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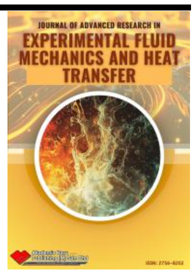

An Experimental Study on the Efficiency of Microbubbles in Enhance Oil Recovery Method (EOR) in Different Types of Oils

Nur Amira Mohd Pouzi[1], Erny Afiza Alias[1,*], Mackeson Pira[1,2], Desigan Mani[1], Syukran Hakim Norazman[3]

[1] Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[2] Centre for Research in Advanced Fluid and Processes, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[3] Faculty of Electric and Electrical Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

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ABSTRACT

Enhanced Oil Recovery (EOR) improves oil extraction beyond what is achieved through primary and secondary recovery methods. EOR techniques, including gas injection, thermal recovery and chemical injection, can recover approximately 45% of the original oil, as some oil remains trapped in the reservoir pores. Recently, a promising EOR technique has emerged that involves the use of microbubbles (MB). These micron-sized bubbles enhance oil displacement efficiency by providing a large surface area, extended residence time and superior mobility within porous media, which can further increase the oil recovery rate. However, the effectiveness of MB-EOR technology is influenced by several factors, including the size of the bubbles and the reservoir conditions, such as the type of oil present. This study investigates the efficiency of MB in EOR using two different oil and water types: light oil (diesel) and heavy oil (engine oil) while for water: seawater and tap water. MB were generated using hydrolysis equipment and their size in seawater was measured with a Digital Holographic System (DHS). Core flooding experiments were conducted to assess their effectiveness in displacing different types of oil. The experimental results indicated that MB effectively displaced both light and heavy oil, although the recovery rates differed significantly. The recovery rate for light oil reached 45.94%, while the recovery rate for heavy oil was much lower at 12.42%. This suggests that MB are more effective at recovering lighter oils, likely due to enhanced fluid mobility and sweep efficiency. In conclusion, MB demonstrates better performance in displacing light oils. This study provides valuable insights into optimizing MB-EOR for various reservoir conditions, paving the way for future advancements in oil recovery technologies.

1. Introduction

The global energy demand has been increasing at an average rate of 1-2% per year, which forces the oil and gas industry to continuously aim to maximize production while minimizing waste from existing reservoirs [1]. Enhanced Oil Recovery (EOR) techniques have been developed to optimize oil

* *Corresponding author.*
E-mail address: erny@umpsa.edu.my (Erny Afiza Alias)

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extraction and improve recovery rates beyond what is achievable with primary and secondary methods. These techniques can allow for additional recovery of 30–60% of the reservoir's oil [2,3]. However, traditional extraction methods are often costly and lack environmental sustainability, in addition to facing various technical limitations that drive research into alternative EOR methods [4].

Recently, MB technology, which involves gas-filled bubbles ranging from nanometres to micrometres in size, has been developed to further enhance the oil recovery rate. MB is characterized by unique properties namely, low rising velocity, high surface area-to-volume ratio and high interior pressure [5-7]. These features can significantly increase EOR rates by reducing interfacial tension, altering wettability and improving sweep efficiency [8]. Additionally, their small size makes them particularly effective at reaching previously inaccessible reservoir space [9]. Research by Telmadarreie *et al.,* [10] has demonstrated that MB improves sweep efficiency in fractured reservoirs, while they also show potential for enhancing heavy oil recovery in heterogeneous reservoirs with low sweep efficiency.

MB-EOR technology has various advantages, including being environmentally friendly and cost-effective. Carbon dioxide-filled MB (CO2-MB) are extensively used because they boost recovery rates while also helping to reduce overall emissions by sequestering some CO2 in the reservoir's pore spaces. It is also considered more sustainable because it decreases chemical and energy uses compared to chemical EOR procedures, where chemical absorption on rock surfaces could cause environmental problems [11]. While there are benefits to MB-EOR, its efficiency is influenced by several factors, namely, the characteristics of the bubbles—such as their size and stability—as well as the properties of the reservoir, which include porosity, permeability, type of surrounding liquid and the type of oil present [12-14].

