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Experimental Study of SDS Foam Stability in the Presence of Silica Nanoparticle

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ABSTRACT

In this study, the effect of silica nanoparticles on the stability of foams that are stabilized with sodium dodecyl sulfate anionic surfactant was investigated. This surfactant can significantly increase the stability of the foam by reducing the surface tension. For experiments, first, the stability of the foam obtained from this surfactant in the presence of deionized water and then in the presence of NaCl solution and seawater was investigated. Then, by changing the salinity of the NaCl solution and seawater, a change in the stability of the resulting foams was investigated, and the results were reported. The effect of the simultaneous presence of different concentrations of silica nanoparticles in the above solutions was investigated, and stability results were reported. According to the experimental results, the amount of foaming and the half-life of foam in the presence of deionized water is equal to 201 minutes, but the addition of brine reduces this amount. The presence of nanoparticles increases stability. In the presence of deionized water and surfactant, it reaches more than 280 minutes. Finally, the surface tension changes in the optimal concentration of the surfactant in exchange for the change in the concentration of nanoparticles were investigated. In the optimal concentration of surfactant and NaCl solution, the surface tension decreased to 21 mN/m.

Introduction

The use of gases to increase oil recovery is one of the common and practical methods in the oil industry. Suppose the gas in the oil is miscible. In that case, it can be replaced in the displacement volume, which due to the rate of unfavorable gas mobility ratio due to the reservoir's heterogeneity and the oil's low viscosity, leads to fingering and reducing the sweeping property of the gas [1- 4]. This way, the combination of water and gas was used to form foam, and the disadvantages of empty gas injection, including low gas sweeping efficiency, were reduced. However, the foam formed is unstable and will not last long. However, surfactants reduce the energy required to develop a liquid-gas surface and create a more stable foam.

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Several types of research have been conducted in this field, the majority of which concern nanoparticle dispersions in the presence of oppositely charged surfactants [5-11]. The stability of dispersion systems such as foams and emulsions is thought to be influenced by the synergetic impact of particle-surfactant combinations [12-14]. The surface characteristics of silicon dioxide nanoparticles added to Sodium dodecyl sulfate (SDS) surfactant solutions are little understood compared to the many studies on systems comprising silicon dioxide nanoparticles and CTAB. Adsorption of an anionic surfactant to the nanoparticle surface and development of a surfactant-nanoparticle complex, as with cationic surfactants, is not predicted, given the same negative electrical surface charge. The central issue is whether the nanoparticle may affect the surface activity of a similarly charged surfactant in this circumstance. A few research has studied the influence of negatively charged hydrophilic silica nanoparticles on the interfacial tension of the SDS surfactant. According to these investigations, the equilibrium interfacial tension of SDS solutions is lower in the presence of nanoparticles. However, these investigations were confined to a small range of nanoparticle concentrations and focused on the equilibrium state of the analyzed systems' interfacial characteristics. The study of systems' dynamic behavior may provide important details concerning surfactant-nanoparticle interactions and their effects on their interfacial characteristics. This understanding is also required when designing fluids for dynamic processes such as foam generation and foam stability [15-17].

This study investigated the effect of salinity and nanoparticles on the stability of foam obtained from surfactant solution at different concentrations. The surfactant used in this research is sodium dodecyl sulfate (SDS) anionic surfactant. The foam's stability in the presence of silica nanoparticles and water in different salinities will be studied, and the most stable state will be determined.

Materials and Methods

SDS (Sodium dodecyl sulfate) and deionized water were mixed using a magnetic stirrer and stirred until a homogenous solution was obtained to create the surfactant solutions. SDS is a surfactant with an anionic structure, as seen in Fig. 1. This is the sodium salt of an organosulfate with 12 carbons. The compound's amphiphilic characteristics are due to its hydrocarbon tail coupled with a polar headgroup.

One of the goals of this research was to see how various salts and concentrations affected SDS foam stability; therefore, five different salts were used to make brines and seawater. The salts employed in this investigation and their properties are listed in Table 1. MERCK Germany provides the salts and the surfactant.

