

Wettability alteration and surfactant adsorption study of methyl ester sulphonate/nano-silica nanofluid on sandstone reservoir rock

Stanley Sim Sze Lim^a, Henry Elochukwu^a, Jobrun Nandong^a, Mohamed Ali Hamid^b, Ziad Bennour^a

^aChemical and Energy Department, Faculty of Engineering and Science, Curtin University Malaysia, Malaysia.

^bSchool of Engineering and Physical Sciences, Heriot Watt University, Malaysia.

E-mail: stanley.ssl@postgrad.curtin.edu.my

Abstract

This research project set out to investigate low salinity water/Methyl Ester Sulphonate (MES) surfactant/nano-silica synergy to enhance oil recovery from sandstone reservoir. A Series of experimental works, including contact angle measurements (Sessile drop technique) and UV-vis spectrophotometer tests, were conducted to ascertain the effect of the synergy solution on wettability alteration and surfactant adsorption reduction. Results showed that MES surfactant at 750 ppm and 1000 ppm reversed oil-wet sandstone to a water-wet state. Further reduction was observed at low salinity (250 ppm CaCl₂) under high pH conditions. The lowest contact angle measured was 18 degrees with the synergy solution of 750 ppm MES and 250 ppm CaCl₂ at high pH conditions. The maximum adsorption capacity was used as criteria to measure surfactant adsorption loss reduction. It was observed that surfactant adsorption capacity reduced from 4.66 mg/g to 0.85 mg/g when 25 ppm nano-silica was added at 70°C temperature. This shows that the synergy was able to restore wettability to preferable water-wet conditions to support oil recovery and reduce the excessive loss of surfactant to the sandstone reservoir rock. Water-wet wettability condition and surfactant adsorption reduction are beneficial to the c-EOR project in terms of efficient cost savings on the quantity of surfactant usage for the project. At the same time, overall additional oil recovery is greatly improved.

1. Introduction

The rapid growth in industries worldwide has raised the energy demand. Therefore, the oil and gas industry are actively seeking optimum ways to enhance oil recovery from reservoirs since there is still a substantial amount of oil remaining in the reservoirs after the primary and secondary oil recovery stages. The chemical enhanced oil recovery (c-EOR) method is one of the common tertiary EOR methods, such as the injection or flooding with polymer, surfactant, or alkali into the reservoir to recover additional oil from the reservoir. However, the conventional single injection of chemical material has several limitations [1]. Several experimental works have indicated that the synergy of different chemicals can efficiently and cost-effectively replace the conventional c-EOR method [2][3].

Investigation of low salinity water (LSW) to enhance oil recovery has raised high interest due to the benefits such as being environmentally friendly, simple, low operating and capital

costs [4]. Previous experimental work showed that low salinity water reduced contact angle from 95.2° to 43.12° on the oil-wet sandstone rock surface. The LSW could relatively shift the oil-wet rock surface toward a water-wet state compared to high salinity water [5]. Thus, the potential of LSW contributing to additional oil recovery by wettability alteration to a desirable water-wet state of the reservoir rock is notable [6][7]. Several driving mechanisms promote the wettability alteration toward the water-wet state, such as multi-ion exchange (MIE), electric double layer expansion (EDLE) and pH effect [8] [9].

MIE has included hydrogen bonding, water bridging, cation bridging, anion exchange, cation exchange, ligand exchange and protonation [10]. Generally, the negatively charged rock surface will attract the positively charged organic compounds through direct bonding. On the other hand, negatively charged organic compounds will be attracted by the positively charged clay surface and form organometallic complexes [11]. The substitution of organometallic complexes and organic polar materials with the Sodium (Na^+) and Hydrogen (H^+) ions promotes the detachment of divalent ions together with organic materials. Hence, the oil molecules could be removed from the rock surfaces. Releasing a large amount of OH^- via proton exchange leads to higher pH values. Thus, a higher repulsive force is generated, positively impacting the wettability alteration. Ligand bonding refers to the attraction between carboxylate groups and divalent cations [12]. The bridging is formed when the functional groups are attracted to the charged rock surface. However, the cation bridging is a weak adsorption mechanism that allows the detachment of oil molecules easily. EDLE occurs at the interface between oil, and clay surface, stimulating the detachment of oil molecules from the clay surface and shifting the oil-wet rock surface toward the water-wet state [13]. A stronger water-wet state could be achieved in conjunction with the pH effect. This is because the pH effect could further increase the repulsive force, promoting the detachment of oil molecules.

