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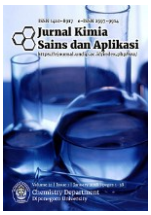

Improved Thermal Stability of Silica Nanofluids Using Anionic Surfactants for Enhanced Oil Recovery Applications

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Abstract

Silica nanoparticles have shown great potential in the oil and gas industry sector, especially in applications for enhanced oil recovery. Silica nanofluids are widely used in EOR applications because they are inexpensive, easy to synthesize, environmentally friendly, can be surface modified, and provide high oil recovery rates. However, silica nanofluids have drawbacks in thermal stability and salinity at high temperatures, adversely affecting their application in oil reservoirs. In this paper, the effects of a surfactant sulfonate compound (SPU11) and a co-surfactant sulfosuccinate compound (SPU22) on the thermal stability of silica nanofluids at temperatures ranging from 60 to 100°C were investigated. Next, the silica nanofluids were analyzed for particle size using a particle size analyzer (PSA), wettability using a sessile drop contact angle, and oil recovery capacity using a core flooding test. The results showed that the silica nanofluid with 0.3% SPU11 and 0.3% SPU22 surfactant showed good thermal stability below 80°C for 3 months in 3 wt% brine; PSA analysis showed that the aggregate diameter was 52.86 nm; wettability analysis showed that the silica nanofluid had a contact angle of 60.8° to 36.6° and the core flooding results of silica nanofluid showed an oil in place recovery (OOIP) of 9.7%.

1. Introduction

Currently, enhanced oil recovery (EOR) plays an important role in increasing crude oil production. However, production continues to decline due to issues such as high surface tension and interfacial tension in the reservoir. EOR, also known as tertiary recovery, improves oil extraction by increasing the amount of oil that can be recovered. Conventional EOR techniques can recover 30- 60% or more of the hydrocarbons, compared to the 20-40% recovery achieved by primary and secondary recovery methods [1]. EOR methods are based on (1) thermal processes, including hot water, steam, and in situ combustion; (2) gas injection, including hydrocarbons, CO_2, nitrogen/exhaust gas chemical methods using alkalis, surfactants, and polymers; and (4) other methods such as microbial, acoustic, and electromagnetic methods [2, 3].

The development and application of nanotechnology has shifted EOR research toward addressing the limitations of existing technologies through the use of nano-assisted EOR techniques [4, 5]. Recent technological advances have focused on miniaturizing particle properties from the millimeter to the micrometer scale, thereby enhancing desirable properties. Such optimization of material properties at the nanoscale level is expected to have a significant impact on their practical applications [6]. Nanoscience, which explores nanoscale materials and phenomena [7], supports nanotechnology, defined as the design, characterization, application, and synthesis of nanomaterials [8].

Nanoparticle technology offers a promising solution to challenges unmet by conventional methods in the upstream petroleum industry. With sizes ranging from 1 to 100 nm, nanoparticles enhance oil recovery (EOR) through their unique size, shape, and surface properties. Their small size allows them to improve fluid displacement in porous media with minimal effect on reservoir permeability, particularly benefiting recovery in the sheaf zone [9, 10].

The unique properties of nanoparticles, such as high surface-to-volume ratio, ability to reduce interfacial tension, and ability to modify wettability, are important factors contributing to their utility in petroleum engineering [11, 12]. To modify wettability, nanoparticles must adsorb to the rock surface [13]. A proposed mechanism to improve contact line motion is the generation of a pressure gradient due to the "wedge" of fluid near the nanoparticles at the three-phase contact line, which reduces friction [14]. From both environmental and economic perspectives, nanotechnology is considered a promising agent to enhance the EOR approach [4].

Nanoparticles are increasingly used in the oil and gas industry, primarily as components of nanofluids—liquid suspensions containing nanoparticles with at least one dimension below 100 nm [15]. This development has introduced nanotechnology as a novel chemical agent for enhanced oil recovery (EOR). Experimental studies using both homogeneous and heterogeneous core samples have shown that nanofluids perform well in improving oil displacement. They can penetrate rock pore networks, modify pore surface properties, enhance particle–pore interactions, and significantly boost displacement efficiency [16]. Among various nanomaterials, silica nanoparticles have been most widely studied for their ability to improve microscopic scavenging efficiency in oil recovery by altering interfacial tension and reservoir wettability [17].

