

Performance Evaluation of Tween 60 Surfactant for EOR: Interfacial Tension Reduction and Microemulsion Formation

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ABSTRACT - Enhanced Oil Recovery (EOR) techniques are essential for maximizing crude oil extraction from mature reservoirs. Surfactant injection, particularly using surfactants such as Tween 60, has shown great potential in reducing interfacial tension (IFT) and enhancing oil recovery. This study evaluates the performance of Tween 60 for EOR applications, focusing on its aqueous stability, phase behavior, IFT reduction, and core flooding efficiency at temperatures of 60°C and 80°C. The research addresses a gap in the literature by examining the long-term stability and phase behavior of Tween 60 at these temperatures. Aqueous stability tests over seven days indicate that Tween 60 remains clear and stable at 60°C but becomes cloudy and unstable at 80°C. Phase behavior tests reveal that a 0.5% concentration of Tween 60 produces the largest middle-phase microemulsion (5.75% volume), forming a bicontinuous Winsor III microemulsion that enhances oil-water interaction. IFT tests using a spinning drop tensiometer show a reduction in IFT to 0.00525 dyne/cm. Core flooding tests confirm that surfactant injection contributes an incremental oil recovery of 8.33% beyond what was achieved by waterflooding without surfactant, increasing the total recovery factor from 62.5% to 70.83%. However, limitations such as the short testing period (14 days) and the use of a single type of oil (39 ° American petroleum institute) underscore the need for further research.

Keywords: enhanced oil recovery, surfactant, Tween 60, phase behaviour, interfacial tension.

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INTRODUCTION

Enhanced Oil Recovery (EOR) is a crucial technique for increasing oil production by extracting oil that cannot be recovered through conventional methods (Sugihardjo 2022). As global oil reserves continue to decline, EOR has become a viable solution to extend the productive life of existing reservoirs and improve overall oil recovery (Massarweh & Abushaikh 2020). Chemical injection offers significant potential in reservoirs or wells that have undergone water flooding but still contain unrecovered residual oil. One promising EOR method is chemical flooding using surfactants, where surfactants are injected to reduce the interfacial tension (IFT) between oil and water, thereby enhancing oil mobilization (Mandal 2015a).

Several views state that the phase behavior test is a more efficient step in determining the IFT value and the performance of the surfactant solution being tested (Wiralodra et al., 2021). Positive results from the phase behavior test indicate that surfactants with certain concentrations and salinities can form middle-phase emulsions (Riswati et al., 2020).

The determination of the phase behavior is Winsor Phase behavior, which is very important in oil acquisition because it determines the efficiency of the surfactant system in reducing the interface tension (IFT) and increasing oil displacement (Shah et al., 2022). In particular, the phase behavior of Winsor I, II, and III has different phase behaviors, for Winsor I and II represent microemulsions of oil-in-water (O/W) and water-in-oil (W/O), respectively. At the same time, Winsor III shows bidirectional microemulsions that can achieve very low IFT and maximize oil gain (Rousseau et al., 2022). The following sections outline the characteristics and implications of these phases. 1). Winsor I is characterized by O/W microemulsion, where water is a continuous phase, suitable for low

salinity conditions; 2). Winsor II: Involve a W/O microemulsion, where the oil is a continuous phase, usually preferred in environments with high salinity; 3). Winsor III: It is a bicontinuous phase that allows for very low IFT, which is critical for EOR, which is achieved through an optimal combination of surfactants and cosurfactants.

Winsor III exhibits a bicontinuous structure in the Middle phase, which means the oil and water phases are interspersed throughout the microemulsion, allowing for efficient interaction between oil and water, which is essential for mobilizing the oil trapped in the porous medium (Rousseau & Courtaud 2022). This middle-phase emulsion phenomenon is one indicator of the success of Enhanced Oil Recovery (EOR) using surfactants, apart from the oil-surfactant IFT value of less than 10^{-3} mN/m. This also involves reducing the IFT between oil and other fluids as well as controlling the wettability in rock pores (Marques & Silva 2013).

The type of surfactant to be used in this study is Tween 60, one of the nonionic surfactants that has shown potential to improve oil recovery due to its ability to form stable emulsions under various conditions (Morales-Garcia et al., 2020). Tween 60 is one of the non-ionic surfactants with a high HLB (Hydrophilic-Lipophilic Balance) consisting of a polysorbate head family as a hydrophilic part and a hydrocarbon chain used as a hydrophobic tail. It has often been used to produce stable O/W emulsions. The reason why Tween 60 surfactant is often used is its low cost, non-toxicity, and biocompatibility. Tween 60 is environmentally friendly and provides high solubility in water (Olabode et al., 2024). Tween 60 is therefore a very convenient and safe choice for formulation and in the production and application stages, affecting the properties of the product so that different distributions of droplet sizes can be achieved. This is why these properties affect the

