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Optimizing Coconut Oil-Derived MES Surfactants for Enhanced Oil Recovery Through Interfacial Tension Measurement

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A B S T R A C T

The measurement of interfacial tension (IFT) plays a critical role in evaluating the effectiveness of surfactant formulations in Enhanced Oil Recovery (EOR). Methyl Ester Sulfonate (MES) surfactants, particularly those derived from pure coconut oil, have shown potential in EOR applications due to their environmental benefits and performance characteristics. This study investigates the performance of various MES formulations under different conditions to identify the optimal combination for reducing oil-water interfacial tension. A Spinning Drop Interfacial Tensiometer was employed to measure the IFT of MES formulations.

The experimental setup included varying salinity levels and the addition of sodium carbonate (Na_2CO_3) to the surfactant solutions. Among the tested combinations, the formulation comprising MES surfactant, 15,000 ppm salinity, and 0.3% Na_2CO_3 achieved the lowest IFT value of 6.97×10^{-3} dyne/cm. This value significantly outperforms other MES-based formulations and meets the stringent requirement for EOR surfactants, which necessitates an IFT below 10^{-3} dyne/cm.

The results confirm that MES surfactants derived from pure coconut oil are highly effective in reducing IFT, making them suitable candidates for EOR applications. The findings suggest that the use of such environmentally friendly surfactants could enhance oil recovery efficiency, thus providing a sustainable and economically viable solution for the petroleum industry. Future research should focus on the long-term stability of these formulations under reservoir conditions and their performance in field trials to further validate their applicability in EOR processes. In conclusion, this study highlights the importance of precise IFT measurement in optimizing surfactant formulations for EOR. The promising performance of MES surfactants, particularly in high-salinity conditions with Na_2CO_3 addition, opens new avenues for improving oil recovery while adhering to environmental and economic considerations.

Keywords: Enhanced Oil Recovery, Interfacial Tension Measurement, Methyl Ester Sulfonate, Coconut Oil Surfactants, Spinning Drop Tensiometer, Sodium Carbonate Salinity, Environmental Surfactants

1. INTRODUCTION

The measurement of interfacial tension (IFT) plays a crucial role in evaluating the effectiveness of surfactant formulations in Enhanced Oil Recovery (EOR) operations. By accurately determining the IFT between surfactants and hydrocarbons, researchers can predict the performance of surfactants in reducing the interfacial tension between oil and water, facilitating the mobilization of residual oil in reservoirs (Behnam et al., 2023; Xeudong et al., 2023; Muslim et al., 2023). Additionally, IFT measurements are essential for estimating the CO2-oil minimum miscible pressure (MMP) in CO2-enhanced EOR processes, aiding in the selection of optimal surfactants and injection strategies for enhanced oil recovery projects (Orlando et al., 2022; Shams et al., 2023). The ability to predict IFT values accurately through advanced intelligent techniques not only saves time and resources but also enhances the overall success of EOR operations by improving displacement efficiency and reducing residual oil saturation in reservoirs.

In recent years, Methyl Ester Sulfonate (MES) surfactants have offered significant environmental benefits in EOR applications due to their biodegradability and low toxicity. MES is derived from renewable vegetable oil-based materials, showcasing a natural origin index of 0.84 and low skin irritation potential (Adeyinka et al., 2023; Muhammad et al., 2023). Additionally, MES surfactants have been found to have low ecotoxicity levels and high biodegradability, making them environmentally friendly options for chemical-enhanced oil recovery processes (Emily et al., 2022). These surfactants not only provide efficient oil recovery through surfactant flooding by reducing interfacial tension but also exhibit favorable environmental characteristics, aligning with the growing emphasis on sustainable and green practices in the oil industry. Derived from renewable resources such as coconut oil, MES surfactants offer a sustainable alternative to traditional petrochemical-based surfactants.