The function of the surfactant is to reduce the interfacial tension (IFT) between oil and brine and support wettability alteration. Anionic surfactant has been found to be suitable for oil recovery from sandstone reservoirs. However, the oil recovery is marred by excessive surfactant loss [14]. Several factors must be considered during surfactant injection, such as the concentration of surfactant, types of reservoirs, and types of surfactants [15]. [16] highlighted that the synergy of anionic surfactant in alkaline condition could mitigate the excessive surfactant loss onto the sandstone rock surface. Implementing surfactant flooding with optimum concentration is crucial to prevent the concentration above the critical micelles concentration (CMC). The surfactant will not contribute further when the surfactant concentration is above the CMC point. A recent study mentioned that the presence of sulfonate in the surfactant could support surfactant loss reduction below the CMC point [17]. The experimental work from [18] revealed that polyacrylate could play the role of a sacrificial agent to reduce the excessive anionic surfactant adsorbed onto the sandstone rock surface. Therefore, it is feasible to reduce the excessive surfactant losses onto rock surfaces in several ways.

Nanoparticles can be produced easily due to technological advancement [19]. The ultra-small size of nanoparticles with a high surface area to volume ratio could exhibit distinctive physical and chemical properties. The smaller nanoparticles size (usually < 50 nm) allow them

to flow through tiny pores and mobilize trapped residual oil [20]. Nanoparticles could form a wedge film at the crude oil-brine-rock interface, which creates a higher disjoining pressure to remove oil from the rock surface [21]. The capability of nanofluid to achieve wettability alteration on oil-wet rock surfaces has been studied extensively and recent studies indicated that nanofluid could enhance the oil recovery from sandstone reservoirs [22] [23]. Experimental work from [24] demonstrated that the dispersion of nano-silica in the salinity water could shift the oil-wet sandstone rock surface toward a water-wet state where the contact angle changed from 120 to 60 degrees. The study from [25] indicated that the nano-silica fluid could increase the ultimate oil recovery from the sandstone rock by up to 13%. Dispersion of nanoparticles in the chemical fluid such as surfactant or alkaline could lead to better performance, enhancing the oil recovery and mitigating the excessive surfactant loss issue [26]. A previous study mentioned that the combination of sodium dodecylbenzene sulfonate (SDBS) with low salinity water and Zirconia nanoparticles could reduce the contact angle significantly and shift from an oil-wet state toward a desirable water-wet state [27]. [28] revealed that combining nanoparticles with surfactant could lead to a larger contact angle reduction on the oil-wet sandstone rock surface compared to surfactant alone. Thus, it is feasible to implement the combinations of chemical materials for the c-EOR technique to enhance the additional oil recovery further.

The findings indicated that low salinity water, surfactant, nanoparticles, and combination of chemicals have the potential to achieve wettability alteration. Thus, the present study utilized the synergy of methyl ester sulphonate (MES) surfactant, divalent salt for low salinity and nano-silica formulated in an alkaline medium. Meanwhile, the low salinity salt serves to alter wettability to a water-wet state. The MES surfactant supports wettability changes and IFT reduction, while alkaline and nanoparticles aid surfactant loss reduction.

2. Experiment and Methodology

2.1 Materials

Sodium Chloride (NaCl, $\geq 99\%$ mass fraction) (Merck), Calcium Chloride (CaCl₂, $\geq 98\%$ mass fraction) (Merck), Magnesium Chloride (MgCl₂, $\geq 98\%$ mass fraction), Methyl Ester Sulphonate (MES) anionic surfactant $\geq 99\%$ mass fraction (Chemithon), Sodium Hydroxide (NaOH, $\geq 98\%$ mass fraction) (Merck), Nano-Silica (SiO₂ $\geq 99\%$ mass fraction) (US Research Nanomaterials), Tapis light crude oil (API gravity of 42.7°) (Petronas Carigali Sdn Bhd), Grey Berea core samples (Kocurek Industries). Grey Berea sandstone is predominantly quartz mineral with less than 10% clay content. The details of Tapis light crude oil from the Malaysia oilfield are listed in Table 1 below.

Table 1: Tapis Crude Oil Details

Crude Oil Types	API Gravity (degree API)	Specific Gravity	Pour Point, °F
Tapis Crude Oil	42.7	0.812	60.8

Table 2 has summarized the properties of the Grey Berea core samples.

Table 2: Grey Berea properties

Types of Sandstone	Grey Berea
Quartz	91%
Kaolinite	8%
Montmorillonite	1%
Smectite	-
Porosity	19% to 21%
Permeability	60mD to 100mD
Grain Size	250 μ m to 500 μ m

2.2. Method

2.2.1. Preparation of solutions

Formation water was prepared with 19000 ppm of NaCl solution. Different concentrations of MES surfactant were prepared, ranging from 100 ppm to 5000 ppm. 250 ppm CaCl₂ was prepared as the divalent low salinity water. Sodium hydroxide was used to adjust the pH of all solutions and maintained at 9.5 pH value. 25ppm of nano-silica was added into the solution, then sonicated for 15 minutes to ensure colloidal stability. Afterwards, Zeta Sizer was used to analyze the stability of the nanofluid. The conductivity method was employed to determine the critical micelle concentration of the MES surfactant. Table 3 shows all the synthesized solutions which will be applied in the present study.