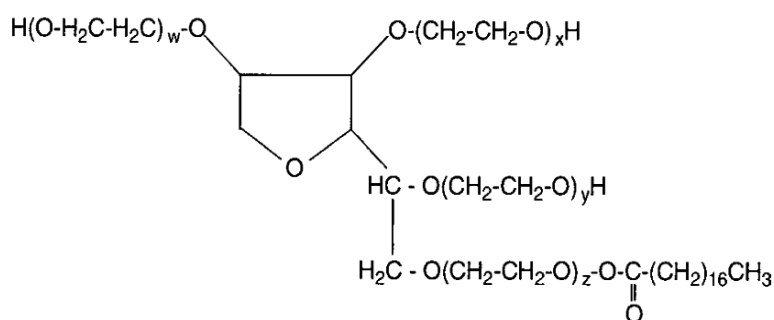


Figure 1. Chemical structure of Tween 60 (Yeh & Pavlostathis 2004)

rheological behavior as well as the microstructure and stability of the emulsion (Alli et al., 2018).

Tween 60 has a chemical structure characterized by a polyoxyethylene sorbitan ester and can be seen in Figure 1, which specifically consists of a sorbitan backbone with a hydrophilic polyoxyethylene chain(Yeh & Pavlostathis, 2004). This structure provides an HLB balance of about 15, making it effective in stabilizing emulsions and microemulsions(Tian et al., 2010). This structure allows Tween 60 to position itself at the oil-water. Despite extensive research on conventional anionic and cationic surfactants, nonionic surfactants such as Tween 60 remain underexplored in EOR applications, especially under harsh reservoir conditions.

Achieving optimal phase behavior requires a well-designed formulation package, as combining multiple surfactants rather than relying on single components helps maintain the appropriate balance and enhances system stability. It should be noted that the aqueous stability of surfactants in the Enhanced Oil Recovery process is an important factor, including Salinas, temperature, and surfactant formulation quality assurance ensures the effective field performance of the surfactant mixture(Gayani Pinnawala, 2024). Surfactant formulations that have high salinity can cause precipitation and degradation of surfactants, especially for anionic surfactants (Alyousef et al., 2024) It should also be noted that high-temperature conditions can exacerbate stability problems, so formulations that can withstand these temperature conditions without loss or change in efficiency (Hussain et al., 2024)

Therefore, this study aims to systematically evaluate the performance of Tween 60, a nonionic surfactant, for enhanced oil recovery under moderate-to-high temperature conditions (60°C and 80°C) in brine with 8000 ppm salinity. While Tween 60 is well-known for forming stable oil-in-water emulsions in other industries, its application in EOR—especially in reservoir-representative conditions—remains underexplored. This research addresses this gap by investigating Tween 60’s aqueous stability, its phase behavior (Winsor classification), its ability to reduce interfacial tension (IFT), and its oil recovery performance through core flooding tests at multiple concentrations (0.5%, 0.7%, 0.9%, 1%, and 1.3%).

By focusing on a biocompatible, non-toxic, and cost-effective surfactant under realistic EOR conditions, this study contributes to the development of environmentally friendly and efficient surfactant

formulations. The findings are expected to enhance the scientific understanding of nonionic surfactants for EOR and inform future surfactant selection strategies for field-scale applications.

METHODOLOGY

The research work steps carried out in this laboratory include preparation of synthetic formation water, preparation of surfactant solution, measurement of physical properties of the solution, measurement of interfacial tension, and surfactant injection. Tween 60, as a nonionic surfactant, has the potential to maintain stability in saline solutions with high salinity. In this study, Tween 60 was tested in saline solutions with a salinity of 8000 ppm in the temperature range of 60°C to 80°C to evaluate its performance in improving oil recovery. This section describes the materials and methods used to test the efficiency of this surfactant.

Materials

This study used Tween 60, a nonionic surfactant, dissolved in synthetic brine with 8000 ppm salinity to evaluate its performance in enhanced oil recovery (EOR). A light crude oil sample (39° American petroleum institute) from a production well and a single core sample were used to represent typical reservoir conditions. While the experiment was conducted without replicates due to material constraints, all procedures followed standardized protocols to ensure consistency and reliability. The results provide indicative insights under the tested conditions, with the composition of surfactant-brine mixtures prepared at concentrations ranging from 0.5% to 1.3%.

Aqueous stability test

Table 1. Composition of surfactant Tween 60 with brine

Salinity (ppm)	Concentration	Tween 60 (ml)	Brine (ml)
8000	0.5	5	995
	0.7	7	993
	0.9	9	991
	1	10	990
	1.3	13	987

The aqueous stability test was conducted to evaluate the stability of the surfactant solution in water with a salinity of 8,000 ppm. Approximately 5 ml of surfactant solution was placed into a test

tube. The samples were then placed in an oven and observed over 7 days at 60 and 80°C, to determine whether the surfactant remained stable and unchanged or exhibited a change in appearance, clear or cloudy.

