Kuwait J. Sci. **46 (4)** pp. 75-82, 2019

Experimental investigation on the mobility reduction factor of surfactant-alternating-gas foam flooding

Hamed Hematpour[1,2], Syed M. Mahmood[1], Negar H. Nasr[1], Mojtaba Karimi[2,*], Mahmood Bataee[1]

[1]*Petroleum Department of Universiti Teknologi PETRONAS*

[2]*Research Institute of Petroleum Industry (RIPI)*

[*]*Corresponding author: mojtabaz.karimi@gmail.com*

Abstract

This study investigates the effect of different existing parameters in current foam models on SAG foam process. Foam flooding is a common Enhanced Oil Recovery (EOR) method to mitigate the drawbacks of the gas injection process. Whereas Surfactant-Alternating-Gas (SAG) is a common technique in real cases, all developed foam flow models have been established based on pre-generated foam flooding. In this study, a set of core flooding experiments were designed to meet the objective. These experiments considered the effect of several parameters on the mobility reduction factor (MRF). The parameters included surfactant types, flow rate, surfactant concentration, and salinity. A high permeable core was considered as the porous medium, three different anionic surfactants (AOS, IOS and MFOAMX) were employed as the foaming agents, and the injected gas was nitrogen. The results were interpreted the SAG foam process. The results show that surfactant concentration plays an imperative role in MRF, but the salinity effect is not significant.

Keywords: Foam flooding; surfactant alternating aas; mobility reduction factor; ANOVA.

1. Introduction

Enhanced Oil Recovery (EOR) mechanisms are categorized into three major groups: gas injection, chemical injection and thermal methods, such as hot water flooding (Shidong *et al*., 2018) . The majority of these processes incorporates a gas phase injection. Inadequate sweep efficiency of gas-assisted EOR is usually a drawback of these processes. These problems are caused by gravity segregation, fingering and channeling of the gas phase through the reservoir (Hematpur *et al.,* 2014). One of the ways to confront the gas-assisted drawback is through the implementation of foam-assisted EOR. This method controls the mobility of gas, and hence improves sweep efficiency.

The foam assisted processes are categorized into five different groups: Pre-generated foam injection, Co-injection, Surfactant Alternating Gas (SAG) injection, Dissolved gas injection, and Co-injection in different layers (Hematpour *et al*., 2016). These methods have their own advantages and disadvantages. However, previous research shows that the SAG foam injection is preferable in field application due to its compatibility with common field facilities abd higher performance (Rossen & Boeije, 2013).

The fundamental concept of all empirical models are the same; these models try to modify the relative permeability of gas during the foam flooding using the Mobility Reduction Factor (MRF). Although the foam affects the relative permeability of a gas, it does not alter the relative permeability of the liquid phase (Holm, 1968; Huh & Handy, 1989 ; Vries & Vit, 1990).

The simplest empirical model considering the constant MRF is:

$$\begin{Bmatrix} k_{rg}^{f} = \frac{k_{rg}}{1+MRF} \\ MRF = \frac{\nabla p_{foam}}{\nabla p_{nofoam}} \end{Bmatrix}, \tag{1}$$

where k_{rg}^{f} and k_{rg} are the relative permeability of foam and gas, respectively. ∇p_{foam} and ∇p_{nofoam} indicate the steady state pressure gradient in the presence of foam and in the absence of foam, respectively. Mohammadi, *et al.* (1995) took the surfactant concentration into account for MRF modeling.

$$MRF = \frac{\nabla p_{foam}}{\nabla p_{nofoam}}\left(\frac{C_s}{C_s^{max}}\right)^{e_s}, \tag{2}$$

where C_s and C_s^{max} are the surfactant concentration and maximum surfactant concentration (fitting parameter) able to generate the foam, respectively. The e_S is the surfactant function exponent to control the sharpness of the function. Table 1 illustrates the different factors considered in simulator models for MRF calculation.

2. Methodology

2.1 Material

In order to achieve the objectives of this study, an Idaho-gray sandstone core sample was selected. It has high permeability to reduce the end capillary effect during the flooding. The properties of the core are shown in Table 2.

The core was homogenous. It was dominated by large pore sizes (around 100 microns) according to the pore-size distribution results from the mercury injection capillary pressure experiment (Figure 1).