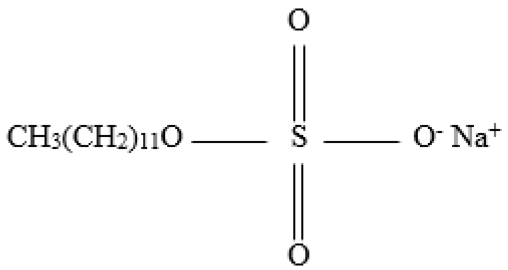

Fig. 1. A schematic of SDS

All the tests in this research were done at room temperature (25°C) and atmospheric pressure. All of the equipment was calibrated before every experiment. All tests were performed at least three times to ensure the correctness of the data, and the average values were provided as the results.

To understand the effect of nanoparticles on the stability of SDS foams, Silicon dioxide (silica) with a mean particle diameter of 30 nm and molecular weight of 60.08 g/mol was used.

Table 1. Salt properties

Salt	Chemical Formula	Concentration (g/L)	Molecular Weight (g/mol)	Density (g/cm^3)	Solubility in 100 g water in 20 ºC (g)
Sodium chloride	$NaCl$	28.281	58.44277	2.16	36.09
Potassium Chloride	KCl	1.013	74.551	1.987	37.2
Sodium sulfate	Na_2SO_4	4.937	142.04	2.664	40.8
Magnesium chloride	$MgCl_2$	14.838	95.211	2.34	54.6
Calcium chloride	$CaCl_2$	1.734	110.99	2.15	100

A cylindrical 1000-cc graduated container with a diameter of 6 centimeters received 20 ml of the surfactant solution to prepare the foam. The cylindrical container's bottom was fitted with a tube whose bottom was connected to a gas source (a high-pressure air capsule). The air was then pumped into the system at a 30 cc.min^{-1} rate via the bottom of the container, and the foam was allowed to build. The foam will continue to build until it reaches the top of the column, at which point the injection will be halted. The foam then begins to destabilize, and the height of the foam lowers. The foam half-life is defined as when the foam height reaches midway of its initial height [18]. While the air was entering the capsule, the mixture was simultaneously agitated with a magnetic stirrer at 400 RPM to ensure a more uniform foam development. A mixture of nanoparticles and surfactant solutions were prepared and placed in the cylindrical container to study the effect of silica nanoparticles on foam stability.

Results and Discussion

According to Fig. 2, using surface tension measurements, the critical micelle concentration of SDS was determined in the vicinity of 2000 ppm. The optimal concentration of SDS was determined to achieve the study's goals of determining the effects of salinity, nanoparticles, and salt type on foam stability. To accomplish so, several SDS solutions with surfactant concentrations of 100, 500, 1000, 1500, and 2000 were created, and the stability of their resulting foams was assessed. The results of these investigations are shown in Fig. 3.

As shown in the Fig. 3, the greater the SDS concentration, the better foam stability, with 1500 ppm providing the optimum stability in the study's concentration range. As a result, for the next tests investigating the effects of salts and nanoparticles, 1500 ppm was chosen as the optimum SDS concentration because the stability changes after this concentration became slight. This happens because the greater the Marangoni effect, the higher the surfactant concentration [19]. The surface tension gradient increases when the surfactant concentration increases, resulting in a greater Marangoni effect and a more stable foam. It is worth noting that all of the foams mentioned in this research up to this point have been generated using a surfactant solution containing 1500 ppm SDS.