Phase behavior test

Phase behavior tests were conducted to observe the interaction between surfactant and oil at various salinities and temperatures. These tests help determine how well the surfactant performs under field conditions and identify the optimal dosage. The expected result is the formation of a microemulsion center phase. The steps are as follows: 1). Add 2 mL of surfactant solution to the tube; 2). Add 2 ml of American petroleum institute 39° light oil to the tube; 3). Shake for 2 minutes or 8 times to mix the liquids or form an emulsion; 4). Record the initial volume of the emulsion; 5). Place the tube in the oven at 60 and 80°C to assess the stability of the emulsion; 6). Observe and record the emulsion at 30 minutes, 1 hour, 2 hours, 1 day, 2 days, 7 days, and 21 days.

Interfacial tension test

IFT testing measures the ability of a surfactant to reduce the tension between oil and water. The

IFT result is influenced by the phase behavior test, which shows the formation of the middle phase of the microemulsion. For this test, a brine solution with Tween 60 surfactant at 8,000 ppm salinity was used, and a Spinning Drop Tensiometer was utilized. Testing the Interfacial Tension value using the Spinning Drop Tensiometer Series 500D which is based on the balance of centrifugal force and interface tension (Gao & Sharma 2013). Firstly, the device and computer were switched on, and a new file named density difference was created. The temperature and spin speed were set, and the camera was configured to take pictures every 120 seconds for 30 minutes. The oil sample is inserted, and the camera position is adjusted. After reaching the target temperature, pictures were taken regularly, and the data were transferred to MS Excel for analysis. Finally, the IFT value was calculated to evaluate the performance of the surfactant in reducing the interfacial tension. Figure.2 is the Spinning Drop tensiometer used to measure IFT (Al-farraj 2019) .

In addition, Figure 3 is an example of the response results from the recorded IFT measurements (Pauhesti 2023a).



Figure.2 Spinning drop tensiometer series 500D

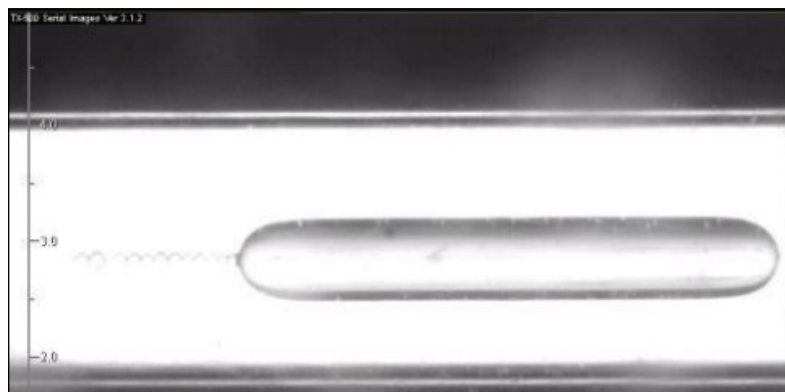


Figure 3. Droplet results of IFT surfactant testing (Pauhesti 2023b)

Core flooding

The core flooding procedure was used to assess the recovery factor and oil recovery efficiency. The procedure begins with brine saturation, where rock samples are placed in a desiccator to remove air and then immersed in a brine solution (8,000 ppm salinity). The dimensions and weight of the sample are measured using a digital balance, and the rock is placed in a core holder. Once saturated, the pore volume (PV) was determined by measuring the wet weight of the sample. Next, oil saturation was performed by injecting oil at a rate of 0.5 cc/min into the brine-saturated rock, removing the brine, and calculating the original oil in place (OOIP). Afterward, water was injected at a flow rate of 0.1-0.5 cc/min to determine oil recovery. Finally, surfactant inundation was performed to increase oil recovery at a flow rate of 0.5 cc/min. The fluid volume was measured using a dropper tube to calculate the recovery factor.

The method used in this study is designed to evaluate the effectiveness of Tween 60 surfactant performance with varying concentrations and under conditions of high salinity and varying temperatures. The data obtained from these experiments will be further analyzed to determine the potential application of Tween 60 in EOR.

RESULT AND DISCUSSION

During the research stages, the following results were obtained: Aqueous stability, phase behavior test, surfactant solution interfacial tension test, sandstone core measurement, and core flooding test. These stages have reliable results because this research is primary data that is directly researched objectively in the laboratory. Consequently, researchers can analyze the performance of Tween 60 surfactant for enhanced oil recovery.

Aqueous stability

Aqueous stability testing is a test conducted to observe the stability of surfactant solutions against time and temperature. From this test, enable the determination of the surfactant's stability profile at specific time points and temperatures. Stability is characterized by the surfactant maintaining its transparency and exhibiting no sediment formation throughout the test. For this study, the aqueous stability test was executed for 7 days at 60°C and 80°C using an oven.