The long-term colloidal stability of nanoparticles under harsh reservoir conditions is essential for successful EOR applications. However, under high salinity and temperature, nanoparticle dispersions tend to lose stability due to van der Waals forces, leading to the formation of aggregates over time. This agglomeration and precipitation can reduce the effectiveness of nanofluids and cause severe formation damage. Electrostatic or steric stabilization mechanisms have been employed to improve the stability of nanodispersions and make them suitable for EOR applications [18].

Surface modification of nanoparticles or the addition of additives can further enhance their long-distance transport and long-term stability while reducing retention and aggregation. Ngouangna *et al.* [19] reported a synthesis process for silica nanofluids with high thermal stability under high temperature and salinity conditions, using a surface modification process with 3-(Dimethyl(3-(Trimethoxysilyl)Propyl)-Ammonio)Propane-1-Sulfonate (SBS) and a surfactant, 3-glycidyloxypropyl trimethoxysilane (GLYMO). Turbiscan analysis revealed that the silica nanofluids were stable for six months at 60°C in 3.5% NaCl saline solution.

Worthen *et al.* [20] compared 7–20 nm silica nanoparticles stabilized by three types of nonionic ligands—GLYMO, polyethylene glycol (PEG), and zwitterionic sulfobetaine (SB)—in seawater and brine. The results indicated that GLYMO and SB ligands could stabilize nanodispersions at 80°C for over 30 days in API brine with a pH of 3.5. However, increasing the stability of silica nanofluids through such methods is considered less economical. In this study, anionic surfactant sulfonate compound (SPU11) and co-surfactant sulfosuccinate compound (SPU22) are used as stabilizing agents for silica nanofluids.

2. Experimental

This section details the materials, preparation, and characterization of silica nanofluids to ensure reproducibility. The study explores nano-silica, surfactants, and crude oil, followed by characterization using analytical techniques. Experimental procedures include nanofluid synthesis, thermal stability assessment, wettability analysis, and core flooding to evaluate EOR effectiveness. The following sub-sections provide specifics on materials, preparation, and characterization methods.

2.1. Materials

The nano-silica used, with a diameter of 8 nm, was sourced from the Nanotechnology Laboratory at Diponegoro University. The commercial anionic surfactant sulfonate compound was obtained from Rachara Chemical Technology, while the sulfosuccinate compound was provided by Evonik. Light crude oil, with an API gravity of 49.80 and a kinematic viscosity of 0.6323 cSt, was supplied by PT. Pertamina from reservoir "X". The synthetic sandstone core was composed of upper grey Berea, and pharmaceutical-grade NaCl and distilled water were used.

2.2. Silica Nanofluid Preparation

The silica nanofluid was synthesized by reacting 0.1% nano-silica with surfactant SPU11 and co-surfactant SPU22, using varying SPU11-SPU22 concentration ratios of 0:0, 0:0.3, 0.1:0.3, 0.2:0.3, and 0.3:0.3%. This mixture was heated to 60°C for 30 minutes. Subsequently, a 3% NaCl solution was added while stirring, followed by additional heating for 10 minutes. The mixture was then subjected to sonication at a frequency of 20 kHz for 5 minutes to ensure proper dispersion of the nanofluid.

2.3. Characterization of Silica Nanofluid

To evaluate the performance of the synthesized silica nanofluid, various characterization techniques were employed. The analysis focused on thermal stability, wettability, and core flooding experiments to determine the effectiveness of the nanofluid in EOR applications. Transmission electron microscopy (TEM) was utilized to analyze the morphology and size distribution of both pure silica nanoparticles and nanofluid samples. TEM images were obtained using a FEI Tecnai G2 20S-TWIN microscope operated at an accelerating voltage of 200 kV.

2.3.1. Thermal Stability

The synthesized silica nanofluid was subsequently analyzed for thermal stability at temperatures of 60, 80, and 100°C using an oven. Samples were visually inspected over a 3-month period to assess changes in stability and phase separation.

