.

Table 6. Density of prepared nanofluid

Fluids	Measured density at room temperature (kg/m ³)	% enhancement in measured density with respect to DDW	Calculated density by basic mixing theory (kg/m ³)	% Deviation between measured and calculated density of nanofluid
DDW	995.52 (Standard)	---	---	---
Nanofluid prepared with SDS	999.45	0.069	1012.03	1.24
Nanofluid prepared with GA	995.85	0.033	1011.07	1.5
Nanofluid prepared with mixed surfactant	999.05	0.029	1011.04	1.18

Nanofluid prepared with all three surfactants showed slightly high density than DDW, as shown in Table 6. Minimum enhancement was observed with nanofluid prepared by mixed surfactant. This enhancement is observed because of the existence of both surfactant molecules and CNT nanoparticles in DDW because CNT as well as surfactant molecules have higher density than DDW. Since enhancement in density is negligible, so it can be concluded that nanofluid prepared with all surfactants can be used as a heat transfer fluid in thermal applications.

6.2. Viscosity

With the dispersion of solid particles in basefluid, viscosity of fluid rises. This viscosity increment of fluid increases the power required to pump the fluid from a storage tank to the test section as well as lowering potential to carry an improved heat transfer rate. Therefore, for the industrialization of nanofluid, it is essential to find out the viscosity of nanofluid. Viscosity of prepared nanofluid was measured using Ostwald viscometer method at room temperature.

Table 7. Viscosity of prepared fluid

Fluids	Measured viscosity at room temperature (mPa.s)	% enhancement in viscosity with respect to DDW
DDW	0.829	---
SDS-water solution	0.845	1.9
GA-water solution	0.881	6.27
Mixed surfactant-water solution	0.861	3.86
Nanofluid prepared with SDS	0.869	9
Nanofluid prepared with GA	0.909	14.04
Nanofluid prepared with mixed surfactant	0.891	7.47

From Table 7, it is observed that viscosity of nanofluid prepared with all three surfactants is a little more than DDW as a result of the presence of surfactant molecules as well as CNT nanoparticles in DDW. Maximum enhancement in viscosity of nanofluid was observed upto 14.04% with surfactant GA due to its nature and minimum enhancement was observed upto 7.47% with mixed surfactant due to its synergetic behavior. Babita *et al.* [33] investigated the viscosity of CNT nanofluid prepared with a mixed surfactant i.e. mixture of SDBS and GA and found a slight enhancement in viscosity than DDW.

6.3. Thermal Conductivity

Thermal conductivity is the most crucial property of fluid for heat transfer applications. It is a measure of the

capability of a substance to transfer energy in the form of heat from one point to another point. The instrument (KD2 pro) works on the theory of the transient hot-wire method. Before the measurement, instrument calibration has been done by glycerin. As described by Eq. (3), thermal conductivity enhancement was calculated below and values are listed in Table 8.

$$\text{Thermal conductivity enhancement} = \frac{k_{\text{nanofluid}} - k_{\text{DDW}}}{k_{\text{DDW}}} \quad (3)$$

Table 8. Thermal conductivity of nanofluid

S.NO.	Nanofluid	Thermal conductivity enhancement (%)
1.	Nanofluid prepared with SDS	33.9
2.	Nanofluid prepared with GA	46.3
3.	Nanofluid prepared with mixed surfactant	54.3

Table 8 shows the comparison in thermal conductivity enhancement of nanofluid prepared by SDS, GA and mixed surfactant. It had been observed that thermal conductivity of nanofluid was dependent on the surfactant. This table shows that mixed surfactant-based nanofluid showed the highest enhancement in thermal conductivity compared to other surfactant-based nanofluid. The main reason may be the higher dispersion stability of CNT nanofluid prepared by a mixed surfactant [51], as found in the above section. In 2018, Babita *et al.* [33] also found mixed surfactant-based CNT nanofluid showed higher dispersion stability and higher thermal conductivity enhancement than single surfactant-based CNT nanofluid. Based on this result, it can be concluded that by adding CNT particles with mixed surfactant in water, the thermal performance of the heat exchanger will improve. This nanofluid can be used as a heat transfer fluid in a heat exchanger due to its high stability, high thermal conductivity and minimum viscosity, which are more required parameters for heat transfer fluid to transfer the heat from one place to another.

7. Conclusion

In this present study, CNT nanofluid was prepared with SDS, GA and mixed surfactant system. It was found that SDS, GA and their mixture gives stable dispersion of CNT in DDW. The surfactant/CNT ratio 1:1 was optimum for all three surfactants. With varying CNT concentrations in DDW, increment trend was observed in CNT dispersion with all three types of surfactants. At each CNT concentration, mixed surfactant showed high dispersion of CNT in comparison to SDS and GA. Also, mixed surfactant system required minimum ultrasonication time

to CNT dispersion whereas as SDS required maximum ultrasonication time. For the stability analysis, it has been found that CNT nanofluid prepared with SDS, GA and mixed surfactant system were stable upto ~90 days, ~150 days and ~200 days, respectively. Also, negligible enhancement in density as well as in viscosity of prepared CNT nanofluid with all three surfactant was observed. Nanofluid prepared with mixed surfactant showed quite significant improvement (upto 54.3%) in thermal conductivity as compared of DDW. Hence, it could be used as a thermal fluid in thermal applications because of higher thermal conductivity and good stability.

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