Table 2. Compatibility of Tween 60 surfactant at 60 and 80 °C

Tween 60 Surfactant Concentration (%)	Temperature 60°C	Temperature 80°C
0.5	Clear	Cloudy
0.7	Clear	Cloudy
0.9	Clear	Cloudy
1	Clear	Cloudy
1.3	Clear	Cloudy

Observations from Table 2 indicate that all five Tween 60 surfactant concentrations maintained clarity at 60°C until the conclusion of the test. Conversely, at 80°C, all samples exhibited turbidity.

There was no sediment or so-called colloid or suspense that could affect the performance of surfactants in urging oil to come out of the rock because the sediment causes plugging in the core (rock). The five concentrations of Tween 60 at 60° C have good performance in terms of stability and can be a good candidate for the next test, namely phase behaviour.

Phase behavior

The phase behavior test was carried out to see the solubility of surfactants in the oil sample, or it can be said to see the compatibility of surfactants with the best characteristics based on the Tween 60 water stability test with American petroleum institute 39° light oil samples. Observations were carried out for 14 days at a temperature of 60°C to prove the existence of a mid-phase microemulsion. The microemulsion formed shows that the surfactant can fuse with the oil sample, which is one of the references for choosing a surfactant with a concentration that can work optimally because it successfully forms an emulsion. The visualization of the formation of phases can be seen in Figure 4. Based on the results of the experiment, the surfactant concentrations of 0.7, 1.5, and 1.3% tend to form the upper phase (Winsor I), where the oil phase dominates and contains a small amount of water that is visible in the oil layer at the top of the tube. At surfactant concentrations of 0.5% and 1.3%, it forms the Middle phase (Winsor III), which is an indication of the formation of bicontinuous microemulsions. In this phase, the oil and water are interconnected and form a stable structure, as seen in Figure 4.

In addition, the largest volume of mid-phase microemulsion (Winsor III) was produced by the Tween 60 surfactant at a concentration of 0.5%,

which is 5.75% of the total system volume (4 ml), while at a concentration of 0.9%, the volume of microemulsions formed was only 0.06%. This shows that the concentration of 0.5% is more effective in forming stable bicontinuous microemulsions. Figure 5. The comparison between the two surfactants shows that both graphs are equally stable and form a critical micelle concentration (CMC) point, but

a concentration of 0.5% still produces the most volume of microemulsions. The formation of this microemulsion is critical in enhanced oil recovery (EOR) applications, as it reduces the stress of the oil-water interface, improves sweeping efficiency, and facilitates the mobilization of trapped oil. Therefore, a concentration of 0.5% was chosen for further testing.