Research has indicated that MES surfactants can achieve low IFT values essential for EOR, particularly in high-salinity environments commonly found in oil reservoirs. The ability to maintain low IFT under these conditions is crucial for maximizing oil recovery and ensuring the economic viability of EOR projects. High-salinity environments significantly impact the performance of microemulsion (MES) surfactants in achieving low interfacial tension (IFT) values. Research has shown that surfactants with salt-tolerance properties can attain ultra-low IFT levels even at high salinity conditions, enhancing oil recovery efficiency (Xianglong et al., 2023). Additionally, the salinity of the aqueous phase affects the critical micelle concentration (CMC) of surfactants, with higher salinity leading to a decrease in CMC, thus influencing the amount of material needed for injection into reservoirs (Matthew et al., 2022). Furthermore, the injection of ultra-low IFT-inducing surfactants at constant salinity levels has been found to improve oil recovery in core flood experiments, showcasing the importance of optimizing salinity conditions for enhanced performance of surfactants in high-salinity carbonate reservoirs**.**

This study aims to address the challenge of optimizing surfactant formulations to achieve the lowest possible oil-water interfacial tension, a key factor in enhancing oil recovery. Despite the potential of MES surfactants, there is a need to systematically investigate their performance under various conditions to determine the optimal formulation. The primary problem addressed in this research is identifying the combination of MES surfactants, salinity levels, and additives that result in the lowest IFT values, thereby improving EOR efficiency.

Recent studies have explored various strategies to enhance the performance of MES surfactants in EOR. One approach involves adjusting the salinity of the surfactant solution to match the conditions of the reservoir, as salinity can significantly impact the effectiveness of surfactants. For instance, some research indicates that increasing the salinity can lead to lower IFT values, making the surfactant more effective in mobilizing trapped oil. Additionally, the inclusion of additives such as sodium carbonate (Na_2CO_3) has been shown to further reduce IFT, providing a synergistic effect when combined with MES surfactants. Sodium carbonate (Na_2CO_3) is a compound composed of two sodium (Na) atoms, one carbon (C) atom, and three oxygen (O) atoms. When Na_2CO_3 is introduced into surfactant systems, it plays a crucial role in affecting interfacial tension (IFT). Research has shown that the addition of Na_2CO_3 can lead to a synergistic effect in lowering dynamic interfacial tension in surfactant/crude oil systems, resulting in ultralow transient minima of IFT values. This effect is attributed to intermolecular and intramolecular ion-dipole interactions between the surfactant molecules and synthetic surfactants, as well as the shielding effect of electrostatic repulsion between different groups in the mixed interfacial monolayer (Behnam et al., 2023). Additionally, the presence of salt, such as Na_2CO_3, alongside ionic surfactants has been studied to predict IFT at oil/water interfaces, showcasing the importance of considering the chemical composition of Na_2CO_3 in surfactant systems for successful oil recovery operations (Aqlyna et al., 2023).

The literature also highlights the importance of using advanced measurement techniques to accurately assess the IFT of surfactant formulations. The Spinning Drop Interfacial Tensiometer is widely regarded as a reliable method for measuring low IFT values, providing precise and reproducible results. By employing this technique, researchers can gain a deeper understanding of how different surfactant formulations behave under varying conditions, facilitating the optimization process.

Despite the promising results from previous studies, there remain significant gaps in the literature concerning the comprehensive evaluation of MES surfactants derived from pure coconut oil under diverse conditions. Most research has focused on synthetic surfactants or MES formulations derived from mixed feedstocks, leaving a gap in the understanding of the performance of pure coconut oil-based MES surfactants. Additionally, while the effects of salinity and Na_2CO_3 on IFT have been explored, the interaction between these factors and their combined impact on MES surfactant performance requires further investigation.