Table 3: Synthesized solutions applied in the present study

Synthesized solutions applied in the present study
100/250/500/750/1000/1250/1500/1750/2000/3000/4000/5000 ppm MES
750/1000 ppm MES + Alkaline
750/1000 ppm MES + Alkaline + 250ppm CaCl ₂
250/500/750/1000/1250 ppm MES + Alkaline + 25ppm nano-silica
250/500/750/1000/1250 ppm MES + Alkaline + 250ppm CaCl ₂ + 25ppm nano-silica
250/500/750/1000/1250 ppm MES + Alkaline + 250ppm MgCl ₂ + 25ppm nano-silica

2.3. Wettability Study Procedure

Contact angle measurement was employed to study the wettability alteration. The sandstone rock samples were cut into a smaller size of about 0.5 cm thickness and then immersed in the formation water for two days. The immersion process was conducted at 70°C to simulate the Tapis oil reservoir temperature condition. After saturation in formation water, sliced samples were then transferred into the Tapis crude oil for three days to ensure samples were in the oil-wet state. Drop shape analyzer DSA 100B (KRÜSS) was used to measure the contact angle between the rock surface and the synthesized solution. The contact angle

measurement was conducted with various synthesized solutions and repeated at least three times to confirm the consistency and accuracy of the results.

2.4. Adsorption Study methodology

The adsorption study aims to investigate the adsorption behavior of MES anionic surfactant onto the sand surface and the potential of nanoparticles to reduce excessive surfactant loss. MES surfactant concentrations applied in this study phase ranged between 250 ppm to 1500 ppm. Firstly, the rock samples were crushed and sieved to obtain fines rock samples with the size (125 μm). The fines rock samples were cleaned with deionized water to remove the impurities and then dried overnight. Afterwards, 2g of the fines rock samples were mixed with 50 ml of the selected synthesized solution in the conical flask. The adsorbent and adsorbate were then placed in the shaking incubator at 150 rpm for 24 hours. The shaking process was applied under two conditions: ambient temperature 25°C and 70°C. After the mixture achieved equilibrium, the supernatant was centrifuged for 30 minutes at 4000 rpm. Lastly, the supernatant solution was collected for test using the UV-Vis Spectrophotometer to measure the absorbance value.

Results and Discussion

2.1. CMC and nanofluid characterization

Critical Micelle Concentration (CMC) of MES surfactant alone and the synergized nanofluid were measured at the MES surfactant concentrations of 1000ppm and 750ppm, respectively. The zeta potential of synergized nanofluids were measured between the range of -35 mV to -60 mV, indicating colloidal stability. The negatively charged nano-silica extended its repulsive force while dispersed in the fluid resulting in a larger resultant net negative charge of the overall nanofluid synergy [29]. Meanwhile, the stable nanofluid allows the nanoparticles to maximize the performance of wettability alteration and excessive surfactant reduction on the sandstone rock surface. Nanofluid particles distribution are in the range of 300-400 d.nm with the polydispersity index (PDI) less than 0.25, which indicates that the nanofluid size distribution is monodispersed and has no agglomeration. Meanwhile, the typical pore throat size of sandstone rocks is greater than 2000nm, and carbonate rocks usually range from 3000nm to 7000nm [30].

2.2. Effect of concentration of MES surfactant on wettability

The contact angle measured between the formation water and the rock surfaces is 91.7°. Figure 1 indicates that the concentration of MES surfactant within 100ppm to 5000ppm positively impacted the wettability alteration. The lowest contact angle was obtained at 1000ppm of MES surfactant, where 73.1% of contact angle reduction was achieved in comparison to the formation water contact angle. The contact angle increased gradually beyond 1000ppm of MES surfactant. This is because the concentration above 1000ppm has reached the CMC point. Electrostatic interaction between the hydrophilic head group of the anionic

surfactant and the charged rock surface allows the adsorption to occur successively with the increase of concentration. Thus, a film is formed at the solid-liquid interface. Meanwhile, the oil-wet rock surface will be shifted toward the water-wet state due to the interaction between adsorbed oil molecules on the rock surface and the hydrophobic part of the surfactant. Nevertheless, the formation and aggregation of micelles occurred when the surfactant concentration was beyond the CMC point. The increase in surfactant concentration will only contribute to the formation of micelles, restricting the release of surfactant molecules to the liquid-rock interface.

