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EXPERIMENTAL INVESTIGATION OF FLOW RATE'S EFFECT ON SURFACTANT-ALTERNATING-GAS FOAM PROCESS

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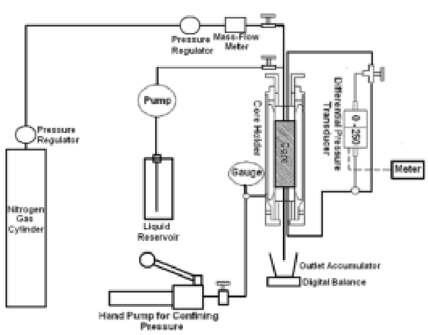
Graphical abstract



Abstract

The gas injection is one of the most common methods to increase oil recovery. However, there are several drawbacks in the application of this method due to density and viscosity differences between displaced and displacing fluids. In order to tackle these drawbacks, gas can be utilized as different forms of foam which one of these methods is called Surfactant-Alternating-Gas (SAG). Although many studies have been conducted on foam flow through porous media, the behavior of foam still is moot to some extent. Since, the elaboration of SAG foam behavior in porous media is the aim of this study. However many parameters affect SAG foam behavior, the injection flow rate plays a significant role in foam behavior. In this study, we investigated the flow rate's effect on SAG behavior. To achieve this target, several cores flooding, in the absence of oil, were conducted and results were interpreted. The experimental design for this work included core flooding apparatus, IOS as surfactant and nitrogen as injected gas. The experiments were interpreted in term of liquid recovery and pressure drop. The results show that the SAG efficiency highly depends on gas flow rate which high injection flow rate, low SAG foam efficiency.

Keywords: Foam Flooding, Surfactant-Alternating–Gas (SAG), Mobility Reduction Factor, Adsorption

1.0 INTRODUCTION

Foam-assisted process as one of enhanced oil recovery method was introduced to overcome problems of gas injection to some extent [1]. The recovery improvement via foam-assisted process was proved by [2]. In this method by adding chemical substances like surfactant to the liquid phase, the foam can be generated. The front stability of foam flooding is considerably higher compared to gas injection due to lowering interfacial tension as well as dramatically decreasing in mobility of gas in the presence of foam. Therefore, foam can be employed to prevent fingering and channeling phenomenon of gas, consequently, amounting the sweep efficiency of flooding process. Although enormous studies have been conducted to find out mechanisms of mobility changing due to foam flooding but still some principles remains moot in this area.

Foam flooding can be conducted with four different approaches as following: first, foams should be prepared on the surface then it can be injected to the reservoir. Second, Surfactant-Alternating-Gas (SAG) in which the gas and surfactant are injected one after other periodically. Once the gas meets the existing surfactant solution the foam can be generated [3]. Third, according to previous studies [4], [5], some surfactants can be dissolved into supercritical CO2, therefore, the foam can be generated once this solution meets the existing water in the reservoir. Fourth, the gas and surfactant solution can be injected simultaneously but in different sections of well [6], [7]. In this study, the behavior of Surfactant-Alternating-Gas in different flow rates has been investigated.

As the definition, the foam is a scattering of gas in liquid solution where the liquid phase is continues and the gas phase spread through the liquid phase[8]. With respect to the number of lamellae in foam texture, the foam can be categorized into two categories; weak foam with coarse texture (large bubble size) and strong foam with fine texture (small bubble size). The ability of the strong foam to reduce gas mobility is higher than weak foam.

It is realized that the lamellae of foam are generated due to three different mechanisms. Firstly, during the invasion of gas into liquid saturated area, the lenses can be deserted behind, this mechanism is called "leave-behind". Secondly, another mechanism is called "snapped-off", in which gas bubbles are created due to driving force of gas applied on gas-liquid interface and push this interface toward the pore throat. Also the fluctuation in capillary pressure leads to the snapped-off mechanism. Thirdly, the pressure gradient affects pre-existing lamellae and force it to move, consequently, it divides into many at the pore junction. This mechanism is called "lamellae division"[9].

The lamellae coalescence results in the destruction of the foam. There are three forces which affect the stability of lamellae; Van der Waals force P_d^{vw}, electrostatic repulsion P_d^{el} and hydration forceP_d^{sh}. The combination of these three forces is called disjoining pressure P_d . Whenever, P_d reach to the maximum value (P_d^{rup}), the film eventually ruptures. The capillary pressure value corresponding to P_d^{rup} is named as critical pressure for rupture (P^*) above which foam films will be destroyed [9]. This phenomenon regularly happen in the snapped-off mechanism which capillary pressure plays the main role.