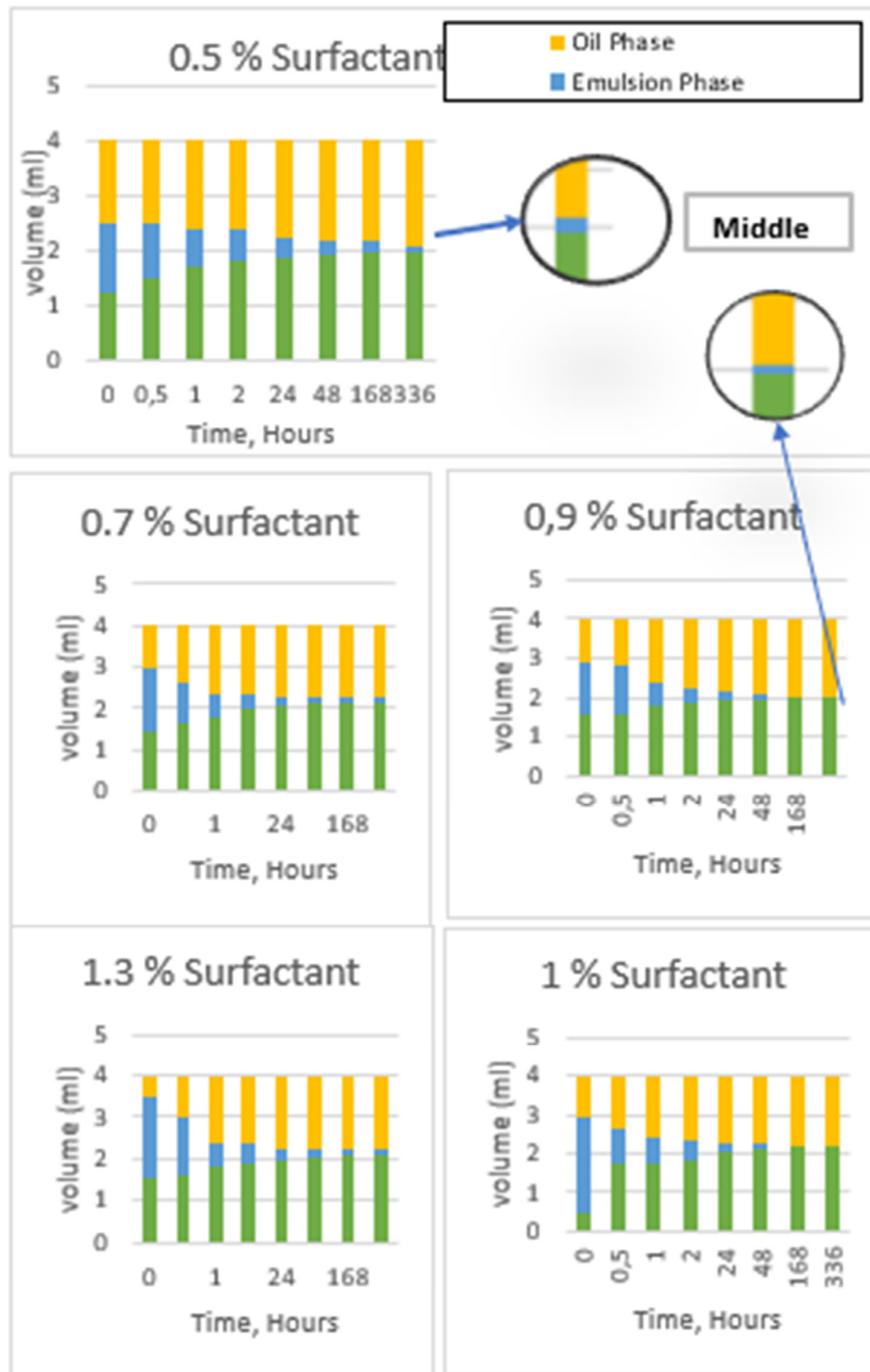


Figure 4. Visualization of phase test behavior of microemulsion formation on tween surfactant with varying concentrations.

Table 3. Result of tween 60 surfactant phase behavior

Oil	Surfactant Composition with Salinity 8000 ppm	Types of Phase emulsions	Volume At Observation Time (Hours)				Total Emulsions (%)	Jenis Emulsi Fasa
			24	48	168	336		
Light Crude Oil 39° API	0.5% Surfactant	Oil	1,75	1,8	1,82	1,92	5,75%	Middle Phase
		Emulsion	0,4	0,3	0,23	0,13		
		Surfactant	1,85	1,9	1,95	1,95		
	0.7% Surfactant	Oil	1,75	1,75	1,75	1,75	2,50%	Upper Phase
		Emulsion	0,2	0,15	0,1	0,1		
		Surfactant	2,05	0,1	2,15	2,15		
	0.9% Surfactant	Oil	1,85	1,95	1,96	1,95	1,50%	Middle Phase
		Emulsion	0,25	0,1	0,06	0,06		
		Surfactant	1,95	1,95	1,98	1,98		
	1% Surfactant	Oil	1,75	1,75	1,8	1,8	1,25%	Upper Phase
		Emulsion	0,35	0,15	0,05	0,05		
		Surfactant	2	2,1	2,15	2,15		
	1.3% Surfactant	Oil	1,75	1,8	1,8	1,8	2,50%	Upper Phase
		Emulsion	0,3	0,15	0,1	0,1		
		Surfactant	1,95	2,05	2,1	2,1		