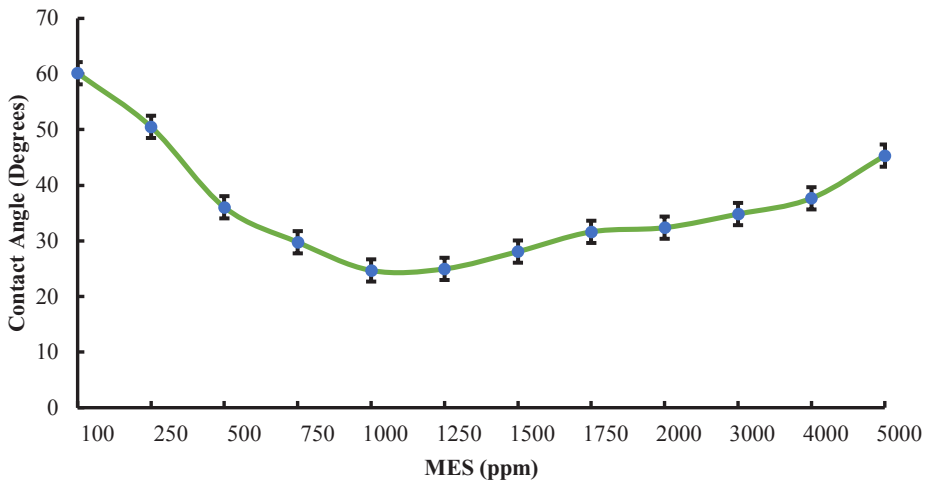


Figure 1: Effect of concentration of MES surfactant on wettability alteration

2.3. Effect of synergized nanofluid on wettability

The results in Figure 2 indicate that all the synthesized solutions with the presence of nano-silica could achieve favorable wettability alteration. The driving mechanism behind the wettability alteration could be due to the more significant disjoining pressure. The nano-silica formed a wedge film at the interface between the oil molecule and the rock surface, creating more considerable disjoining pressure and detaching the oil molecule from the rock surface. The advancement of the size of nano-silica allowed it to penetrate the tiny pores and mobilize the residual oil from the pores. Besides, the smaller size of nanoparticles possesses a larger surfaces area, which creates larger repulsive forces [31]. Meanwhile, the detachment of oil molecules from the rock surface could be more easily.

The 25ppm of nano-silica combined with selected synthesized solutions, which are (MES/alkaline condition), (MES/alkaline condition/250 ppm of CaCl_2) and (MES/alkaline condition/250 ppm of MgCl_2). The concentrations of MES were narrowed down to the ranges between 250 ppm and 1250 ppm. This is because the concentrations of MES surfactant within these ranges performed better on wettability alteration. The lowest contact angle measured at different conditions with the presence of nano-silica was listed in Table 4. The synthesized

solution of (25 ppm nano-silica + 750 ppm MES surfactant + alkaline condition + CaCl₂) showed the best results among all conditions with the presence of NPs where 77.4% of contact angle reduction was achieved in comparison to formation water.

Figure 2 also revealed that the synergy of nanoparticles with optimum low salinity water (divalent cations) under alkaline conditions could relatively reduce the contact angle. This could be attributed to the mechanisms such as the multi-ion exchange (MIE), electric double-layer expansion, and pH effects. The presence of divalent cations, including Mg²⁺ ions and Ca²⁺ ions will induce the formation of cation bridging, where the divalent cations will connect the oil molecules with the negatively charged rock surface [32]. However, the cation bridging has a weak connection, and thus, the monovalent ions in the fluid would replace the divalent cations on the rock surface. As a result, the divalent cations will be released together with the oil molecules from the rock surface and shift the wettability towards a desirable water-wet state is achieved. The alkaline condition could turn the rock surface to be more negatively charged [33]. Low salinity water injection would destabilize the equilibrium of the brine/oil/rock system, incurring the substitution between H⁺ ions, Ca²⁺ ions, OH⁻ ions and Na⁺ ions. The substitution is to re-establish the equilibrium of the brine/oil/rock system. Meanwhile, the pH value will increase due to a large number of OH⁻ released and resulting in higher repulsive force. The larger repulsive force promotes the detachment of the oil molecule and leads to favorable wettability alteration. Therefore, the synthesized solution with the presence of low salinity water further improved the performance of wettability alteration on the sandstone rock surface.