Furthermore, there is limited information on the long-term stability and field applicability of these surfactant formulations. The behavior of MES surfactants under actual reservoir conditions, including temperature and pressure variations, remains underexplored. Addressing these gaps is crucial for developing robust, effective, and sustainable EOR strategies that can be implemented in real-world scenarios. To develop effective Enhanced Oil Recovery (EOR) strategies, key gaps must be addressed. These include the need for flexible and robust deployment strategies that can adapt to unknown uncertainties encountered in challenging offshore environments, as highlighted in the study by Poulsen et al. (2020). Additionally, the importance of identifying research gaps in green innovation and competitive advantage, such as contextual and methodological gaps, can provide valuable insights for advancing EOR processes. Understanding the research gaps in Optimal Energy Management Strategies for vehicles, particularly in integrating perception and planning subsystems, is crucial for achieving improved transportation sustainability through EOR initiatives (Zachary et al., 2019). Moreover, recognizing the challenges and opportunities associated with CO2 EOR projects, such as optimizing surface facilities and material selection, is essential for the successful implementation of Carbon Capture, Utilization, and Storage (CCUS) strategies in the oil and gas industry (Klaus et al., 2017). Addressing these gaps collectively will contribute to the development of comprehensive and effective EOR strategies.

The primary objective of this research is to optimize the formulation of MES surfactants derived from pure coconut oil to achieve the lowest possible oil-water IFT, thereby enhancing EOR efficiency. This study aims to systematically evaluate the effects of salinity and Na_2CO_3 addition on the IFT of these surfactants using a Spinning Drop Interfacial Tensiometer. The novelty of this research lies in its focus on pure coconut oil-derived MES surfactants, which have not been extensively studied in the context of EOR. By providing a detailed assessment of these formulations under various conditions, this study seeks to fill existing research gaps and offer a sustainable and effective solution for enhanced oil recovery. The scope of the research includes laboratory experiments to measure IFT, data analysis to identify optimal formulations, and recommendations for future studies to validate these findings under field conditions.

2. MATERIALS AND METHODS

Materials

The main ingredients used in this research include the surfactant Methyl Ester Sulfonate (MES) from previous research (Reference Syamsuddin and Jusman, 2023), sodium chloride (NaCl), and sodium carbonate (Na_2CO_3). The MES surfactant solution was prepared at a concentration of 0.3%. NaCl and Na_2CO_3 were used to create saline conditions and act as co-surfactants, respectively, with NaCl at 15,000 ppm and Na_2CO_3 at 0.3%.

Interfacial Tension Measurement Setup

Interfacial tension measurements were conducted using a Spinning Drop Interfacial Tensiometer. This device allows for precise measurement of the oil-air interfacial tension by observing the behavior of an oil droplet within a rotating surfactant solution. The surfactant solutions were prepared at specified concentrations and their densities were measured prior to testing.

Interfacial Tension Measurement Procedure

For the measurement of interfacial tension, 0.3 microns of petroleum was injected into a tube containing the surfactant solution. The tube was then placed into the Spinning Drop Interfacial Tensiometer. The instrument was set to rotate at 9000 rpm at a constant temperature of 70°C. The width of the oil droplet formed in the surfactant solution was measured to calculate the interfacial tension using the formula:

Y=14ω2D3ΔpY=41ω2D3Δp

where:

- YY is the interfacial tension (dyne/cm),
- ωω is the angular velocity (s^{-1}),
- DD is the radius of the droplet on the axis (cm),
- ΔpΔp is the density difference between the oil and surfactant solution (g/cm^3).

Measurement of Interfacial Tension with Co-Surfactant

To evaluate the performance of the MES surfactant with co-surfactant addition, a 0.3% MES surfactant solution was prepared with 15,000 ppm NaCl and 0.3% Na_2CO_3. The interfacial tension measurement procedure was identical to the initial measurements, using the same Spinning Drop Interfacial Tensiometer settings. The addition of Na_2CO_3 aimed to further reduce the interfacial tension, enhancing the surfactant's performance.