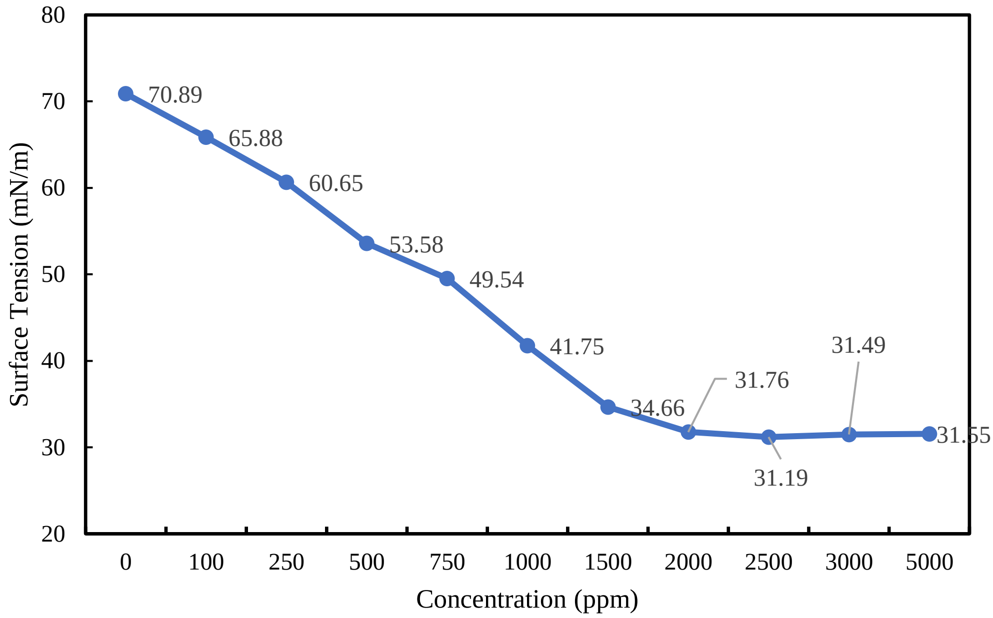

Fig. 2. Surface tension changes with SDS concentration

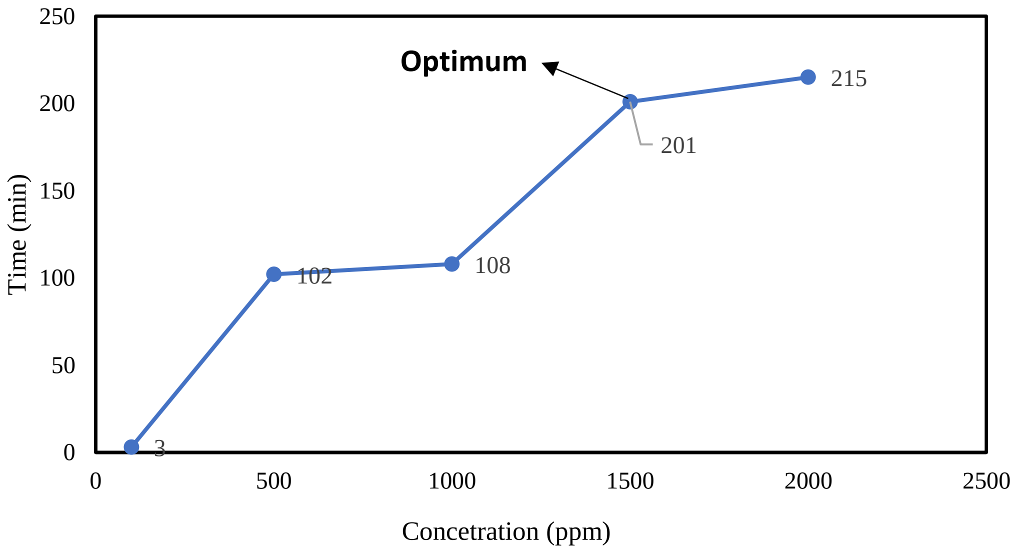

Fig. 3. Stability vs. SDS concentration

At crucial micellar concentration (CMC), the lowest concentration at which surfactant molecules exist in the form of aggregates, the slope of the graph changes, as seen in the figures [20]. Although raising the SDS concentration enhances foam at concentrations over the CMC, the half-life rises at a steep angle when the concentration is below the CMC. Other physical factors, such as electrical conductivity and surface tension, may also cause a change in slope [21-22]. On the other hand, surface tension essentially remains unchanged after reaching the CMC. This is also true for the foams' stability. Because of the optimal surface characteristics and surface tension of the solutions at CMC, it is anticipated that stability does not improve considerably after CMC [21-22].