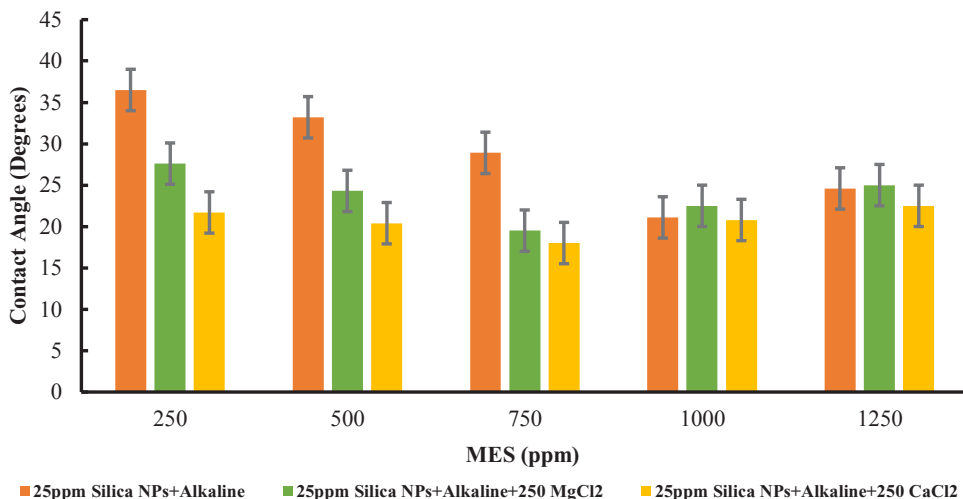


Figure 2: Effect of nano-silica on wettability alteration

Table 4: Lowest contact angle measurement with the presence of nano-silica

Nanofluid	Contact Angle (°)
250 ppm MES + Alkaline + 250ppm CaCl ₂ +25ppm nano-silica	21.7
500 ppm MES + Alkaline + 250ppm CaCl ₂ +25ppm nano-silica	20.4

750 ppm MES + Alkaline + 250ppm CaCl ₂ +25ppm nano-silica	18.0
1000 ppm MES + Alkaline + 250ppm CaCl ₂ +25ppm nano-silica	20.8
1250 ppm MES + Alkaline + 250ppm CaCl ₂ +25ppm nano-silica	22.5

2.4. Synergistic nanofluid adsorption study

Figure 3 shows the adsorption capacity of prepared solutions and nanofluids. The nanofluid containing 750ppm MES, 250ppm CaCl₂, and 25ppm nano-silica in an alkaline medium showed the lowest adsorption capacity. This shows that the presence of nano-silica, which acts as a sacrificial agent, reduces the excess surfactant adsorption from 6.11 mg/g to 4.97 mg/g. Nano-silica plays the role of a sacrificial agent so that a competitive condition to adsorb onto the rock surface is created between the anionic surfactant and the nano-silica. Nano-silica is promptly attached to the sandstone rock surface because it has a lower negative charge. This situation makes more surfactant available to interact with crude oil, thereby reducing IFT and supporting wettability alteration. Higher MES concentration had higher adsorption capacity despite reduction due to nano-silica. This is uneconomical as a substantial amount of surfactant adsorbs onto the rock.

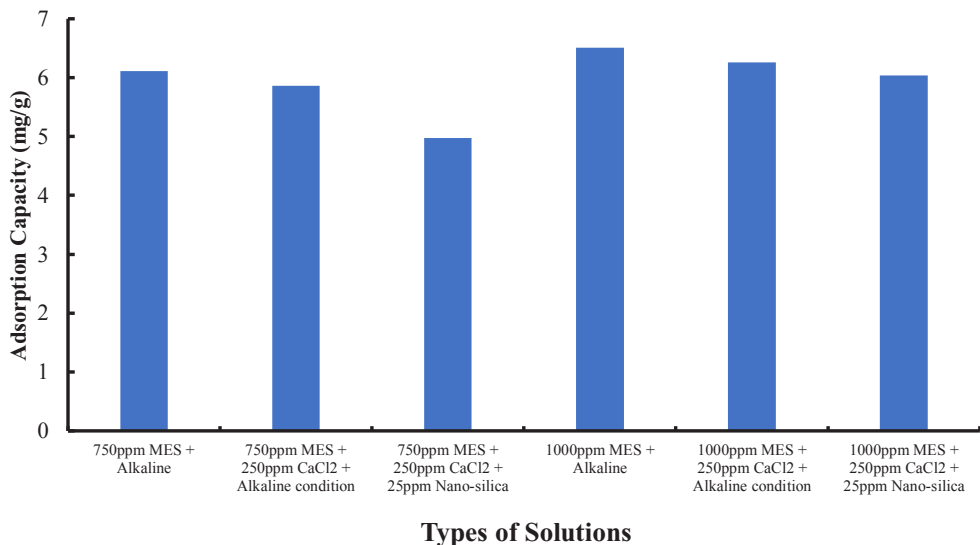


Figure 3: Adsorption capacity at ambient temperature

The adsorption behavior of the MES surfactant is further analyzed through the Langmuir and Freundlich isotherm models, where the results of R² values are tabulated in Table 5. The overall results depicted that the R² values obtained from the Langmuir isotherm were higher than the Freundlich isotherm. Therefore, the Langmuir isotherm model is a more accurate fit for the analysis and validation of MES surfactant adsorption behavior on the rock surface. The higher R² values obtained from Langmuir isotherm indicate the higher potential for monolayer adsorption to occur. In comparison, the R² values obtained from Freundlich isotherm are lower, indicating that the tendency for the formation of multilayer adsorption is lower. Nevertheless, some cases might have multilayer adsorption due to the relatively high R² values obtained from the Freundlich isotherm. The synthesized solution of 750ppm/1000ppm

of MES surfactant with 250ppm of CaCl₂ under alkaline conditions showed relatively high R² values, whether in Langmuir or Freundlich isotherm models. Thus, the multilayer adsorption behavior could occur instead of monolayer adsorption. Meanwhile, the synergized solution of 750ppm MES + 250ppm CaCl₂ + Alkaline condition + 25ppm Nano-silica obtained a high R² value in Langmuir isotherm and a low R² value in Freundlich isotherm, demonstrating the occurrence of single-layer adsorption behavior.