The surface charge measurement for this core showed the negative charges for the sample as shown in Figure 2. In addition, the Critical Micelle Concentration (CMC) values for these surfactants were measured using the conductivity method. The results are shown in Table 3.

Table 1. Different foam models parameters

ECLIPSE	STARS, CMG	UTCHEM
- Water saturation - Oil saturation - Velocity - Surfactant concentration - Surfactant type	- Water saturation - Oil saturation - Velocity - Surfactant concentration - Critical generation capillary number Salinity - Mole fractions of oil components - Surfactant type	- Water saturation - Surfactant concentration - Velocity - Surfactant type

Table 2. Properties of the core sample

Sample Dry Weight (gr)	Pore Volume (cc)	Porosity (%)	Absolute gas Permeability (md)
138.925	23.296	29.7	2973.809

Table 3. CMC values of surfactants

Surfactant Type	CM Value
AOS	344 ppm (0.033 wt%)
IOS	160 ppm (0.016 wt%)
MFOAMX	624 ppm (0.062 wt%)

2.2. Experimental procedure

2.2.1 Gas flooding

To calculate the MRF of foam, the pressure gradient of gas flooding as the base line was required. Hence, in the first stage, the core sample was saturated with the brine using the core saturator. The core was placed in the BPS-805 core flooding system (Figure 3), and a confining pressure of 1000 psi was applied on the core. Then it was flooded by nitrogen gas at a rate of 2cc/min (around 8 ft/day). Meanwhile, differential pressures and recovery were measured throughout the flooding process. Finally, the differential pressure versus pore volume injection was plotted to generate the base line for foam flooding analysis.

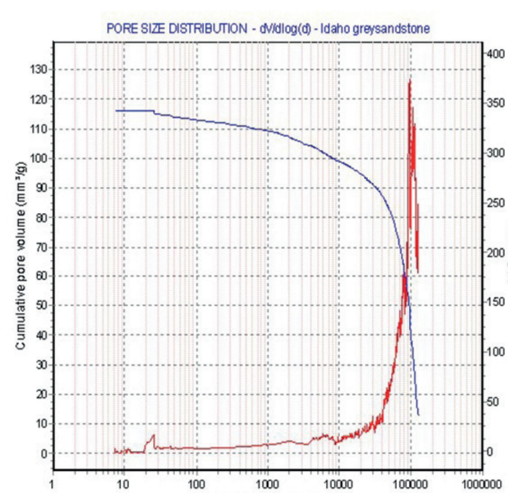

Fig. 1. Pore-size distribution of the core sample

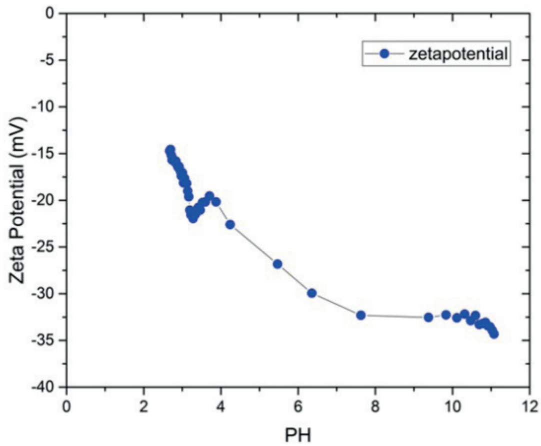

Fig. 2. Zeta potential measurement

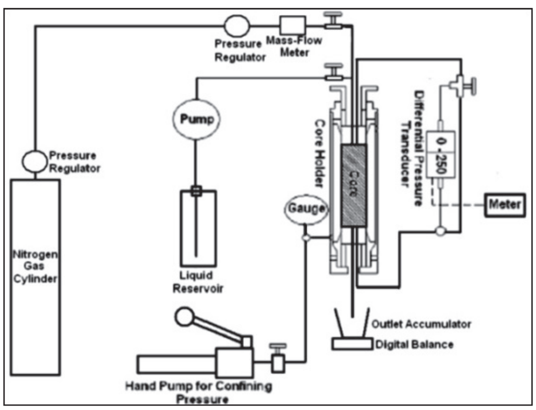

Fig. 3. BPS-805 core flooding system

2.2.2 SAG flooding

A different set of experiments was designed to investigate the effect of parameters on the SAG foam flooding. In all case, the core sample was first saturated with brine using the core saturator device. Then it was flooded by the surfactant solution for five pore volume at a low rate of 0.5 cc/min. This was to make sure that the surfactant adsorption was completed. After conducting each experiment, the core sample was cleaned and dried in order to be prepared for the next experiment. The experimental details are as follows:

The surfactant type section comprised three experiments with three different surfactant types: AOS, IOS, and MFOAMX. These surfactant solutions were prepared with a concentration of 1 wt% in the synthetic sea water brine (35000 ppm). In the flow rate section, four different injection flow rates of 2, 5, 10 and 20 cc/min were utilized to inject the nitrogen gas into the surfactant saturated core. The MFOAMX solution with a concentration of 1 wt% and a salinity of 35000 ppm was selected for this part. In order to analyze the influence of the surfactant concentrations on SAG, three different concentrations (0.1 wt%, 1 wt%, and 2 wt%) of MFOAMX were prepared and employed in the synthetic sea water brine (35000 ppm) for the SAG flooding experiments. In the last set of experiments, the impact of salinity on the SAG was examined.

Regarding the differential pressure of gas flooding (baseline), the average value for the MRF in each experiment was computed and compared to others.

In order to evaluate the influence of different factors on the SAG foam process, the Analysis of Variance (ANOVA) method was utilized. Generally, ANOVA is an appropriate method to compare means of three or more groups/variables for statistical significance.

3. Results and Discussion

As mentioned before, emphasis was placed on the impact of the five parameters on the SAG foam process. ANOVA was used to interpreting the results of the influence of the three factors on the SAG. The results are discussed in 3.1

3.1. Gas flooding

To generate the baseline for the MRF calculation, the observed data (differential pressure and recovery) for gas flooding was recorded and plotted versus the gas pore volume injection. These results are shown in Figure 4. Although the pressure data were smoothed using Origin Lab software, few fluctuations were still noticeable.