Effect of Salinity on Stability

In this part of the manuscript, the effect of salinity on foam stability is investigated. The composition of seawater based on the Persian Gulf is given in Table 1. As shown in Fig. 4, seawater reduced its stability relative to deionized water. One of the reasons for this is the release of ions after the dissolution of salts. The SDS surfactant releases Na^+ after dissolution, while the salt releases positive and negative ions, which release the positive ions, reducing the stability because the positive ions overshadow the SDS structure due to the polarity of the foam structure and the surfactant chain. The ions in the lamella structure begin to move due to the forces of attraction and repulsion. The increase in the repulsive forces between the ions and the ions released from the surfactant disturbs the lamella's balance, which eventually causes the lamella to disappear.

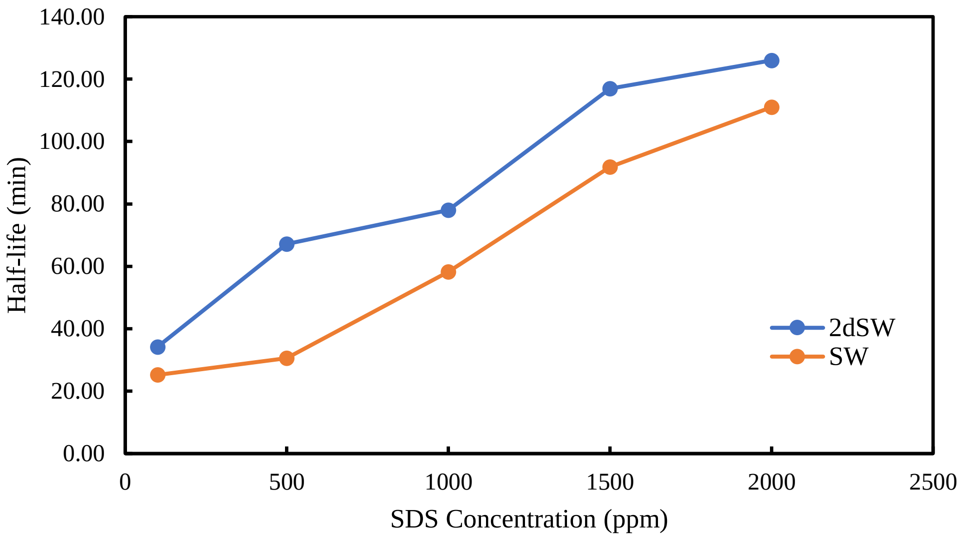

Fig. 4. Effect of seawater and diluted seawater on foam stability

As the concentration of SDS increases, the stability of the foam also increases. Because with increasing concentration, the amount of surfactant at the interface increases and reduces surface tension.

Seawater with two-fold dilution has more stability for two reasons: first, in this case, fewer ions are released than in seawater, resulting in less disturbance of electrostatic forces, which results in greater stability, and second, the pH changes, in this case, are such that the surface tension is further reduced and as a result, it is more stable.

Fig. 5 also shows the effect of NaCl on the foam stability with 46000 and 2300 ppm NaCl solution. The increase in foam stability due to the increase in salt concentration in the solution can be since increasing salt concentration, and dissolution in water increases the ionic strength in water and repels the components in the solution.

The Na^+ attached to the anionic group of the surfactant dissolves in water by dissolving the SDS surfactant in water. This ion in the solution prevents the surfactant from sticking together and prevents the collapse of the foam column by creating an electrostatic repulsion force. Now, with increasing the concentration of Na^+ ion in the anionic surfactant sample, the concentration of ions with opposite charges of the polar head of the surfactant increases, and the stability of the foam increases sharply. By increasing the concentration of NaCl in water, the concentration of dissolved Cl^- in the sample increases and causes disturbance to the efficiency of the positive ion for stabilizing the foam. According to findings, stability has decreased sharply by increasing the salt concentration from 23000 ppm to 46000 ppm.