In a study focused on flotation applications, it was observed that small MB with a size range of 10-50 µm were effective in recovering oil [15]. This indicates that small MB have an advantage in enhancing the efficiency of oil recovery due to their increased surface area. Another study by Natawijaya *et al.,* [16] found that smaller bubbles, ranging from 10 to 50 microns, can penetrate low permeability areas and enhance sweep efficiency, resulting in a 26.38% improvement in oil recovery, while larger bubbles, ranging from 70 to 150 microns, improve gas blocking capability by increasing injection pressure by 27.5%. These findings emphasize the importance of comprehending MB size in EOR in order to maximize oil recovery. The size of created bubbles is known to be affected by a variety of parameters, including the generation process, the surrounding liquid characteristics and the temperature. While numerous studies have investigated bubble size characteristics in various liquids, particularly when comparing tap water and seawater, there is a lack of comprehensive studies that have investigated MB properties in both types of water while also evaluating their efficiency in EOR applications. Addressing this knowledge gap is critical for optimizing the MB application in EOR applications, especially for reservoirs with varied water type characteristics.

Additionally, reservoir conditions such as porosity, permeability, pressure and the types of water and oil also affect the behaviour of MB, playing a critical role in determining the efficiency of MB-EOR. For example, the presence of certain oil types may also impact the stability of the bubble surface, influencing their life span and thus, their performance in recovering the oil [14]. The composition of oil, whether light or heavy and lighter and heavier oils interact differently with MB, influencing attachment, displacement and overall efficiency [17]. In heavy oil reservoirs, the high viscosity and complex flow behaviour can hinder the movement and recovery efficiency of MB; however, they can assist by dissolving in the oil and lowering its viscosity, which improves flow and extraction [10]. Light oil, on the other hand, has lower viscosity and surface tension, impacting MB buoyancy and penetration into reservoirs [18]. While MB solubility in light oil is lower than in heavy oil, it still plays a role in oil displacement efficiency [19]. Understanding the interaction between MB and different types of oil is crucial for assessing its impact on oil recovery efficiency, a topic that has been previously underexplored which hinders the optimization of MB efficiency in EOR.

Furthermore, the type of liquid in the reservoir influences MB-EOR efficiency. Crude oil is often found in underground reservoirs and offshore areas, where the fluids in the surrounding environment vary by region. These differences alter the liquid's qualities such as density, viscosity and pH, which can have a substantial impact on the oil's behaviour and, as a result, its effectiveness in EOR. The size of bubbles created by breaking waves varies greatly between saltwater and tap water, with seawater producing a higher density of larger bubbles, probably due to its chemical composition [20]. In a study investigating the effects of salinity on bubble size and lifespan, it was found that MB with diameters greater than 100 microns have a longer lifespan than smaller bubbles that measure less than 40 microns. Additionally, the lifespan of MB increased with salinity levels up to 35%; however, it begins to decrease when salinity levels rise further, reaching around 45% [21]. Meanwhile, the velocity of rising bubbles decreases with smaller bubbles formed in a higher salt concentration liquid due to reduced surface tension and the suppression of bubble coalescence as reported by Kawahara *et al.,* [22]. Although many studies were conducted to examine the effect of variation in surrounding liquids on the bubble properties, their subsequent efficiency in oil recovery remains underexplored.

Thus, this study attempts to bridge the critical gaps by systematically investigating:

i. MB size characteristics in tap water and seawater.
ii. The efficiency of MB on oil recovery on two different types of oil (light oil and heavy oil) under different types of surrounding liquids (tap water and seawater).

MB was generated via the hydrolysis method as it is non-intrusive and produces bubbles of more uniform size compared to other methods, such as the venturi system, which relies on flow rate and pressure [23]. The bubble size will be measured using a holography system, an effective non-invasive method that preserves bubble integrity during measurement. This approach provides high-resolution 3D imaging, ensuring greater accuracy compared to alternative methods [24]. A core flooding experiment will be conducted to investigate the efficiency of oil recovery for two types of oil—heavy oil and light oil—under both types of surrounding liquids. This study employs engine oil to simulate heavy oil and diesel oil to represent light oil, building on findings from previous research Strelets *et al.,* [25].