2.3.2. Wettability

To investigate the effect of surfactants and nanoparticles on the wettability of the porous media, the sessile drop method was employed. Small slices of a clean core plug (thin-section core) were prepared and immersed in a silica nanofluid solution within the sessile drop apparatus. Crude oil was then injected from underneath the thin-section core, allowing for the measurement and analysis of the contact angle between the crude oil and the core surface. This approach allowed a detailed evaluation of the wettability changes induced by the nanofluid.

2.3.3. Core Flood

The upper grey Berea core, measuring 2 inches in length and 1.5 inches in diameter, was analyzed for its porosity and permeability. The core was initially saturated with water, followed by saturation with crude oil. The saturated cores were then placed in a core holder within a core flooding apparatus. The flooding process involved an initial injection of 3% NaCl brine, followed by nanoflooding with silica nanofluid, and then a post-flush with formation water. The core flooding experiment was performed at a temperature of 60°C with an injection rate of 0.3 cc/min.

3. Results and Discussion

3.1. Characterization of Thermal Stability Silica Nanofluids

Thermal stability tests were conducted to evaluate the resistance of silica nanofluid to heat under varying temperatures and surfactant concentrations. This assessment is crucial for determining the suitability of silica nanofluids in EOR applications, where high temperatures and salinity may affect their stability and performance. The temperatures employed in this study were 60, 80, and 100°C to simulate subsurface reservoir conditions. The nano-silica concentration was maintained at 0.1% within a 3% brine solution, ensuring consistent conditions across all samples. To investigate the impact of surfactant addition on thermal stability, the surfactant concentrations of SPU11 and SPU22 were varied according to specific ratios: 0:0, 0:0.3, 0.1:0.3, 0.2:0.3, and 0.3:0.3%. Thermal stability was observed over 3 months to assess long-term stability under static conditions.

The visual observations of nanofluid stability are illustrated in Figure 1. The results from this study indicate that at 60°C and 80°C, the silica nanofluids containing 0.3% SPU11 and 0.3% SPU22 exhibited remarkable stability over the designated period. These nanofluids, labeled as SNF 5 and SNF 10, remained homogeneous without visible phase separation or significant sedimentation. In contrast, samples containing lower surfactant concentrations or lacking surfactants entirely showed evident precipitation and agglomeration, particularly at elevated temperatures. The stability observed in SNF 5 and SNF 10 suggests that the presence of both SPU11 and SPU22 surfactants plays a vital role in preventing nanoparticle aggregation, thereby enhancing dispersion stability in saline environments.

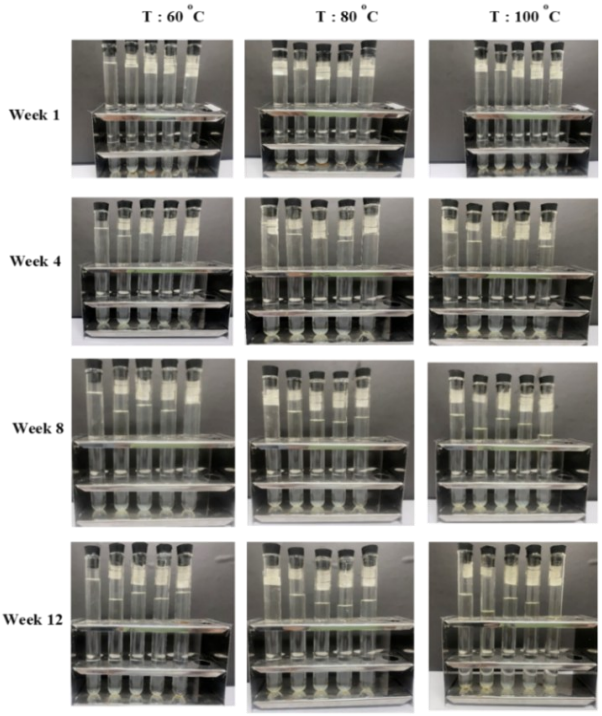

Figure 1. Visual observation of the thermal stability of silica nanofluid

Table 1 presents a summary of the thermal stability results, highlighting the influence of temperature and surfactant concentration on nanofluid stability. It is evident that increasing the surfactant concentration to 0.3% for both SPU11 and SPU22 significantly enhances the stability of silica nanofluids at 60°C and 80°C. However, at 100°C, none of the tested formulations maintained stability over the observation period, indicating that additional modifications, such as further optimization of surfactant ratios or the introduction of stabilizing agents, may be necessary for applications in high-temperature reservoirs.