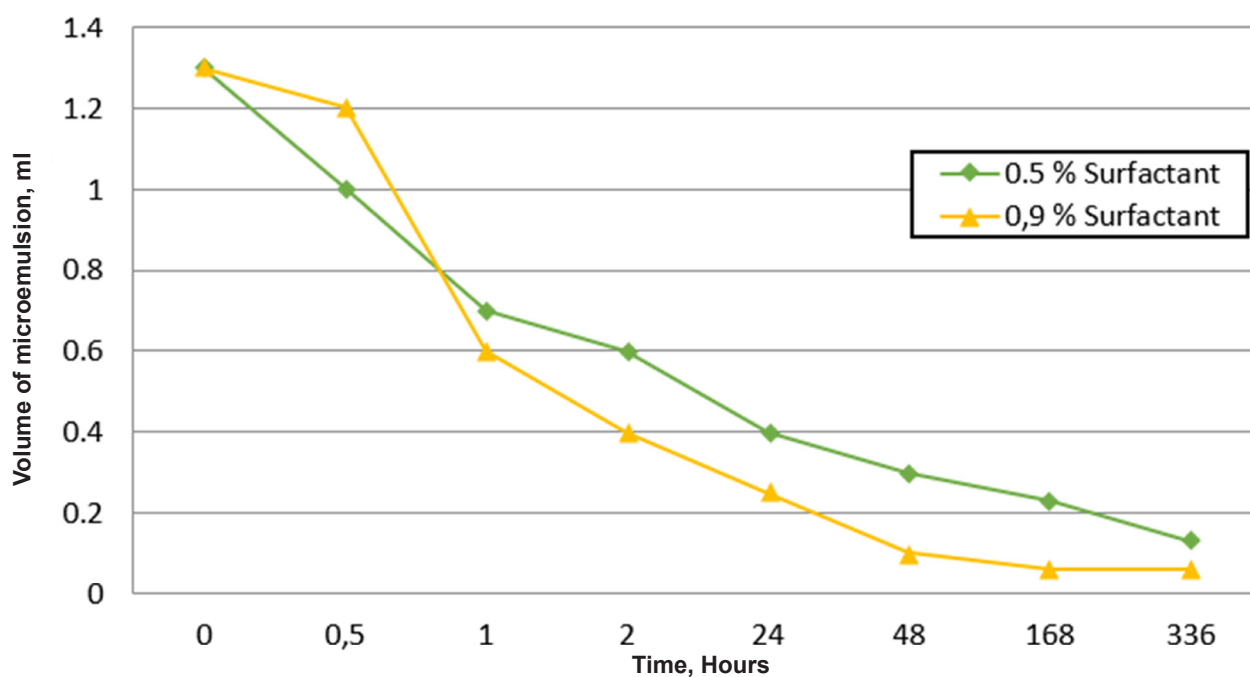


Figure 5. Phase behavior of 0.5 And 0.9% tween 60 surfactant at 60°c in 8000 ppm salinity

Interfacial tension (IFT)

IFT value is measured using a spinning drop tensiometer by inserting 2 ml of surfactant in a cAmerican petroleum institute llary tube, then dripping American petroleum institute 39° light crude oil, which aims to measure the interfacial tension between crude oil and surfactant. Good IFT results are if the oil droplet has a diameter and length that are increasingly flat and elongated in accordance with the provisions of the IFT value of 10^{-3} (Marques & Silva 2013). Measurement of the IFT value was carried out using a stable surfactant in the phase behavior test, namely, Tween 60 surfactant with a concentration of 0.5%. Surfactant and crude oil were put into the spinning drop tensiometer, then the cAmerican petroleum institute llary tube will rotate in the spinning drop at 6,000 rpm for 30 minutes at a temperature of 60 °C.

The results of the IFT value obtained from the spinning drip tensiometer recording on a computer stated that the surfactant Tween 60 concentration of 0.5% has met the criteria following the standard of 10^{-3} which is 0.00525 dyne/cm, so that the surfactant is able to reduce the interfacial tension to the maximum. Figure. shows flattened and elongated oil droplets following the provisions of 10^{-3} .

Core sample test

Before core flooding, the rock samples must be measured for physical properties and saturated with brine and light oil solutions for reservoir zone interpretation. Physical properties, including diameter, height, and weight, are measured using calipers to determine the bulk volume of empty rock.

Table 4. Measurement of rock sample

Rock Type	Sandstone
Diameter (cm)	2.61
Height (cm)	3.56
Bulk volume (cc)	19.054
Dry Core (gr)	40.86
Wet Core	43.77
Pore volume (cc)	2.907
Porosity (%)	19
Permeability (mD)	170

Table 4 shows the results of the physical properties of the rock core samples.

Sandstone samples were measured at 60°C. After measurement, the samples were saturated with brine by placing them in a measuring cup and leaving them in a desiccator for 24 hours until no bubbles escaped. Next, oil saturation was performed by injecting American petroleum institute 39° light oil into the rock, displacing the brine in the pores, with the volume of displaced brine indicating the oil content.

Core flooding

Core flooding is the last stage in the research to prove the effectiveness of surfactants in reducing interfacial tension so as to increase oil production recovery (Morales-Garcia et al., 2020). Core flooding uses a tool called a core holder and was conducted to determine the oil yield from surfactant injection that had passed the aqueous stability and phase behaviour tests. The surfactant that met the criteria was Tween 60 surfactant with a concentration of 0.5%. The injection test itself is divided into two, namely water



Figure 6. Droplet results of IFT tween 60 concentration 0.5%

injection (water flooding) and surfactant injection (surfactant flooding).

The first injection performed was water flooding. Water flooding is a second-stage recovery method by injecting water into the reservoir so that the remaining oil can be pushed to the production well (Alhaj & Saleh, 2024). The results for both water flooding and surfactant flooding are shown in Table 5. In this table, the Amount of injected (PV) indicates the total pore volumes of fluid injected relative to the core’s pore volume, while Oil produced represents the incremental oil from each stage, not the overall cumulative amount.

Table 5. Results of water flooding and Injection result of Tween 60 surfactant 0.5% concentration

Parameters	Water Flooding	Surfactant Flooding
Amount of injected (PV)	3	4
Oil produced (cc)	0.75	0.1
Recovery Factor (%)	62.50	8.33
Remaining oil (CC)	0.45	0.35
Residual oil saturation (%)	15.48	12.04

The next stage of core flooding is surfactant injection. Surfactant injection is useful for sweeping oil that cannot be produced by water injection. The surfactant used is Tween 60, with a concentration of 0.5%, as it has passed the aqueous stability, phase behavior, and IFT tests, allowing it to reduce the interfacial tension and facilitate oil production. Table 5 explains that the amount of surfactant injection can sweep 0.10 cm³ of oil. The surfactant injection results show that the addition of 0.5% Tween 60 surfactant can increase oil recovery by 8.33%. Figure 6 explains the RF vs PV graph, where when water injection is 3 PV, the maximum RF is 62.5%, and it can be seen that when surfactant injection occurs, RF increases to 70.83 %. This, in turn, is an indication that a concentration of 0.5% in Tween 60 surfactant with 8000 ppm salinity can improve oil recovery.