This study aims to provide a comprehensive dataset that compares three key variables: MB size, the type of surrounding liquids and the type of oil. This comparison will be conducted under controlled experimental conditions and will offer valuable insights for practical applications in various reservoir scenarios.

2. Methodology

2.1 Properties of Liquids (Seawater and Oils)

The experimental setup includes laboratory tests to examine seawater and oil samples' liquid properties, specifically viscosity, density and pH. The tests are conducted using the HAAKE MARS™ Rheometer to measure viscosity. The density of seawater and tap water are measured with the Stabinger Viscometer SVM™ 3001, while pH levels are determined using the Thermo Scientific™ Eutech™ PC 450 Meter for both light oil (diesel oil) and heavy oil (engine oil), as well as the Seven Compact pH Meter for seawater. Samples are prepared and analysed at a controlled room temperature of 25°C to ensure accurate and reliable results for all three properties. The properties obtained for all samples are presented in Table 1. The results indicate that the viscosity, density and pH of seawater are slightly higher than that of tap water. This finding aligns with previous studies, which attribute the difference to the presence of dissolved salts in seawater, primarily sodium chloride (NaCl). This increased concentration of salt contributes to the slight difference in properties of seawater compared to tap water. As for the oil, heavy oil has significantly higher viscosity, density and pH compared to light oil.

Table 1
Properties of seawater and oils types at 25° temperature

Liquid Properties	Seawater	Tap Water	Heavy Oil	Light Oil
Viscosity (kg/m.s)	0.0009814	0.0009260	0.4638889	0.005297
Density (kg/m^3)	1019.08	998.22	867.90	835.30
pH	6.44	6.38	6.34	5.26

2.2 MB Size Measurement

As illustrated in Figure 1, MB is produced using the O_2 Grow Emitter in a beaker filled with seawater. The O_2 Grow Emitter (Item number 2010) is a generator of micro and nanobubbles that utilizes hydrolysis principles to create bubbles suitable for use in 37.8 litres of liquid. It features a titanium emitter and requires 7 watts of power to operate. The emitter operates for 15 minutes to ensure that the water/seawater becomes fully saturated with MB. After the saturation process, samples were collected using a cuvette cube and were observed using a digital holography system (DHS). The DHS connects to a monitor and collects high-resolution holographic images of the MB. The images were reconstructed and processed using the ImageJ program to estimate the size distribution of MB.

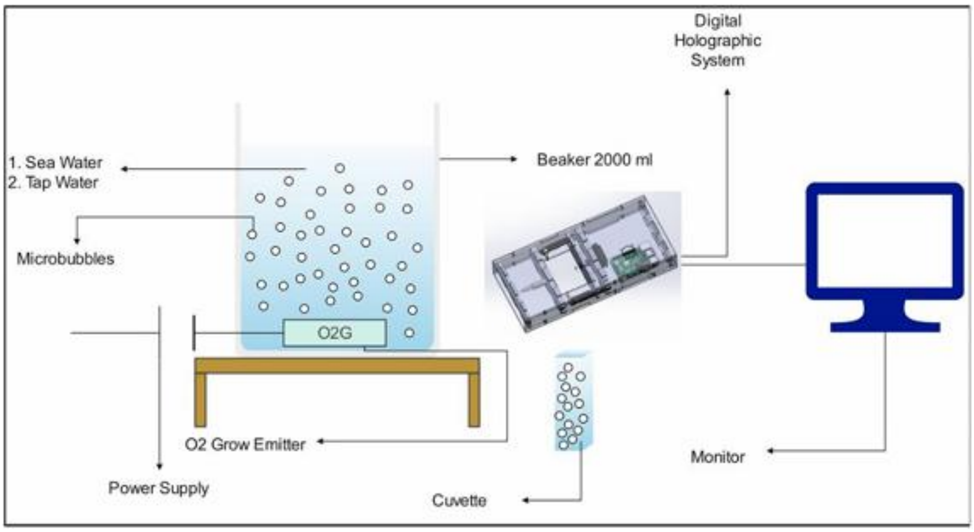

Fig. 1. Schematics experiment setup to measure the MB diameter

Figure 2 shows a raw image obtained from DHS (left) and the reconstructed image from ImageJ (right). Multiple images were captured and reconstructed, resulting in an average bubble size of 122 µm for seawater and 90 µm for tap water. This finding agrees with previous literature, which indicates that a larger range of bubble diameters tends to be produced in seawater compared to tap water due to the chemical composition of seawater. However, this finding contradicts Kawahara's report, which stated that smaller bubbles tend to be generated in fluids with higher salt concentration levels.