The stability performance of SNF 5 and SNF 10 highlights their potential use in EOR applications in reservoirs with salinities below 3% and temperatures below 80°C. The ability to maintain colloidal stability under these conditions suggests that silica nanofluids with optimized surfactant compositions can effectively function as EOR agents, potentially improving oil recovery rates by maintaining nanoparticle dispersion and preventing pore-blocking due to particle aggregation.

Overall, these findings highlight the critical role of surfactant concentration in improving the thermal stability of silica nanofluids. The ability of SPU11-SPU22 surfactant combinations to prevent aggregation under moderate temperature conditions suggests their applicability in oil reservoirs with mild to moderate thermal stress. However, the instability observed at 100°C indicates potential limitations for high-temperature applications. Future studies should focus on modifying the formulation by incorporating additional stabilizers or altering surfactant chemistry to enhance thermal resistance for higher-temperature reservoir conditions.

Table 1. Thermal stability of nanofluid

Code	Temperature (°C)	Anionic surfactant (%)		Result
		SPU11	SPU22	
SNF 01	60	0	0	Unstable
SNF 02		0	0.3	Unstable
SNF 03		0.1	0.3	Unstable
SNF 04		0.2	0.3	Unstable
SNF 05		0.3	0.3	Stable
SNF 06	80	0	0	Unstable
SNF 07		0	0.3	Unstable
SNF 08		0.1	0.3	Unstable
SNF 09		0.2	0.3	Unstable
SNF 10		0.3	0.3	Stable
SNF 11	100	0	0	Unstable
SNF 12		0	0.3	Unstable
SNF 13		0.1	0.3	Unstable
SNF 14		0.2	0.3	Unstable
SNF 15		0.3	0.3	Unstable

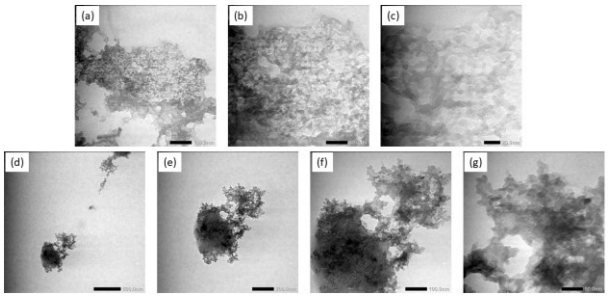

Figure 2. TEM images of pure silica nanoparticles with scale bars of (a) 100 nm, (b) 50 nm, and (c) 20 nm, and silica nanofluids at (d) 500 nm, (e) 200 nm, (f) 100 nm, and (g) 50 nm

3.2. Microstructure of Silica Nanofluid

The TEM micrographs of pure silica nanoparticles are shown at varying magnifications (Figure 2a-c), illustrating the morphology and dispersion of the silica nanoparticles. The particles appear to be spherical with relatively uniform size distribution, and no significant agglomeration is observed at these scales. Meanwhile, Figures 2d–g present the TEM analysis of silica nanofluids conducted at varying imaging magnification. These images reveal the interaction and distribution of silica nanoparticles within the fluid medium. Compared to the pure silica nanoparticles, the nanofluid shows a more dispersed structure with potential indications of stabilization, suggesting the effectiveness of the fluid medium in maintaining nanoparticle dispersion.

3.3. Characterization of PSA Silica Nanofluid

The aggregate diameter of silica nanofluids plays a crucial role in determining their ability to traverse porous rock formations. In EOR applications, smaller aggregate sizes are preferred as they reduce the likelihood of pore clogging, ensuring efficient transport through reservoir formations. To assess the particle size distribution of the synthesized silica nanofluids, PSA was conducted.

The results, summarized in Table 2, reveal that the introduction of surfactants significantly affects the aggregate size distribution of the silica nanofluids. Notably, all measured particle sizes remain well below the typical pore size range of reservoir rocks (5-50 µm), reinforcing their suitability for low-permeability reservoirs with small pores and narrow pore throats.