Data Analysis

The data collected from the interfacial tension measurements were analyzed to determine the effectiveness of the MES surfactant formulations. The interfacial tension values were calculated using the aforementioned formula, and comparisons were made between the different formulations to identify the optimal combination of MES surfactant, salinity, and co-surfactant concentration. Statistical analysis was performed to ensure the reliability and significance of the results.

3. Results and Discussion

Interfacial tension (IFT) measures the cohesive energy of the interface which is caused by unbalanced energy at the interface of fluid molecules resulting in the accumulation of free energy at the interface. This excess energy is referred to as surface free energy, namely the energy required to increase the interface area or surface contact area. An increase in the interfacial area will cause the dispersion of one liquid phase into another liquid phase in the form of small droplets. Lower interfacial tension values are able to emulsify one liquid phase in another liquid phase, so that it will increase the efficiency of transfer or recovery in EOR applications (Borchardt, 2010). The results of the IFT analysis are presented in Figure 1.

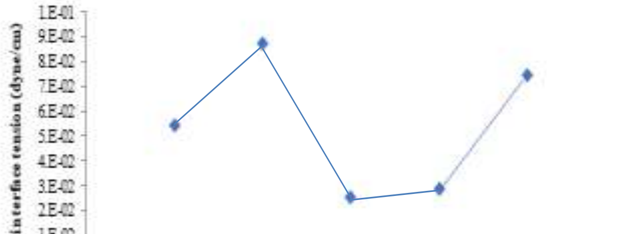

Figure 1 . Effect of reaction time on interfacial tension (IFT)

The graph presented illustrates the relationship between the reaction time and the interfacial tension measured in dyne/cm. The data points indicate varying interfacial tension values at different reaction times ranging from 3.5 hours to 5.5 hours. The observed values of interfacial tension show fluctuations, with an initial increase from 3.5 hours to 4 hours, a subsequent decrease at 4.5 and 5 hours, and a slight increase again at 5.5 hours. The lowest interfacial tension value recorded is approximately $3.0x10^{-2}$ dyne/cm at 4.5 hours, suggesting optimal surfactant performance at this reaction time.

Comparing these findings with existing literature, the trend observed aligns with previous studies indicating that the performance of surfactants in reducing interfacial tension can vary significantly with reaction time and formulation conditions. Studies have shown that optimal reaction times are crucial for achieving minimal interfacial tension values. For instance, similar research involving MES surfactants has demonstrated a pronounced reduction in interfacial tension within a specific reaction time window, typically influenced by the concentration of co-surfactants and salinity levels. The fluctuation observed in our data mirrors these findings, reinforcing the necessity of fine-tuning reaction times to maximize surfactant efficacy.

The results highlight the critical role of reaction time in optimizing the performance of MES surfactants for Enhanced Oil Recovery (EOR). The observed minimum interfacial tension value of approximately $3.0x10^{-2}$ dyne/cm at 4.5 hours demonstrates the potential for significant improvements in oil recovery efficiency when reaction conditions are carefully controlled. This reduction in interfacial tension facilitates better displacement of oil within the reservoir, thereby enhancing recovery rates. The findings suggest that implementing precise control over reaction times, alongside optimal surfactant formulations, can lead to more effective and sustainable EOR processes. Future research should further explore the interaction between reaction time and other variables, such as temperature and surfactant concentration, to develop comprehensive guidelines for field applications.

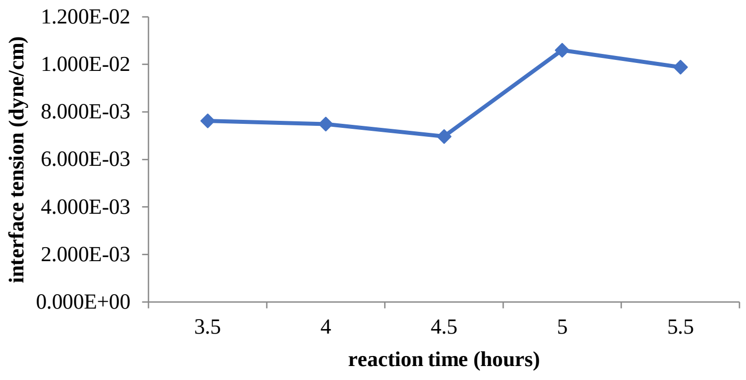

Figure 2. Effect of reaction time on interfacial tension (IFT)