It's important to note that the bubble generation method used in this study (electrolysis method) differs from that in Kawahara's research (shear-induced MB generation), which may contribute to the discrepancies in the findings [22].

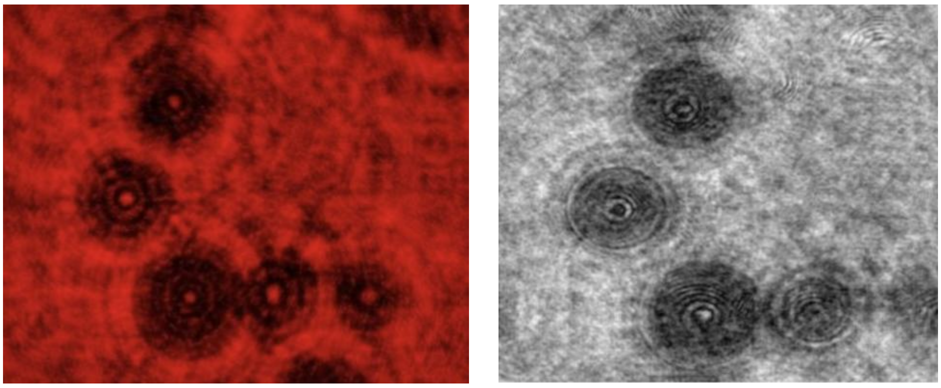

Fig. 2 Obtained images in seawater from the DHS, raw image (left) and reconstructed image (right)

2.3 Core Flooding Experiment

Figure 3 illustrates the schematic of the experimental setup for the core flooding experiment. The setup consists of an acrylic tube with an inner diameter of 7.5 cm and a length of 30 cm, featuring removable lids on both ends. Tubes are connected to the lids, serving as the inlet and outlet for the sand pack. Sandstone is used to simulate reservoir rocks, which will be placed inside the acrylic tube. The experiment begins by measuring the pore volume (PV) of 800 mL of seawater. The acrylic tube cylinder is initially filled with seawater, followed by the gradual addition of an 8 mm sand pack. As the sand pack is added, the displaced seawater volume represents the PV which will be used to determine the total 2.0 PV needed for this experiment. Then, the porosity and permeability of the corepack were calculated using the equations below:

$$Porosity = \frac{Pore\ volume\ (PV)}{Total\ volume} \quad (1)$$

$$Permeability, k = \frac{Q\mu L}{A\Delta P} \quad (2)$$

Where, k is denoted as the permeability or Darcy, Q the flow rate, μ the viscosity, L the length of the corepack, A the cross-sectional area of the sample and ΔP the pressure dropped across the sample. The calculated value for porosity and permeability are 12.1% and $3.41\text{x}10^{-12}$ m^2, respectively.

The oil is injected into the sand pack cylinder at a constant flow rate of 2.97 ml/s, using a peristaltic pump for the oil saturation process. The effluent containing oil and water was measured to calculate the Original Oil in Place (OOIP) and the irremovable water, as shown in the formulas below:

$$Original\ Oil\ In\ Place, OOIP = \frac{Oil\ in - Oil\ out}{Oil\ in} \times 100\% \quad (3)$$

$$Irremovable\ water = \frac{water\ in - water\ out}{water\ in} \times 100\% \quad (4)$$

Water flooding (secondary recovery) involved injecting 2.0 PV of water into the acrylic tube cylinder, measuring the recovered oil and water every 0.5 PV to calculate the recovery rate. This was followed by injecting another 2.0 PV of MB in tap water, with volumes measured again at 0.5 PV intervals to assess recovery. The experiment is then repeated using diesel oil and seawater to investigate the efficiency. After all tests are completed, the data is examined to estimate the oil recovery efficiency under different conditions.