A clear trend emerges from the data, indicating that the addition of surfactants (DLS and AOS) leads to variations in the aggregate diameter. For instance, the baseline sample (NS 0.1% + NaCl 3%) exhibits a relatively small aggregate size, with a Z-Average of approximately 171.7 nm to 188.7 nm. The incorporation of DLS at 0.3% slightly increases the Z-Average to 194.4 nm but results in a wider size distribution, as evidenced by the Z- Intensity values. The presence of AOS, even at low concentrations (0.1% and 0.2%), induces further modifications in particle size, with a notable reduction in Z-Number values, suggesting a more dispersed and stable system.

Interestingly, the sample containing NS 0.1% + NaCl 3% + DLS 0.3% + AOS 0.2% demonstrates an unexpected increase in Z-Average and Z-Intensity, reaching values as high as 343.7 nm and 404.1 nm, respectively. This suggests potential nanoparticle agglomeration at higher surfactant concentrations, which may influence the overall performance of the nanofluid in EOR applications. These findings highlight the importance of optimizing surfactant concentrations to maintain a balance between stability and mobility within porous media.

The ability of silica nanofluids to maintain small and stable aggregate sizes is critical for their effective deployment in subsurface reservoirs. Excessive aggregation could hinder their transport efficiency, whereas well-dispersed nanoparticles enhance the wettability alteration and oil displacement mechanisms required for improved oil recovery. Future work should investigate the underlying mechanisms driving aggregation at higher surfactant concentrations and explore alternative stabilization strategies.

The aggregate diameter is critical in assessing the ability of silica nanofluids to pass through rock pores, with smaller aggregate sizes being less likely to clog the pores. Therefore, PSA was performed to determine the aggregate diameter of the synthesized silica nanofluids. The results shown in Table 2 indicate that the addition of surfactant significantly influences the diameter of the silica nanofluid aggregates. Notably, the produced aggregates are relatively small, well below the typical pore size range of 5-50 µm. This characteristic enhances their applicability in low-permeability reservoirs containing small pores and narrow pore throats [21].

These findings underscore the complex interplay between nanoparticle concentration, surfactant interactions, and aggregation dynamics. The results emphasize the necessity of precise formulation control in designing silica nanofluids for EOR applications to optimize performance and ensure stability under reservoir conditions.

Table 2. PSA results of the silica nanofluid

Sample	Z-Average (nm)	Z-Intensity (nm)	Z-Number (nm)	Z-Volume (nm)
NS 0.1% + NaCl 3%	171.7	156	81	135.4
	188.7	185.6	55.68	164.4
	172.9	258.1	63.1	86.27
NS 0.1% +NaCl 3% +DLS 0.3%	194.4	77.81	249	105.4
	185.1	261	72.77	100.9
	189.5	189.8	22.62	24.5
NS 0.1% + NaCl 3% + DLS 0.3% +AOS 0.1%	153.9	211.3	69.34	94.5
	153.9	202.3	23.32	25.52
NS 0.1% + NaCl 3% + DLS 0.3% +AOS 0.2%	169.1	233.6	60.57	80.47
	167.9	196	111.2	120.6
	170.2	215.8	100.2	114.5
NS 0.1% + NaCl 3% + DLS 0.3% +AOS 0.2%	343.7	404.1	52.86	491.6
	367.7	420.4	55.07	502.4
	338.1	412.2	71.11	475.3

3.4. Analysis of Silica Nanofluid Wettability

The measurement of contact angle (θ) is an essential parameter in determining the wettability of a rock surface, as it directly influences the efficiency of the EOR process. Wettability governs fluid distribution and displacement within reservoir formations, with water-wet conditions generally favoring improved oil displacement. Naturally, reservoir rocks tend to be water-wet; however, prolonged crude oil exposure causes a gradual shift toward an oil-wet state due to adsorption and deposition of asphaltenes, resins, and other hydrocarbons onto the rock surface. This transition to oil-wet reduces oil recovery efficiency, as adhesive forces between oil and rock increase, trapping oil within pore structures.

The fundamental goal of this study is to modify the wettability of the rock surface from oil-wet to water-wet, thereby enhancing oil displacement efficiency and facilitating recovery. Wettability classification is based on contact angle values, where water-wet conditions correspond to ($0° \leq \theta < 75°$), intermediate-wet conditions range between ($75° \leq \theta \leq 105°$), and oil-wet conditions are identified by ($105° < \theta \leq 180°$). In oil-wet reservoirs, capillary forces serve as the dominant mechanism impeding oil flow, necessitating wettability alteration to minimize these forces and improve oil mobilization [22].