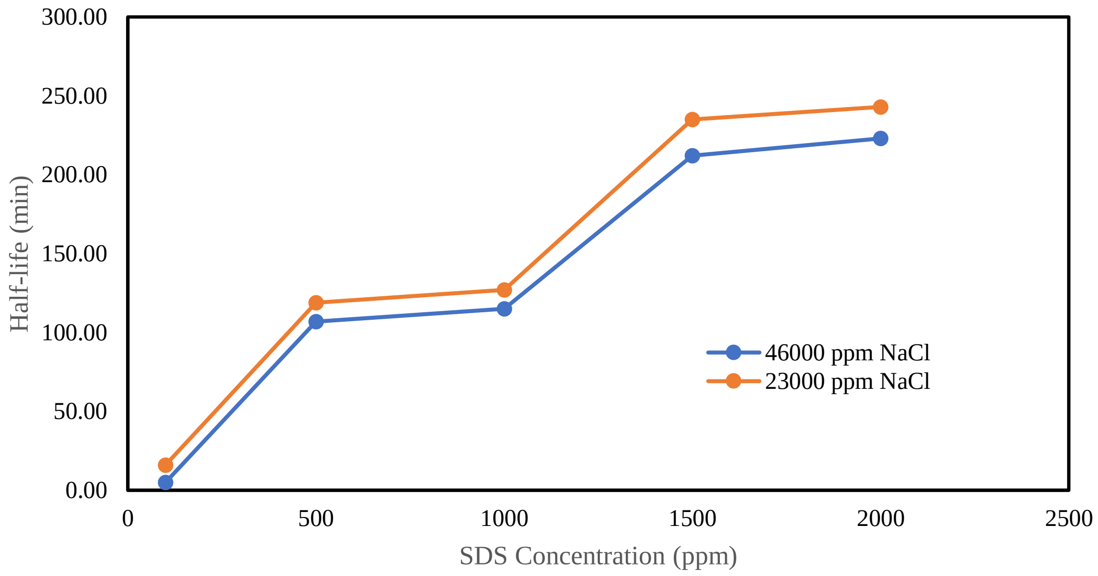

Fig. 5. Effect of brine composition and salinity on foam stability

Effect of Nanoparticles on Stability

This section investigated the effect of silica nanoparticle concentration on foam stability in the optimum concentration of SDS surfactant (1500 ppm). Due to the extremely water-wet silica surface and the lack of a hydrophobic hydrocarbon chain to establish weak bonds with the gas phase, silica nanoparticles alone cannot stabilize the thin layer and thus create foam. Silica nanoparticles have a hydrophilic head. According to Fig. 6, due to the increasing concentration of nanoparticles, a strong bond is established between the hydrophilic head and the solution, increasing stability. Also, nanoparticles with a large surface area are placed between the two fluids and act as a barrier to prevent gas from escaping and the foam from collapsing. According to the obtained results, the mechanism of surface stabilization by nanoparticles is slightly different from surfactants. According to Gibbs Marangoni's theory of two miscible fluids, surfactants in the interface move to the nodes in the foam, thus reaching a half-life sooner as the volume of the foam increases. However, due to its high surface area and placement in the interface of two immiscible fluids and high zeta potential at the surface, the nanoparticles are distributed throughout the interface. Therefore, the stability increases linearly with increasing nanoparticle concentration and does not reach its half-life quickly.

According to Fig. 6, for seawater and 46000 ppm NaCl solution, as can be seen, the foam's stability increases with increasing nanoparticle concentration. So that the stability at the concentration of 2000 ppm reaches more than 100 minutes; however, it is still less stable than deionized water due to the release of ions. Also, in this case, the stability of the foam column is greater than the solution without nanoparticles. Silica nanoparticles have a hydrophilic head, which as a result of increasing the concentration of nanoparticles, a strong bond is established between the hydrophilic head and the solution, which increases the stability. However, in this case, due to the release of Na^+ from the salt and Na^+ released from the surfactant, a strong repulsive force is formed, resulting in the formation of almost stable bubbles with a nanoparticle barrier during gas injection. The gas bubbles released in this case are fragile and have a low lamella width, so stability is reduced.