Table 5: Adsorption capacity at ambient temperature

Synthesized solution	Adsorption Capacity (mg/g)	Langmuir Model R ²	Freundlich Model R ²
750ppm MES + Alkaline	6.11	0.9237	0.7344
750ppm MES + 250ppm CaCl ₂ + Alkaline condition	5.86	0.9628	0.9338
750ppm MES + 250ppm CaCl ₂ + Alkaline condition + 25ppm Nano-silica	4.97	0.9753	0.6245
1000ppm MES + Alkaline	6.51	0.9237	0.7344
1000ppm MES + 250ppm CaCl ₂ + Alkaline condition	6.26	0.9628	0.9338
1000ppm MES + 250ppm CaCl ₂ + Alkaline condition + 25ppm Nano-silica	5.90	0.9753	0.6245

Figure 4 presents the adsorption capacity results for Grey Berea at 70°C temperature conditions. Compared to the ambient temperature of 25°C, the adsorption capacity reduction under higher temperature conditions demonstrated a lower adsorption reduction. In the case of (750ppm of MES surfactant + alkaline condition), the adsorption capacity obtained from ambient and 70°C temperature conditions are correspondingly 5.86mg/g and 2.58mg/g. Meanwhile, increasing the temperature from ambient to 70°C temperature significantly reduces the adsorption capacity of the synergized solution (750ppm MES + 250ppm CaCl₂ + Alkaline condition + 25ppm Nano-silica), where it reduces from 4.66 to 0.85mg/g as shown in Figure 4 below. This further shows that nano-silica and higher temperatures reduced surfactant adsorption on the rock surface. The adsorption capacity reduction occurred at a higher temperature which is attributed to the exothermic process and reduction of viscosity [34]. Therefore, the synergized nanofluid is feasible and suitable for the c-EOR process as the reservoir temperatures are typically at high-temperature conditions. The present adsorption study proved that the synergy of nanoparticles with surfactant could relatively reduce excessive surfactant loss. Meanwhile, the results indicated that higher temperatures showed a better reduction of excessive surfactant loss.

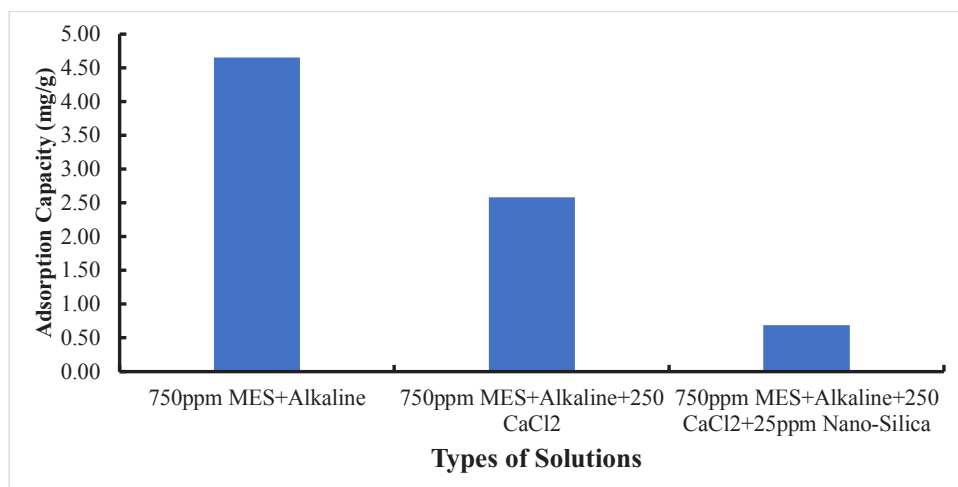


Figure 4: Amount of surfactant adsorbed at reservoir temperature condition (70°C)

3. Conclusion

In this present study, the potential of methyl ester sulphonate/nano-silica nanofluid to achieve wettability alteration toward a strong water-wet state was investigated. The results proved that the combination of 750ppm MES surfactant + alkaline condition + 250ppm CaCl₂ + 25ppm nano-silica led to the best results among different synthesized solutions in this study. The contact angle was reduced from 91.7° to 18°. On the other hand, the adsorption study showed the tendency of nano-silica to reduce the excessive surfactant adsorption on the rock surface. It is notable that 750ppm MES surfactant + alkaline condition + 250ppm CaCl₂ + 25ppm nano-silica had the lowest adsorption capacity at 25°C and 70°C temperature conditions. This study demonstrated the significant potential of nano-silica to achieve favorable wettability alteration and mitigate surfactant adsorption losses. This shows that at reservoir conditions, nanofluid of nano-silica and methyl ester sulphonate under alkaline conditions can be economical as it saves on surfactant usage and support additional oil recovery.