The results of the wettability analysis, as illustrated in Figure 3, indicate that the use of SPU11-SPU22 surfactants at concentrations of 0.3%-0.3% produces a negligible reduction in contact angle. This suggests that surfactants alone may not be sufficient to significantly modify the wettability of the rock surface. Conversely, the introduction of silica nanofluids leads to a substantial decrease in contact angle, reducing it from 60.84° to 36.63°. This marked reduction confirms the effectiveness of nanosilica in enhancing water-wet conditions, which is a crucial factor in optimizing oil displacement efficiency.

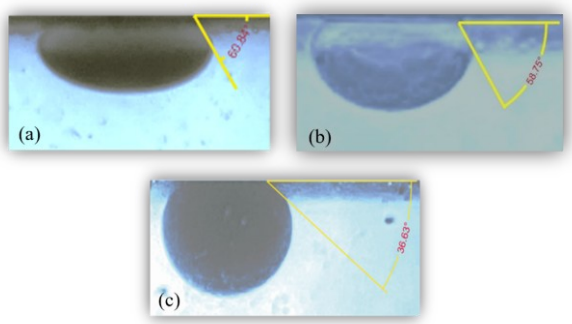

Figure 3. Contact angle analysis results of silica nanofluid: (a) 3% brine solution, (b) 0.3%:0.3% SPU11–SPU22 surfactant solution, and (c) SNF-05 silica nanofluid

The enhanced wettability alteration achieved through silica nanofluid application can be attributed to its unique physicochemical properties, including its high surface energy, nanoscale size, and ability to modify rock-fluid interactions. These characteristics enable nanosilica to displace oil films adhered to the rock surface, thereby restoring water-wet conditions and reducing the capillary barriers that restrict oil flow. Furthermore, nanosilica particles may enhance disjoining pressure at the oil-rock interface, weakening adhesive forces and promoting oil detachment. Given these findings, the incorporation of silica nanofluids into EOR strategies represents a promising approach for improving oil recovery, particularly in reservoirs with high oil-wet tendencies.

3.5. Characterization of Core Flooding Silica Nanofluid

The results of the core flooding experiments, as presented in Table 3 and Figure 4, demonstrate the effectiveness of both water flooding and nanofluid flooding in enhancing oil recovery. Initially, water flooding alone achieved a recovery factor of 46.9% of the original oil in place (OOIP), highlighting its ability to displace a significant fraction of the crude oil from the

core sample. Water flooding operates primarily by creating a pressure gradient that drives oil out of the porous medium; however, it has inherent limitations. A substantial portion of the oil remains trapped within the rock due to capillary forces, poor sweep efficiency, and the inability of water to effectively displace oil in tighter pore spaces, especially in cases of oil-wet or intermediate-wet reservoir conditions. This residual oil requires additional EOR strategies to be mobilized effectively.

To further improve recovery efficiency, nanofluid flooding was conducted using silica nanofluid SNF 05, formulated with 0.1% nano-silica, 3% NaCl, 0.3% SPU11, and 0.3% SPU22. This injection led to an incremental oil recovery of 9.7% OOIP, increasing the total recovery factor to 56.6%. The improvement in oil displacement during nanofluid flooding is attributed to several mechanisms, primarily the reduction of interfacial tension, wettability alteration, and possible structural disjoining pressure effects facilitated by the presence of nanosilica at the oil-rock interface. The reduction in IFT weakens the capillary forces that trap oil within the porous medium, thereby enhancing oil mobility. Additionally, the contact angle reduction observed in the wettability studies confirms that silica nanofluids effectively shift the rock surface from an oil-wet state to a more water-wet condition, further facilitating oil displacement.