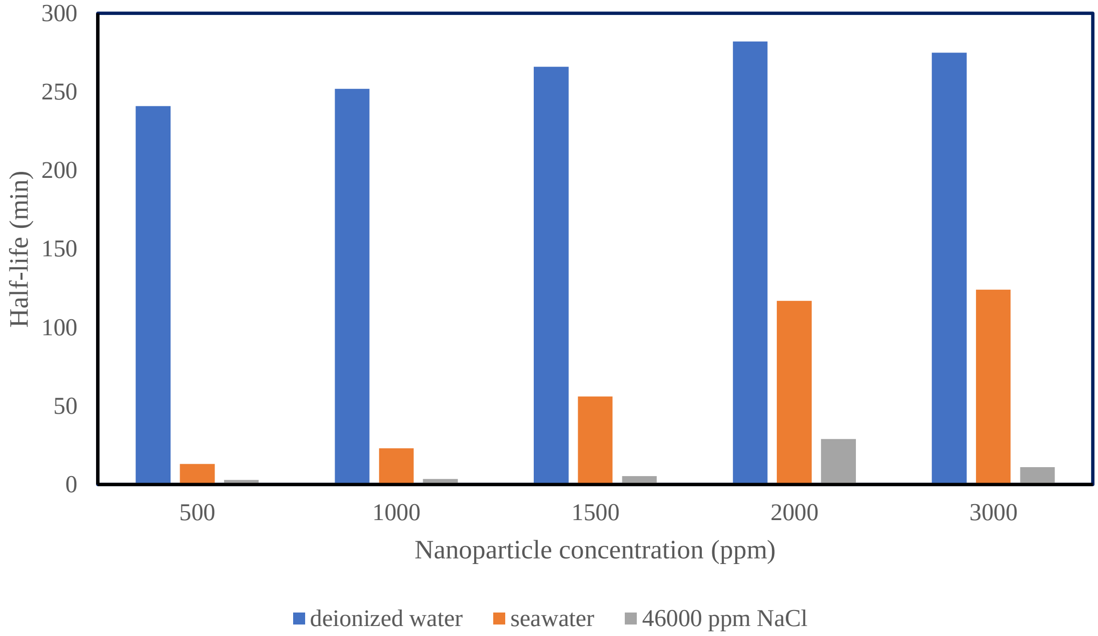

Fig. 6. Effect of nanoparticle concentration on foam stability

Effect of nanoparticles on surface tension

Fig. 7 shows the changes in surface tension relative to the changes in silica nanoparticle concentration. The surface tension of water without nanoparticles is 71-72 mN/m. At low nanoparticle concentrations, there is almost no change in the surface tension of the fluid. By increasing the concentration of nanoparticles in deionized water, the nanoparticles gradually affect the surface, and the amount of surface tension decreases. So that at concentrations above 1500 ppm, the nanofluid surface tension fluctuates between 60-65 mN/m. Due to their strong hydrophilicity, silica nanoparticles come to the fluid interface and can change the surface tension of the fluid to a small extent.