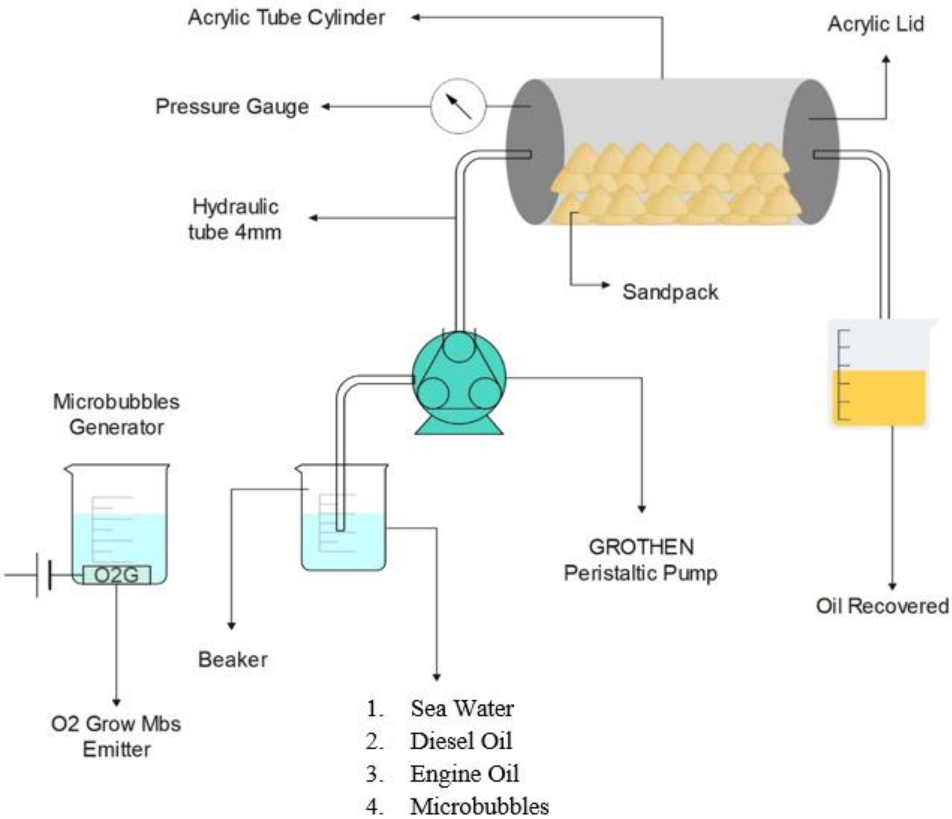

Fig. 3. Schematics experimental setup for core flooding experiment

3. Results

3.1 Comparison of Oil Recovery Efficiency with MB in Different Types of Oil

Figure 4 depicts the oil recovery rate utilizing MB in heavy and light oils with tap water and seawater. Overall, the oil recovery rate for all types of oil increased steadily as PV increased from secondary to tertiary recovery. In secondary recovery, the cumulative oil recovery percentage in tap water for light oil was 30.33%, whereas heavy oil recovered 4.69%. During the tertiary recovery, as MB is injected, an additional 9% of light oil and 4.22% of heavy oil were recovered, resulting in cumulative recoveries of 39.33% for light oil and 8.91% for heavy oil. Meanwhile, as for seawater in the secondary recovery phase, the total percentage of oil recovered from light oil using tap water was 32.5%, whereas heavy oil only reached a recovery rate of 6.97%. During the tertiary recovery phase, with the injection of MB, an additional 13.44% of light oil and 4.22% of heavy oil were recovered. Consequently, the cumulative recovery rates rose to 39.33% for light oil and 5.45% for heavy oil. This result aligns with the previous study that utilized non-chemical carbon dioxide MB in EOR experiments, yielding 68.15% and 46.63% under different permeability and porosity conditions of the sand pack [11]. It's important to highlight that the notable difference in cumulative recovery values could be attributed to the use of carbon dioxide in the generation of MB. Utilizing CO_2 in this process has the potential to enhance the efficiency of MB in EOR as it delays the CO2 breakthrough and significantly increases sweep efficiency [26]. Moreover, the result obtained suggests that recovering light oil is easier than recovering heavy oil, which is most likely due to the differences in physical qualities between the two types of oils. According to Sun *et al.,* [27], heavy oil reservoirs often have inferior recovery rates due to their high viscosity and heterogeneity. Heavy oil's high viscosity impedes flow, resulting in drastically reduced mobility.