Acknowledgement

This work is supported by the Ministry of Higher Education, Malaysia under the Fundamental Research Grant Scheme: FRGS/1/2020/TK0/CURTIN/03/10.

References

- [1] Gbadamosi, A. O., Junin, R., Manan, M. A., Agi, A., & Yusuff, A. S. (2019). An overview of chemical enhanced oil recovery: recent advances and prospects. *International Nano Letters*, 9(3), 171-202.
- [2] Abdullahi, M., Jufar, S., Kumar, S., Al-shami, T., & Negash, B. (2022). Synergistic effect of Polymer-Augmented low salinity flooding for oil recovery efficiency in Illite-Sand porous media. *Journal of Molecular Liquids*, 358, 119217.
- [3] Wei, J., Chen, Y., Zhou, X., Wang, L., Fu, P., Yakushev, V., Zhou, R. (2022). Experimental studies of surfactant-polymer flooding: An application case investigation. *International Journal of Hydrogen Energy*.

- [4] Kakati, A., Kumar, G., & Sangwai, J. S. (2020). Oil recovery efficiency and mechanism of low salinity-enhanced oil recovery for light crude oil with a low acid number. *ACS omega*, 5(3), 1506-1518.
- [5] Khishvand, M., Kohshour, I. O., Alizadeh, A. H., Piri, M., & Prasad, S. (2019). A multi-scale experimental study of crude oil-brine-rock interactions and wettability alteration during low-salinity waterflooding. *Fuel*, 250, 117-131.
- [6] Farhadi, H., Fatemi, M., & Ayatollahi, S. (2021). Experimental investigation on the dominating fluid-fluid and rock-fluid interactions during low salinity water flooding in water-wet and oil-wet calcites. *Journal of Petroleum Science and Engineering*, 204, 108697.
- [7] Mokhtari, R., Anabaraonye, B. U., Afrough, A., Mohammadkhani, S., & Feilberg, K. L. (2022). Experimental investigation of low salinity water-flooding in tight chalk oil reservoirs. *Journal of Petroleum Science and Engineering*, 208, 109282.
- [8] Lager, A., Webb, K. J., Black, C., Singleton, M., & Sorbie, K. S. (2008). Low salinity oil recovery-an experimental investigation1. *Petrophysics-The SPWLA Journal of Formation Evaluation and Reservoir Description*, 49(01).
- [9] Yue, L., Pu, W., Zhao, S., Zhang, S., Ren, F., & Xu, D. (2020). Insights into mechanism of low salinity water flooding in sandstone reservoir from interfacial features of oil/brine/rock via intermolecular forces. *Journal of Molecular Liquids*, 113435.
- [10] Purswani, P., Tawfik, M. S., & Karpyn, Z. T. (2017). Factors and mechanisms governing wettability alteration by chemically tuned waterflooding: a review. *Energy & Fuels*, 31(8), 7734-7745.
- [11] Bhicajee, P., & Romero-Zerón, L. (2021). Effect of different low salinity flooding schemes and the addition of alkali on the performance of low-salinity waterflooding during the recovery of heavy oil from unconsolidated sandstone. *Fuel*, 289, 119981.
- [12] Katende, A., & Sagala, F. (2019). A critical review of low salinity water flooding: mechanism, laboratory and field application. *Journal of Molecular Liquids*, 278, 627-649.
- [13] Xie, Q., Liu, F., Chen, Y., Yang, H., Saeedi, A., & Hossain, M. M. (2019). Effect of electrical double layer and ion exchange on low salinity EOR in a pH controlled system. *Journal of Petroleum Science and Engineering*, 174, 418-424.
- [14] Saxena, N., Kumar, A., & Mandal, A. (2019). Adsorption analysis of natural anionic surfactant for enhanced oil recovery: The role of mineralogy, salinity, alkalinity and nanoparticles. *Journal of Petroleum Science and Engineering*, 173, 1264-1283.
- [15] Khayati, H., Moslemizadeh, A., Shahbazi, K., Moraveji, M. K., & Riazi, S. H. (2020). An experimental investigation on the use of saponin as a non-ionic surfactant for chemical enhanced oil recovery (EOR) in sandstone and carbonate oil reservoirs: IFT, wettability alteration, and oil recovery. *Chemical Engineering Research and Design*, 160, 417-425.
- [16] Kalam, S., Abu-Khamsin, S. A., Kamal, M. S., & Patil, S. (2021). A review on surfactant retention on rocks: mechanisms, measurements, and influencing factors. *Fuel*, 293, 120459.
- [17] Southwick, J. G., van den Pol, E., van Rijn, C. H., van Batenburg, D. W., Boersma, D., Svec, Y., Raney, K. (2016). Ammonia as alkali for alkaline/surfactant/polymer floods. *SPE Journal*, 21(01), 10-21.
- [18] Liu, Z., Hedayati, P., Ghatkesar, M. K., Sun, W., Onay, H., Groenendijk, D., Sudhölter, E. J. (2021). Reducing anionic surfactant adsorption using polyacrylate as sacrificial agent investigated by QCM-D. *Journal of Colloid and Interface Science*, 585, 1-11.
- [19] Bashir, A., Haddad, A. S., & Rafati, R. (2021). A review of fluid displacement mechanisms in surfactant-based chemical enhanced oil recovery processes: analyses of key influencing factors. *Petroleum Science*.