Discussion

The main objective of this study is to analyze the performance of Tween 60 surfactant as a chemical injection for enhanced oil recovery (EOR), specifically in brine solutions with a salinity of 8000 ppm. This research aims to answer the question of how Tween 60 surfactant affects the interfacial tension (IFT) between oil and water, and how this decrease in IFT contributes to increased oil mobilization in the reservoir. Additionally, this study aims to determine the impact of temperature

variation of 60 and 80°C on the effectiveness of Tween 60, as well as the optimal concentration variation that results in the best EOR performance. The hypothesis put forward in this study suggests that Tween 60 will significantly reduce IFT and increase oil recovery efficiency under the conditions tested, with surfactant performance expected to improve as temperature increases. It was hypothesized that higher concentrations of Tween 60 would achieve the most substantial results in reducing IFT and improving the EOR surfactant injection process.

The results showed the effectiveness of Tween 60 surfactant in increasing oil recovery through various tests. The water stability test showed that all concentrations of Tween 60 remained clear at 60°C, indicating good stability, while at 80°C, the solution turned cloudy. This loss of stability at higher temperature is likely due to partial dehydration of the ethoxylate head group, which reduces steric stabilization in high-salinity brines. In the phase behavior test, 0.5% Tween 60 concentration formed the largest mid-phase microemulsion (5.75%), indicating optimal compatibility with oil. This mid-phase emulsion, also known as Winsor III, exhibits a bicontinuous structure where the oil and water phases are interspersed through the microemulsion. The formation of this bicontinuous phase promotes efficient oil-water contact, enhancing mobilization of trapped oil in the porous medium. Higher concentrations, such as 0.9%, resulted in smaller microemulsion volumes, possibly due to surfactant crowding at the interface, which can hinder optimal packing and reduce interfacial curvature matching. This structure allows for efficient interaction between oil and water, which is essential for mobilizing the oil trapped in the porous medium(D. , L. G. C. , W. N. , & C. T. Rousseau, 2022). The interfacial tension test (IFT) showed that the surfactant reduced the IFT significantly, with a value of 0.00525 dyne/cm, confirming its ability to facilitate oil mobilization. Although droplet shape analysis was not quantitatively conducted, visual inspection during spinning drop tensiometry suggested elongated droplet morphologies typical of ultra-low IFT systems, supporting the measured values. During core flooding, surfactant injection increased oil recovery by 8.33%, with a recovery factor of 70%, compared to water flooding which achieved 62.5%. These results highlight the potential of Tween 60 as an efficient agent for enhanced oil recovery (EOR), especially under high salinity conditions.