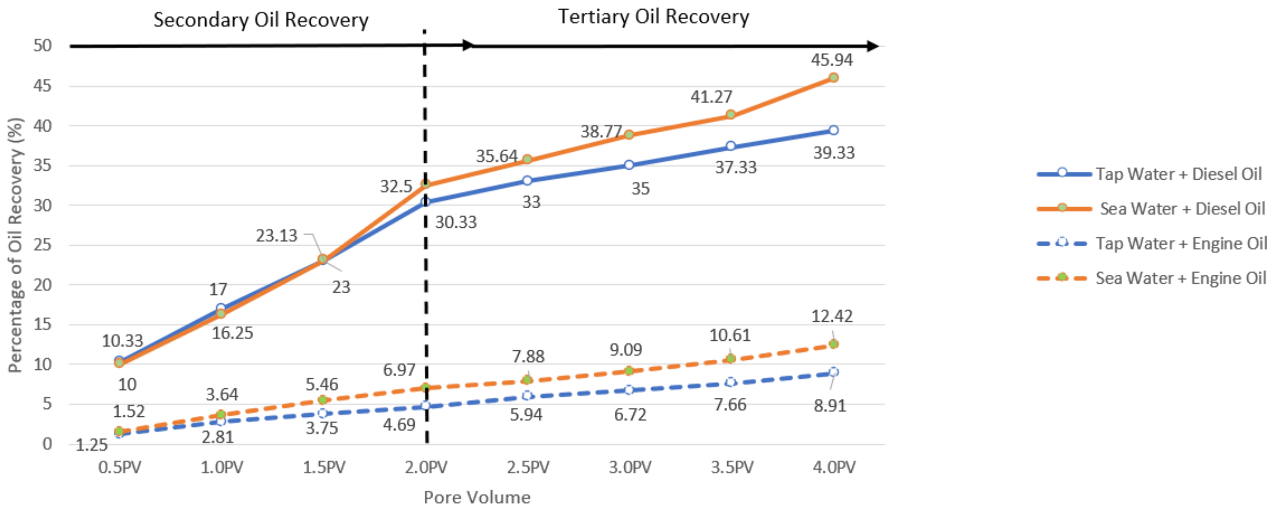

Fig. 4. Percentage of secondary and tertiary oil recovery for heavy (engine oil) and light oil (diesel oil) by using seawater and tap water

Table 2 shows the percentage of EOR efficiency for different types of oil under tap water and seawater. From the results, the percentage of oil recovery calculated from the difference between MB in light oil and heavy oil indicates that the percentage recovery for heavy oil for seawater is 87.76%, which is higher than light oil, 78.23%. The percentage recovery for tap water in heavy oil is 85.97% higher compared to light oil which is 73.74%. This shows that the use of MB in tertiary oil recovery is more efficient for recovering heavy oil compared to light oil. This is due to varying oil viscosity and solubility. Heavy oil is highly viscous [28], making conventional extraction problematic. However, MB can dissolve in heavy oil, reducing viscosity and boosting flowability, hence increasing displacement efficiency. Furthermore, MB produces stable emulsions with heavy oil due to the presence of higher average molecular masses in asphaltenes and resins than in light oil [27,29,30], which increases sweep efficiency as reported by Mandal *et al.,* [31]. In contrast, light oil has a reduced viscosity, which allows it to flow more easily. As a result, the MB may disintegrate faster or agglomerate, reducing its efficacy when compared to MB in heavy oil.