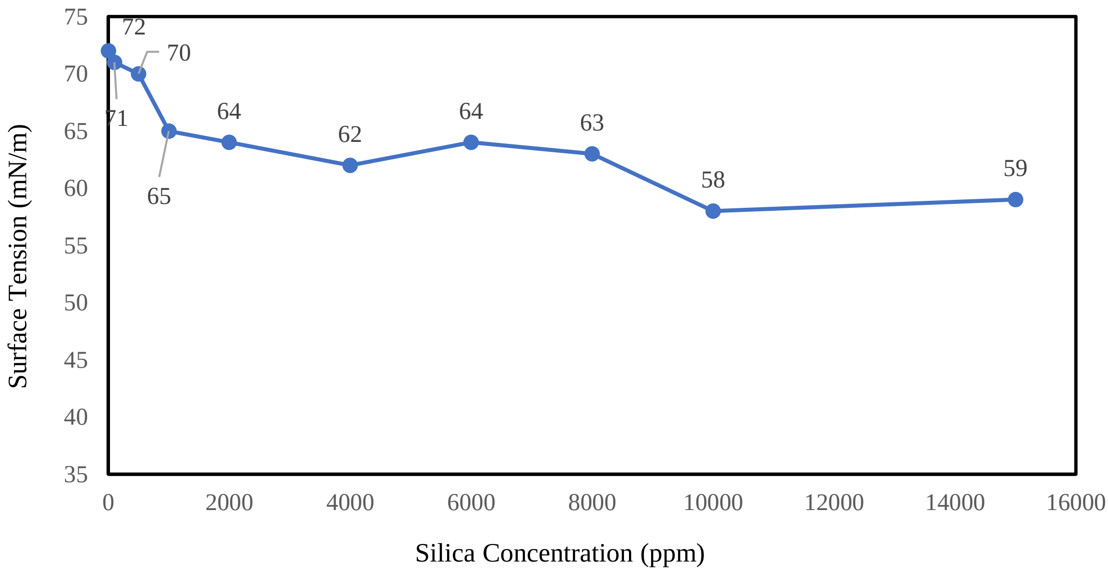

Fig. 7. Surface tension changes in the presence of silica nanoparticles

Fig. 8 shows the effect of nanoparticle concentration on interfacial tension (IFT). It should be noted that SDS surfactant with a concentration of 1500 ppm has been used in the tests. It is the optimum concentration of SDS discussed in detail previously.

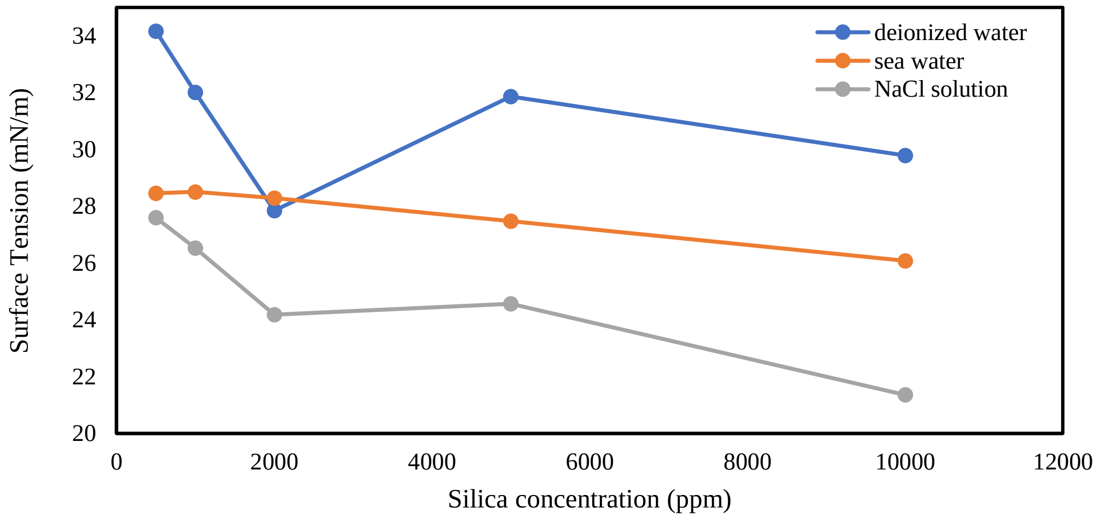

Fig. 8. Surface tension changes in the presence of silica nanoparticles, SDS surfactant, and various waters

Nanoparticles, in general, can improve oil recovery for a long time by changing the wettability from oil-wet to water-wet, reducing surface tension, reducing oil viscosity, and creating a suitable mobility ratio in the injection fluid.

Silica nanoparticles behave similarly to surfactants due to their long chains in the hydrophobic and hydrophilic parts with high carbon content. They are well placed in the interface and reduce surface tension. The presence of surfactant also reduces surface tension, which is intensified by nanoparticles. The surface tension of deionized water in the absence of nanoparticles is 71 mN/m. As the concentration of nanoparticles increases, the surface tension decreases further. Surface tension at a concentration of 10,000 ppm is approximately 29 mN/m. Due to the large volume and the large number of organic chains placed on the nanoparticles to change the wettability state, the amount of nanoparticles on the surface increases very quickly. With the change in concentration, the surface tension decreases rapidly.