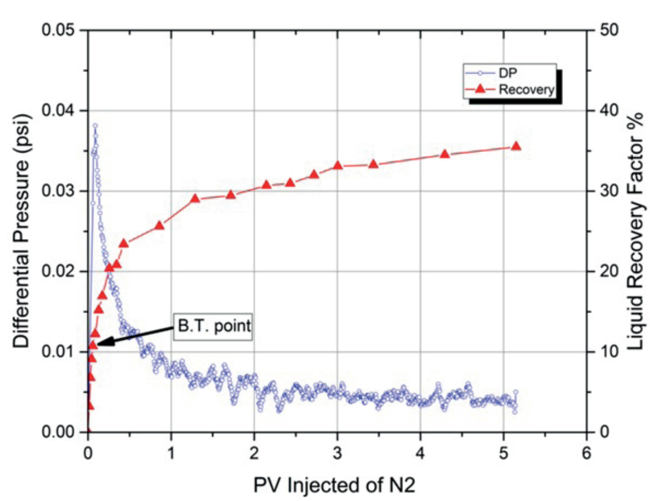

Fig. 4. Differential pressure and recovery of gas

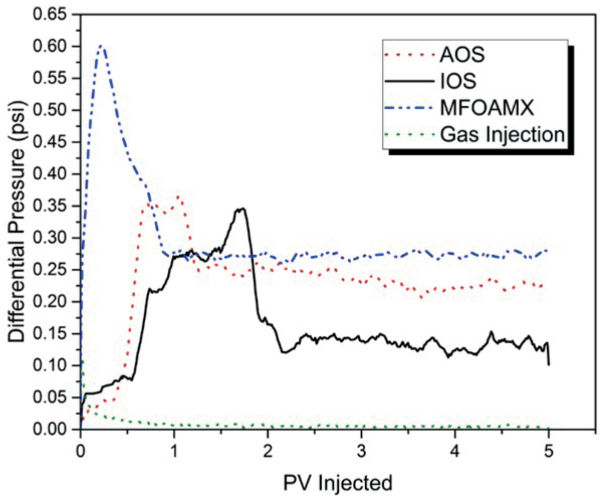

Fig. 5. Differential pressure for different surfactants

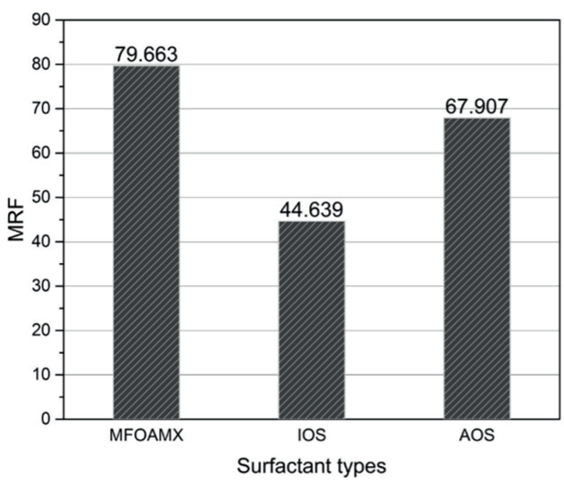

Fig 6. Average MRF for different surfactant

3.2 Influence of surfactant types

The experimental results for three surfactant types were analyzed by calculating the MRF and by using the differential pressure for gas and foam flooding. Figure 5 shows the results of differential pressure and MRF for AOS, IOS, and MFOAMX foam flooding. Figure 6 depicts the average MRF for all three surfactants types after five pore volume injection. This result indicates that using MFOAMX provides the highest average MRF among all three types.

3.3 Influence of injection rates

As mentioned in the previous section, MFOAMX 1 wt% was selected as the foaming agent for this set of experiments. The results are illustrated in Figure 7, Figure 8 shows the average MRF for the different injection rates based on the observed differential pressure data during the five-pore volume of nitrogen injection. It is evident that the injection rate of 2min/cc resulted in the highest average MRF (around 80) in comparison to other rates.