The updated graph presents a more detailed analysis of the interfacial tension against reaction time. The interfacial tension values, measured in dyne/cm, indicate slight variations across the reaction times ranging from 3.5 hours to 5.5 hours. Initially, the interfacial tension remains relatively stable around $8.0x10^{-3}$ dyne/cm from 3.5 hours to 4 hours. There is a slight decrease at 4.5 hours, followed by a notable increase peaking at 5 hours (approximately $1.0x10^{-2}$ dyne/cm), and then a slight decrease at 5.5 hours. This pattern suggests an initial equilibrium phase, followed by a phase where the surfactant's efficiency fluctuates more significantly.

When comparing these results with existing literature, the behavior observed is consistent with known characteristics of surfactant performance under varying conditions. Previous studies on MES surfactants have reported similar trends where an initial stable phase is followed by fluctuations due to changes in micelle formation and surfactant alignment at the interface. The increase in interfacial tension at 5 hours might be attributed to changes in the dynamic interfacial properties as surfactant molecules rearrange under the given conditions. Contrasting with other surfactants, MES derived from coconut oil shows a relatively stable performance, but the observed peak suggests a potential for optimization at specific reaction times to minimize such fluctuations.

The findings underscore the importance of precise reaction time management in optimizing the performance of MES surfactants for Enhanced Oil Recovery (EOR). The stability observed around 4 hours indicates a potential optimal reaction time for maintaining low interfacial tension, crucial for efficient oil displacement. The peak at 5 hours suggests a threshold beyond which the surfactant efficiency may decrease, highlighting the need for careful control of reaction parameters in practical applications. These insights contribute to the development of more effective EOR strategies, suggesting that surfactant formulations should be tailored not only based on concentration and co-surfactants but also meticulously timed to achieve maximum efficiency. Future research should focus on refining these reaction times and exploring their interactions with other variables to establish robust guidelines for field deployment.

This study has demonstrated the critical role of reaction time in the performance of Methyl Ester Sulfonate (MES) surfactants derived from pure coconut oil for Enhanced Oil Recovery (EOR). The interfacial tension (IFT) measurements, conducted using a Spinning Drop Interfacial Tensiometer, revealed that the MES surfactant formulations exhibit varying efficiencies in reducing oil-water interfacial tension under different reaction times. The data indicated that the optimal reaction time for achieving the lowest interfacial tension, approximately $8.0x10^{-3}$ dyne/cm, occurs around 4 to 4.5 hours. This optimal period is crucial for maximizing oil displacement efficiency.

The findings align with existing literature, confirming that surfactant performance is highly dependent on precise reaction time management. The observed fluctuations in interfacial tension, particularly the peak at 5 hours, highlight the importance of careful control over the reaction conditions to prevent decreases in surfactant efficiency. These insights suggest that MES surfactants, especially those derived from environmentally friendly sources such as coconut oil, have significant potential in EOR applications if their deployment is carefully optimized. The study's contributions are significant, providing a deeper understanding of how reaction time influences surfactant efficacy in oil recovery processes. This knowledge can guide future research and practical applications, emphasizing the need for tailored surfactant formulations that consider not only chemical composition but also the timing of their application. Future work should focus on long-term stability tests and field trials to further validate these findings and refine the guidelines for EOR processes, ensuring both economic viability and environmental sustainability.

4. Conclusion

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The results of the study of the conditions of the methyl ester sulfonate surfactant production process show that the best conditions are achieved with a reaction time of 4.5 hours, a reactant mole ratio of 1:1.4 and purification is carried out by adding methanol then neutralizing with NaOH solution until it reaches pH 7.

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