Water cut (WC) data, also illustrated in Figure 4, provides critical insight into fluid production behavior throughout the flooding stages. Initially, during water flooding, the WC rose rapidly to nearly 100%, indicating a high-water production rate and signaling the nearing of water breakthrough. Upon switching to nanofluid injection (N1+S), the WC experienced a brief drop, which correlates with the mobilization of previously trapped oil due to improved displacement efficiency. This drop in WC is a positive indicator that the nanofluid was actively contributing to oil recovery during its injection. However, the WC quickly returned to nearly 100% and remained stable during the post-flush stage, confirming that no additional oil was recovered after nanofluid displacement. The transient reduction in WC demonstrates the role of nano fluid in temporarily increasing oil production before complete water dominance.

Despite the promising enhancement observed during nanofluid flooding, no further incremental oil recovery was recorded in the post-flushing stage. This indicates that the injected nanofluid had already reached its maximum displacement potential under the given experimental conditions. The absence of post-flush recovery suggests that the effectiveness of nanofluid flooding depends primarily on altering rock-fluid interactions during the injection phase rather than relying on continued mobilization during subsequent flushing. This finding is significant, as it highlights the importance of optimizing nanofluid formulations and injection strategies to maximize their efficiency in field applications.

Table 3. Core flooding data

Parameter	Yield
Core dimensions	
Diameter (inc)	1.5
Long (inc)	2
Properties core	
Pore volume (cc)	11.6
Porosity (%)	20
Permeability (mD)	352
OOIP in core	
Oil (cc)	6.4
Oil (%)	55.1
Recovery factor of water flooding	
Oil recovery (cc)	3
OOIP (%)	46.9
Recovery factor of nano-flooding	
Oil recovery (cc)	0.6
OOIP (%)	9.7
Recovery factor of post-flush	
Oil recovery (cc)	0
OOIP (%)	0
Total recovery factor	
Oil recovery (cc)	3.6
OOIP (%)	56.6

The core sample used in this study had a pore volume of 11.6 cc, porosity of 20%, and permeability of 352 mD, which are representative of moderately permeable reservoir formations. The efficiency of nanofluid flooding may vary depending on reservoir heterogeneity, permeability variations, and initial oil saturation. Additionally, the potential for nanoparticle aggregation or adsorption onto rock surfaces should be considered, as these factors could influence long-term stability and performance in field-scale applications. Future research should focus on optimizing nanofluid composition, investigating stability under reservoir conditions, and evaluating scalability for field deployment.

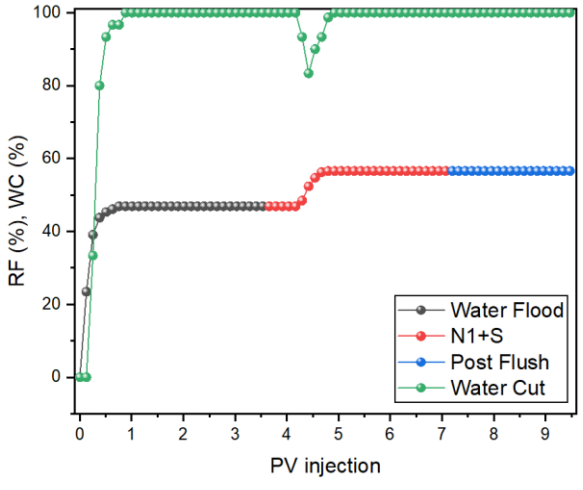

Figure 4. Oil recovery performance using silica nanofluid

4. Conclusion

This study investigated the formulation and stability of advanced nanofluids incorporating oppositely charged silica nanoparticles in conjunction with anionic surfactants SPU11 and SPU22. The findings demonstrate that the synergistic addition of these surfactants significantly improves the thermal stability of the silica nanofluids under moderate temperature and salinity conditions, with sustained stability observed over a period of three months. Furthermore, the presence of SPU11 and SPU22 leads to an increase in the aggregate size of silica nanoparticles, indicating enhanced colloidal interactions and structural integrity within the dispersion. The incorporation of nanosilica also contributes to a substantial alteration in rock surface wettability, promoting a transition toward less water-wet conditions, which is advantageous for oil mobilization. When applied in core flooding experiments, the optimized nanofluid formulation—comprising nanosilica and both anionic surfactants—exhibited a marked improvement in oil recovery efficiency. Collectively, these results underscore the potential of silica-surfactant nanofluid systems as effective agents for enhanced oil recovery, offering improvements in thermal stability, interfacial properties, and overall displacement performance.

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