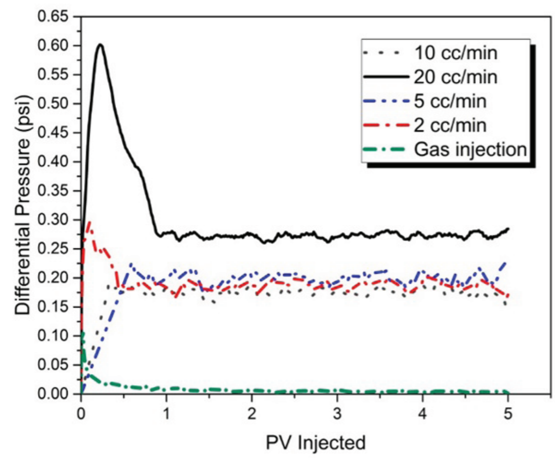

Fig. 7. Differential pressure of different flow rates flooding

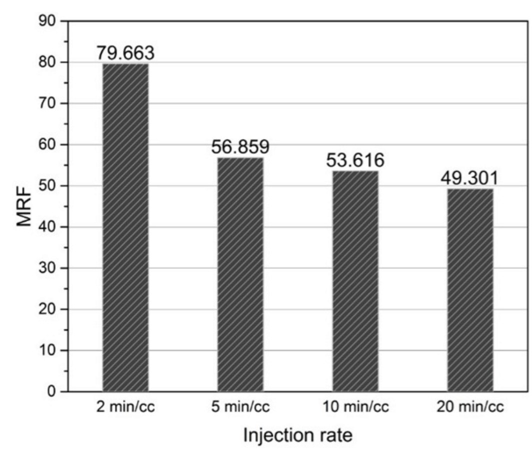

Fig. 8. Average MRF for different injection rate

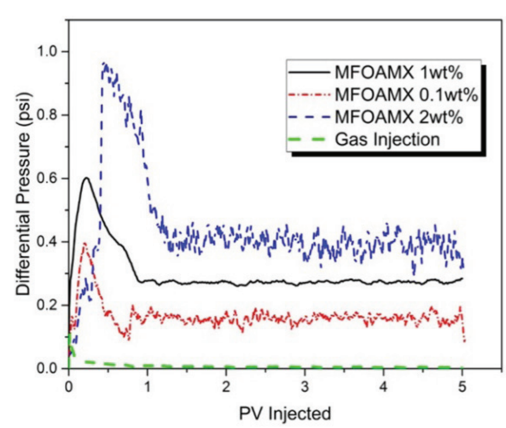

Fig. 9. Differential pressure for different surfactant concentration

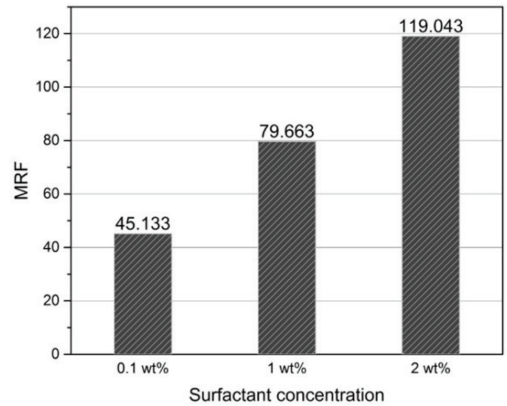

Fig. 10. Average MRF for different surfactant concentration

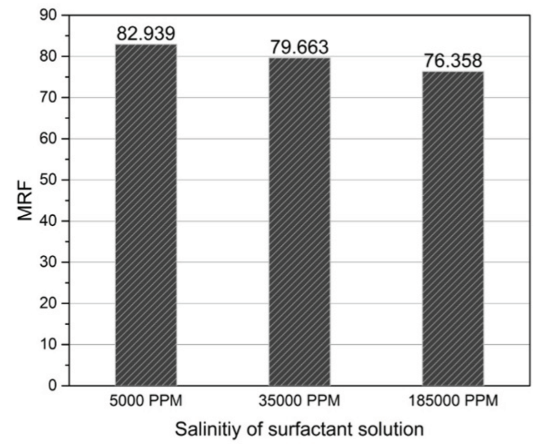

Fig. 12. Average MRF for different salinities of solutions

3.4 Influence of surfactant concentration

Three different concentrations of MFOAMX (0.1 wt%, 1 wt%, and 2 wt%) were tested in SAG foam flooding. The data results for differential pressures are shown in Figure 9. This graph depicts the observed differential pressures and calculated MRF for the three MFOAMX concentrations.

Figure 10 illustrates the calculated average MRF for different MFOAMX concentrations based on the observed pressures data during five pore volume injection.

3.5 Influence of salinity

The differential pressure data for the three different salinities of surfactant solutions (river water, seawater, and harsh environment) foam flooding are depicted in Figure 11. In addition, Figure 12 illustrates the average MRF for different salinities of MFOAMX solution based on the observed differential pressure data during five-pore volume injection.