In the presence of seawater, surface tension at a nanoparticle concentration of 10,000 ppm is approximately 26 mN/m, according to Fig. 8. In this case, we see more significant reduction in surface tension than in the deionized water case. The reason for this is the increase in density due to the use of seawater. As a result, the amount of surface tension decreases with increasing density.

For the NaCl solution case, surface tension at a nanoparticle concentration of 10,000 ppm is approximately 21 mN/m; in this case, we see a greater reduction in surface tension than in other cases. The reason for this is the increase in density due to the use of NaCl solution. The densities of these cases are reported in Fig. 9 and show ascending in density as discussed.

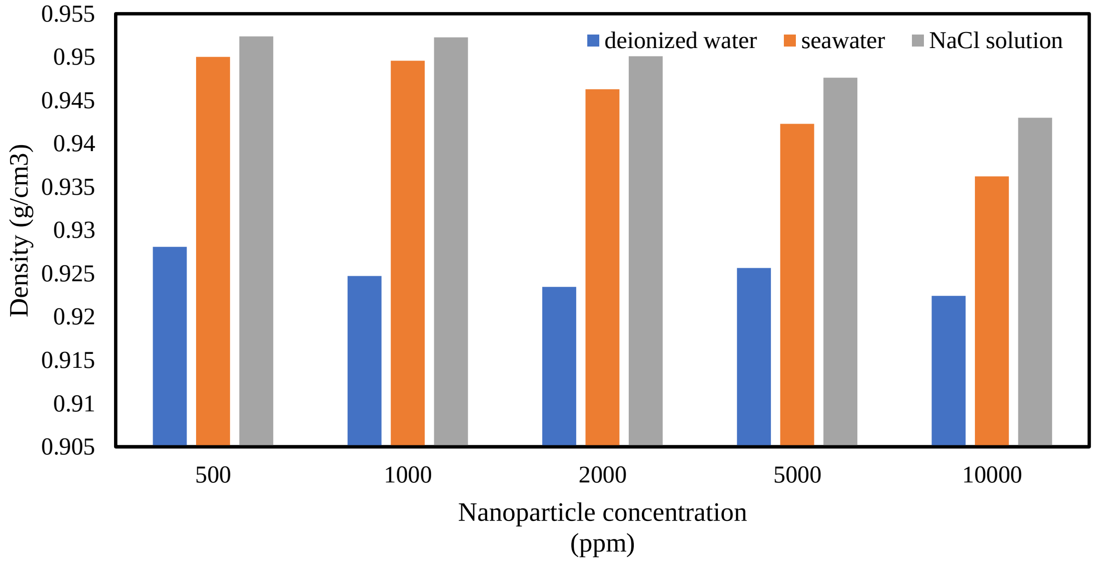

Fig. 9. Density changes in the presence of deionized water, seawater, and NaCl solution

Conclusion

This study performed various experiments on surfactant solutions based on deionized water, seawater, and NaCl solution with different concentrations. The different effects of solutions on the stability of the resulting foam were investigated. The results of each of them were reported separately.

According to the foam stability tests obtained from different concentrations of SDS surfactant and deionized water, the optimal stability occurs in SDS concentration of 1500 ppm, which has a half-life in deionized water of about 200 minutes.

According to the foam stability tests obtained from different concentrations of SDS surfactant and seawater (containing different ions), positive and negative ions in brine reduce the stability. The diluted seawater makes the foam more stable.

According to the results of foam stability tests obtained from different concentrations of SDS surfactant and NaCl solutions, at a concentration of 23000 ppm NaCl salt due to the positive effect of the presence of Cl^-, the stability increases significantly. When NaCl salt doubles to 46000 ppm, the stability decreases compared to the previous state.

By adding silica nanoparticles to the foam from SDS surfactant and deionized water, the stability of the foam was significantly increased. Also, by changing the deionized water to seawater, the effect of the presence of silica nanoparticles was positive and increased the stability of the foam. As a result, adding nanoparticles to the surfactant solution and brine increases the stability. The foam stability of the surfactant solution and NaCl salt decreases with the presence of nanoparticles.

The presence of SDS surfactant and silica nanoparticles reduces surface tension. NaCl solution has more effect on reducing surface tension than deionized water and seawater because of its high density.

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