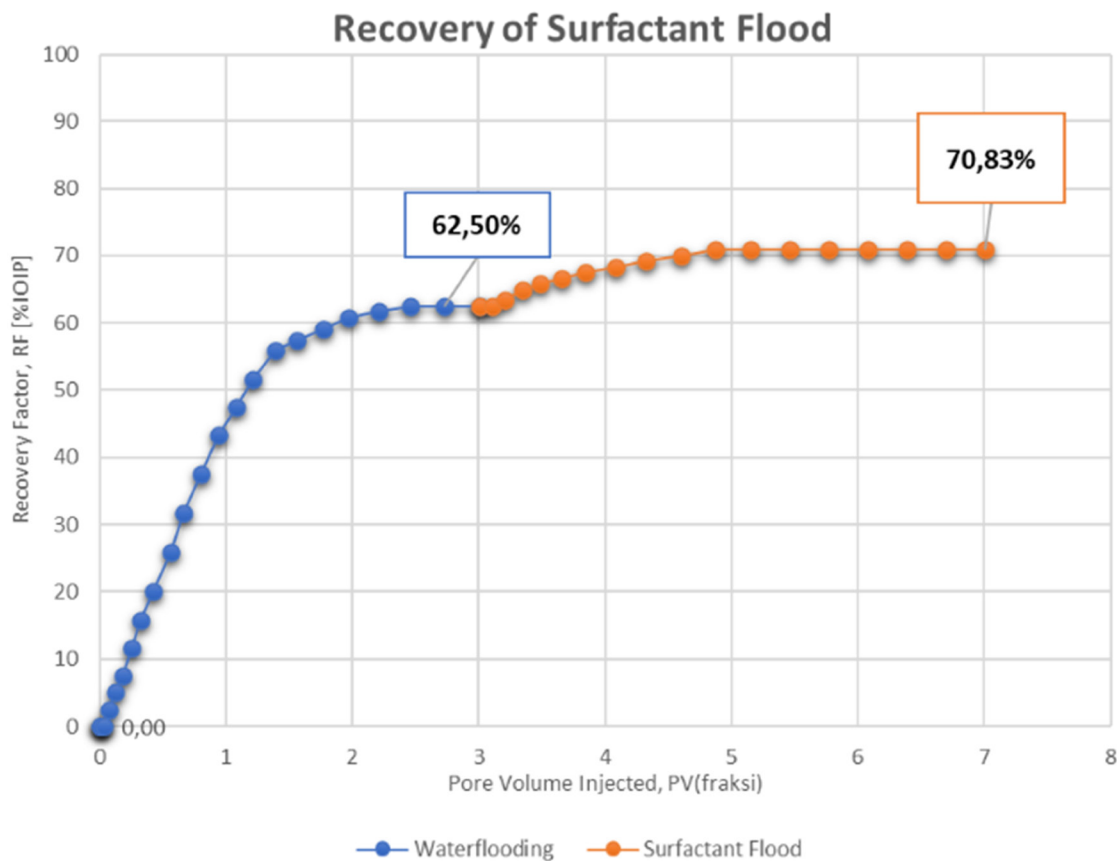


Figure 7. Graph of Recovery factor (RF) vs Porevolume (PV) injected

In evaluating the findings with previous literature, the study of the performance of Tween 60 surfactant in enhanced oil recovery (EOR) is in line with existing surfactant theory. Previous research has shown that surfactants effectively reduce interfacial tension (IFT) and form emulsions, thereby increasing oil recovery in reservoirs (Morales-Garcia et al., 2020). In this study, Tween 60 showed good aqueous stability at 60°C, which is consistent with previous findings indicating that stable surfactant formulations are key to successful EOR (Mandal 2015b). Phase behavior tests confirmed the formation of a mid-phase emulsion, an essential indicator of surfactant efficacy in oil recovery, as reported in a similar study (Novriansyah et al., 2020). The 0.5% concentration of Tween 60 was selected for further testing because it produced the largest volume of microemulsion (5.75%) compared to the 0.9% concentration, which only formed 1.5%. This aligns with the principle that a surfactant capable of achieving a lower IFT while forming a larger volume of microemulsion is generally preferred, as it enhances the stability of microemulsion and improves the efficiency of the surfactant flooding process (Kong Zheng Chen

& Chee Wee 2021). Additionally, reducing IFT by 0.00525 dyne/cm with 0.5% Tween 60 supports the idea that lower IFT significantly improves oil mobilization. Core flooding tests further validated these results, showing a marked increase in recovery factor, similar to previous surfactant flooding studies (Marques & Silva 2013)

While the results are promising, this study is limited by the use of only one crude oil and one core sample, and no experimental replication, which reduces statistical robustness. Therefore, the findings should be interpreted as indicative rather than conclusive. Future work should include replicate experiments, quantitative droplet morphology analysis for IFT validation, and testing across a wider range of salinities and temperatures to strengthen the mechanistic understanding of Tween 60 performance in EOR applications.

CONCLUSION

The results from this study are promising, showing that Tween 60 surfactant can effectively

reduce interfacial tension (IFT) and form stable microemulsions, which significantly improve oil recovery. The stability of the surfactant at 60°C, the formation of a biocontinuous Winsor III microemulsion at 0.5% concentration, and successful core flooding tests support its potential for enhanced oil recovery (EOR). These findings align with previous literature, where surfactants have demonstrated similar behavior in enhancing oil mobilization through IFT reduction and microemulsion formation. The reduction in IFT to 0.00525 dyne/cm and increase in recovery factor to 70.83% with 0.5% Tween 60 highlights the surfactant's potential to increase oil production in real-world applications, making it a strong candidate for EOR processes.

However, this study has some limitations. The relatively short testing period (14 days) for phase behavior may not fully represent the long-term performance required for field applications, which can vary significantly. Additionally, using only one type of oil (39° American petroleum institute) may not account for the variability in different reservoir oils, which could affect surfactant performance. Future research should explore the impact of different oil types, longer test periods, and field-scale application to further validate these results and optimize surfactant formulations for diverse reservoir conditions. Investigating the performance of tween 60 at higher temperatures and varying brine conditions could also provide deeper insights into its applicability in more challenging reservoir environments.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
API gravity	A measure of crude oil density relative to water; a higher API indicates lighter oil.	°API
IFT EOR	Interfacial Tension Enhanced Oil Recovery	mN/m; dyne/cm
HLB	Hydrophilic-Lipophilic Balance	
Tween 60	A nonionic surfactant (polyoxyethylene sorbitan monostearate) used for emulsification and stabilization of oil–water systems	
Winsor I, II, III	Classification of microemulsion systems Winsor I (O/W) Winsor II (W/O) Winsor III (bicontinuous phase with ultra-low IFT)	
Salinity	Measure of salt concentration in brine solution, expressed in parts per million.	ppm
RF	Recovery Factor	Percent (%)
PV	Pore Volume	

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