3.6 Analysis of influence of different parameters on SAG.

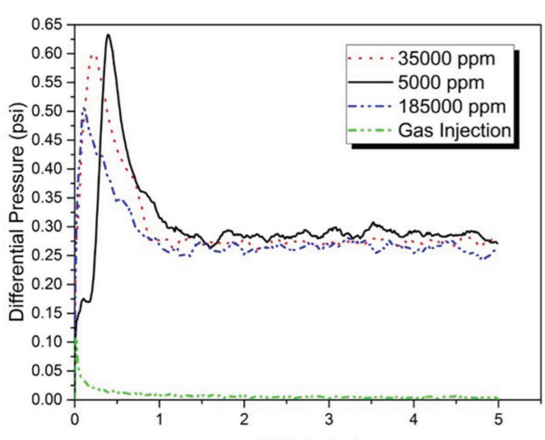

Fig. 11. Differential pressure for different salinities of solutions

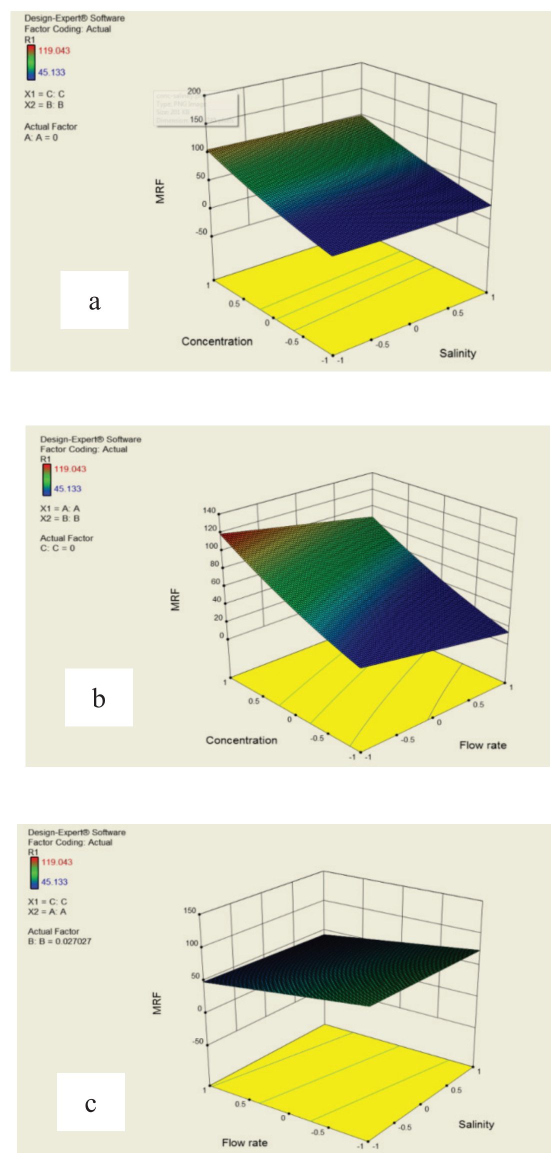

Fig. 13. Response surface results different factors: (a) Concentration and Flow rate, (b) Flow rate and Salinity, (c) Concentration and Salinity

ANOVA analysis was performed on the results of MFOAMX foam flooding. All parameters have been normalized (between -1 to 1) in order to put them all on the same scale. The best model which can fit the observed data is shown in the following equation:

$$MRF = +61.08 - 15.50 \times Flow\ rate + 36.96 \times Concentration - 2.96 \times Salinity + 5.31 \times Concentration^2 \quad (3)$$

Table 4 gives the ANOVA summary results of the aforementioned model. This table illustrates the P-value from the ANOVA analysis for different factors of the mentioned model and the P-value for the whole model. According to a literature survey on ANOVA analysis by Karimi *et. al*, (2017), the P-value is the probability that results from a specific model in terms of the statistical summary, which would be equal or more extreme than the real observed data. A low P-value represents the significant factor, and vice versa.

Table 4. ANOVA results of MFOAMX foam flooding

Parameter	Value
P-value for flow rate	0.7650
P-value for concentration	0.0151

4. Conclusions

Bearing in mind the results obtained from this study, the following conclusions were made:

- The surfactant concentration has the highest impact on the mobility reduction factor (MRF) among other parameters. The average MRF value (during 5-pore volume injection) was raised about 50% by increasing the surfactant concentration from 1 to 2 wt%. This behavior indicates that an increase in surfactant concentration leads to a boost in the SAG foam performance. On the contrary, the salinity of the solution had a minimum influence on the average MRF to the extent that increasing the salinity from 5000 ppm (river water) to 185000ppm (harsh environment) reduced the average MRF by only 7%. This reduction in MRF indicates that the foam lamella becomes more unstable, to some extent, in the presence of higher salinity.
- The SAG foam performance was affected by the gas injection rate in the way that increasing the injection rate led to a lower MRF value. This is because of the earlier breakthrough and less time it took to generate foam. In addition, increasing the injection rate caused a higher driving force and capillary number. Hence, there was more destruction in lamella.
- Although the above-mentioned factors influenced the MRF for SAG foam performance, the type of surfactant also had a considerable effect on SAG foam behavior (up to 33% changes in MRF). Additionally, water saturation played an important role in SAG foam performance. This is because during the injection (changing the in-situ water saturation), the MRF changed significantly.

ACKNOWLEDGEMENTS

This project was granted by SHELL and PETRONAS companies. The authors are grateful to these companies for graduate assistantship support. We are also thankful to the petroleum department of the Universiti Teknologi Petronas which gave us access to the laboratory and research facilities.