Table 2
Percentage of EOR efficiency for diesel oil and engine oil across different kind types of water

Type of Water	Type of Oil	
	Diesel Oil (%)	Engine Oil (%)
Seawater	78.23	87.76
Tap water	73.74	85.97

This finding was consistent with Hayat [32], who indicated that coalescence took longer to complete as the oil phase viscosity increased. The spreading coefficient, which quantifies the tendency of oil to spread over the MB surface, can explain MB's greater stability in heavy oil [33]. A low spreading coefficient suggests that the oil has a limited ability to spread quickly throughout the MB, allowing it to maintain structural integrity for a longer period by slowing the rising velocity [34]. This prolonged stability is crucial because it allows MB to remain attached to an oil droplet for longer periods [35], enhancing oil displacement efficiency performance in EOR processes. According to Shen *et al.,* [34], the spreading time (usually <10 ms) of oil droplets on the bubble surface is reversely proportional to the spreading coefficient and directly related to the oil viscosity, with heavy oil being characterized as having high viscosity. As a result, MB-assisted EOR is especially useful for increasing the recovery of heavy oil reserves.

In a study conducted by Huang *et al.,* [36], various types of gas, including CO2, associated gas, flue gas and deoxygenated air, were injected to investigate their efficiency in EOR. Among all the gases used for oil recovery, associated gas yielded the highest recovery rate, achieving a final recovery percentage of 41.87%. This was followed closely by CO2 at 40.89%, flue gas at 29.56% and deoxygenated air at 28.08%. Comparing the results of the current study on light oil with previous research, it is evident that MB performed better than all four types of gas injection in oil recovery. This can be attributed to the unique properties of MB, such as their large surface area and small size, which enable them to interact better with the oil, enhance sweep efficiency, delay gas breakthrough and penetrate small spaces [16,37].

3.2 Comparison of EOR Across Different Types of Water

According to Table 2, the seawater-MB displaced 78.23%, which is higher than the tap water-MB at 73.74%. A similar trend is observed with engine oil, where the seawater-MB shows a displacement rate of 87.76%, compared to the tap water-MB's 85.97%. The data demonstrate that seawater-generated MB are more effective at displacing both light and heavy oil than tap water MB due to their increased stability, smaller size and improved oil mobilization processes. This finding concludes that the MB is more useful under seawater to recover the heavy oil due to its high salinity. According to a previous study, salinity improves bubble lifetime, which leads to efficient oil mobilization and release from the rock surface [38]. The high salinity and ionic strength of saltwater have increased bubble longevity and stability while also promoting wettability change, making the reservoir rock more water-wet [39]. These features of seawater improve displacement efficiency by allowing MB to interact with restricted oil more effectively.

4. Conclusions

The effectiveness of MB in EOR for various oil types specifically, light and heavy oil under different types of surrounding liquid, seawater and tap water is examined in this study. The MB-EOR experiment demonstrates its effectiveness in displacing oil better compared to the traditional methods. This is due to unique characteristics possessed by MB which offer advantages, to displace the oil. Generally, MB is known for its slow rise velocity, high surface area-to-volume and small size of bubble diameter which influence the efficiency of the water displacement. Overall, the mean bubble size generated in seawater is slightly bigger in comparison to MB generated in tap water. As for the core flooding experiment, the results demonstrate that seawater-generated MB outperforms tap water MB in terms of oil recovery, displacing 1.79% and 4.49% for engine and diesel oil, respectively. Studies have shown that salinity increases bubble lifetime, lowers oil viscosity and promotes wettability change, making the reservoir rock more water-wet and therefore improving oil displacement efficiency. In terms of oil type, MB-EOR is more efficient for heavy oil than light oil because of the viscosity and solubility of the oil. MB can dissolve in heavy oil despite its high viscosity, leading to a reduction in its viscosity and increasing flowability. The findings contribute to the understanding of the effect of MB in EOR for different types of oil under different types of surrounding liquids, which will ultimately contribute to the exploration of methods to increase its efficiency. It is important to recognize that various reservoir properties significantly influence oil recovery through MB. Factors such as porosity, permeability and reservoir temperature can affect the transport, stability and sweep behaviour of MB. However, a detailed analysis of these mechanisms is beyond the scope of this work. Future investigations in this area are expected to provide a more comprehensive understanding of the applicability of MB across different reservoir conditions.

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