- [20] Kazemzadeh, Y., Shojaei, S., Riazi, M., & Sharifi, M. (2019). Review on application of nanoparticles for EOR purposes: A critical review of the opportunities and challenges. *Chinese Journal of Chemical Engineering*, *27*(2), 237-246.
- [21] Panchal, H., Patel, H., Patel, J., & Shah, M. (2021). A systematic review on nanotechnology in enhanced oil recovery. *Petroleum Research*.
- [22] Aji, A., Junin, R., Abdullah, M. O., Jaafar, M. Z., Arsad, A., Sulaiman, W. R. W., Gbadamosi, A. (2020). Application of polymeric nanofluid in enhancing oil recovery at reservoir condition. *Journal of Petroleum Science and Engineering*, *194*, 107476.
- [23] Behera, U. S., & Sangwai, J. S. (2022). Silica nanofluid in low salinity seawater containing surfactant and polymer: Oil recovery efficiency, wettability alteration and adsorption studies. *Journal of Petroleum Science and Engineering*, *211*, 110148.
- [24] Rostami, P., Sharifi, M., Aminshahidy, B., & Fahimpour, J. (2019). Enhanced oil recovery using silica nanoparticles in the presence of salts for wettability alteration. *Journal of Dispersion Science and Technology*.
- [25] Youssif, M. I., El-Maghraby, R. M., Saleh, S. M., & Elgibaly, A. (2018). Silica nanofluid flooding for enhanced oil recovery in sandstone rocks. *Egyptian journal of petroleum*, *27*(1), 105-110.
- [26] Rashidi, M., Kalantariasl, A., Saboori, R., Haghani, A., & Keshavarz, A. (2021). Performance of environmental friendly water-based calcium carbonate nanofluid as enhanced recovery agent for sandstone oil reservoirs. *Journal of Petroleum Science and Engineering*, *196*, 107644.
- [27] Jha, N. K., Ali, M., Iglauer, S., Lebedev, M., Roshan, H., Barifcani, A., Sarmadivaleh, M. (2019). Wettability alteration of quartz surface by low-salinity surfactant nanofluids at high-pressure and high-temperature conditions. *Energy & Fuels*, *33*(8), 7062-7068.
- [28] Yekeen, N., Padmanabhan, E., Syed, A. H., Sevo, T., & Kanesen, K. (2020). Synergistic influence of nanoparticles and surfactants on interfacial tension reduction, wettability alteration and stabilization of oil-in-water emulsion. *Journal of Petroleum Science and Engineering*, *186*, 106779.
- [29] Youssif, M. I., El-Maghraby, R. M., Saleh, S. M., & Elgibaly, A. A. (2018). Sol-Gel Tailored Synthesized Nanosilica for Enhanced Oil Recovery in Water-Wet and Oil-Wet Bentheimer Sandstone. *Energy & Fuels*, *32*(12), 12373-12382.
- [30] Sofla, S. J. D., James, L. A., & Zhang, Y. (2018). Insight into the stability of hydrophilic silica nanoparticles in seawater for Enhanced oil recovery implications. *Fuel*, *216*, 559-571.
- [31] Eltoun, H., Yang, Y.-L., & Hou, J.-R. (2021). The effect of nanoparticles on reservoir wettability alteration: a critical review. *Petroleum Science*, *18*(1), 136-153.
- [32] Aminian, A., & ZareNezhad, B. (2019). Wettability alteration in carbonate and sandstone rocks due to low salinity surfactant flooding. *Journal of Molecular Liquids*, *275*, 265-280.
- [33] Rezaei, A., Riazi, M., Escrochi, M., & Elhaei, R. (2020). Integrating surfactant, alkali and nano-fluid flooding for enhanced oil recovery: A mechanistic experimental study of novel chemical combinations. *Journal of Molecular Liquids*, *308*, 113106.
- [34] Saha, R., Uppaluri, R. V., & Tiwari, P. (2017). Effect of mineralogy on the adsorption characteristics of surfactant—Reservoir rock system. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *531*, 121-132.