Nomenclature

k_{rg}^{f}	Foam relative permeability
k_{rg}	Gas relative permeability
∇P	Pressure gradient
C_s	Surfactant concentration
e_s	Exponent of surfactant function
ANOVA	Analysis of Variance
AOF	ALPHA OLEFIN SULFONATE C14-16
CMC	Critical Micelle Concentration
IOS	Internal olefin sulfonate
MRF	Mobility Reduction Factor
PV	Pore Volume
SAG	Surfactant Alternating Gas

References

Hematpur, H., Karimi, M. & Rashidi, M. (2014). A brief review on foam flow modeling through porous media. International Journal of Petroleum and Geoscience Engineering (IJPGE), pp.104–119.

Hematpur, H., Mahmood, S.M. & Amer, M.M. (2016). Experimental investigation of flow rates effect on surfactant-alternating-gas foam process. Jurnal Teknologi, **78**(6–4): 55.

Holm, L.W. (1968). The mechanism of gas and liquid flow through porous media in the presence of foam. Society of Petroleum Engineers Journal, **8**(4): 359–369.

Huh, D.G. & Handy, L.L. (1989). Comparison of steady and unsteady state flow of gas and foaming solution in porous media. Society of Petroleum Engineers Journal, **4**(1): 77–84.

Karimi M., Mortazavi A. & Ahmadi, M. (2017) Applying an optimized proxy-based workflow for fast history matching. Arab Journal of Geoscience, **10**: 462.

Mohammadi, S., Collins, J. & Coombe, D.A. (1995). Field application and simulation of foam for gas diversion. In IOR 1995-8th European Symposium on Improved Oil Recovery 15-17 May, Vienna, Austria.

Rossen, W.R. & Boeije, C.S., (2013). Fitting foam simulation model parameters for SAG foam applications. In SPE Enhanced Oil Recovery Conference held in Kuala Lumpur, Malaysia, 2-4 July. pp. 2–4.

Shidong W., Zijian X., Yi P., Hai L. & Shuangchun, Y. (2018). Experimental study on pressure field of combined well pattern by water flooding. Kuwait Journal of Science and Engineering, **45**(1): 115-120.

Vries, A.S.D. & Wit, K. (1990). Rheology of gas/water foam in the quality range relevant to steam foam. SPE Reservoir Engineering, **5**(2): 185–192.

Submitted : 07/10/2017

Revised : 04/04/2018

Accepted : 05/04/2018

دراسة تجريبية عن معامل اختزال الحركة في عملية الغمر بالرغوة باستخدام تقنية Surfactant-Alternating-Gas

[1,2]حامد حمتبور، [1]سيد محمد محمود، [1]نجار نصر، [2]مجتبى كريمي، [1]محمود بطائي

[1]قسم البترول في جامعة تكنولوجي بتروناس

[2]معهد بحوث الصناعات البترولية (RIPI)

الملخص

يُعد الغمر بالرغوة أحد الأساليب الشائعة لاستخلاص الزيت المُحسن (EOR) للتخفيف من عيوب عملية حقن الغاز. وحيث أن Surfactant-Alternating-Gas (SAG) هو أسلوب شائع في الحالات الحقيقية، فقد تم تطوير جميع نماذج تدفق الرغوة المُطورة استناداً إلى الغمر بالرغوة المتولدة مسبقاً. تهدف هذه الدراسة إلى دراسة تأثير المعلمات المختلفة الموجودة في نماذج الرغوة الحالية على عملية الغمر بالرغوة باستخدام تقنية SAG.

تم تصميم مجموعة من تجارب الغمر الأساسية لتحقيق الهدف المذكور أعلاه. درست هذه التجارب تأثير العديد من المعلمات على معامل اختزال الحركة (MRF) بما في ذلك: أنواع خافض التوتر السطحي، ومعدل التدفق، وتركيز خافض التوتر السطحي ودرجة الملوحة. تم اعتبار النواة عالية النفاذية كوسيط مسامي، وتم استخدام ثلاثة عوامل سطحية أنيونية مختلفة (AOS و IOS و MFOAMX) كعوامل الرغوة، وتم استخدام غاز النيتروجين كغاز محقون. تم تفسير النتائج باستخدام طريقة تحليل التباين (ANOVA) لمعرفة المعلمة الأكثر فعالية في عملية الغمر بالرغوة باستخدام تقنية SAG. وأظهرت النتائج أن تركيز خافض التوتر السطحي يلعب دوراً أساسياً في MRF، لكن تأثير الملوحة ليس كبيراً.