As mentioned above, the number of lamellae in foam texture determines the strength of the foam. The number of lamellae per unit volume is a dimensionless parameter and considered as foam texture (n). Although it is a paramount parameter to describe foam behavior, there is no reliable procedure to determine it directly through the porous media. Therefore, the pressure gradient is usually used to describe foam instead of foam texture[3]. Regarding the pressure gradient, the strength of foam can be determined; the fine bubble (strong foam) depicts the high pressure gradient and reduce the gas mobility significantly, on the other hand, coarse bubble (weak foam) shows the low pressure gradient and low reduction in gas mobility. The pressure gradient and mobility of foam are shown in equation 1 and 2, respectively.

$$\nabla P_{foam} = \frac{v\mu_g}{kk_{rf}} \quad (1)$$

$$M_{foam} = \frac{k_{rf}}{\mu} \quad (2)$$

Where v is superficial velocity, μ_g is viscosity, K and k_{rf} are absolute and relative permeability, respectively. As these two equations show, the mobility of foam is related to relative permeability of foam and this relative permeability affect the pressure gradient. Accordingly, the pressure gradient is a good indicator to infer the foam influence on mobility reduction of gas. The primary foam model was proposed based on pressure gradient [10] . The new parameter was defined to show the strength of the foam. This parameter is called the mobility reduction factor (MRF) which can be calculated by equation 3.

$$MRF = \frac{\nabla P_{foam}}{\nabla P} \quad (3)$$

In this study, the influence of gas injection flow rate on the behavior of foam was examined via mobility reduction factor, pressure gradient and liquid recovery. Since the foam behavior in SAG foam process still is moot to some extent [11], the effect of presence of oil was ignored in this study to simplify the interpretation.

2.0 METHODOLOGY

2.1 Experimental Setup

In order to conduct SAG foam process the experimental set up, shown in
was utilized at ambient back pressure and ambient temperature. The core holder placed in vertical position to prevent buoyancy effects and gas overriding phenomena. Also, 1000 psi was applied for all runs as the confining pressure to isolate the core.

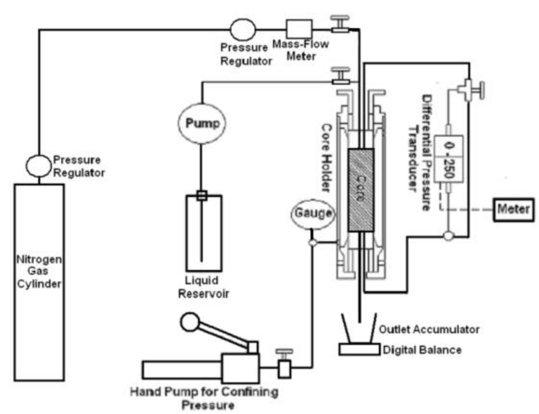


Figure 1 Experimental Setup

In this study the Idaho greysandstone core was used to perform experiments. These type of cores have a high permeability according to result of air permeability experiment as shown in Table 1.

Table 1 Properties of core

Length (cm)	Diameter (cm)	Vp(cc)	φ(%)	K[air](mD)
7.157	3.736	23.29631	29.69289	15028.56

The mercury porosimetry was conducted to find out the average size of pores since the maximum sizes of foam's bubble in porous media are always less than size of pores. The results of this experiment was illustrated in Figure 1. This diagram shows that the average pore size is around 100 µm which can be considered as large pore size medium.

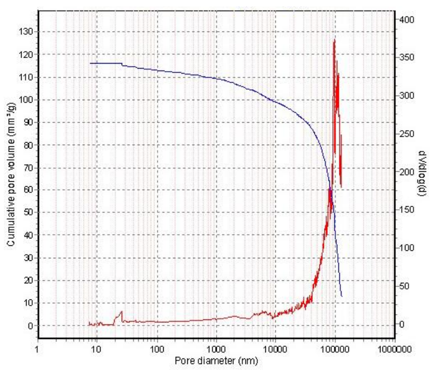


Figure 1 Pore size distribution

Since, investigation of SAG-foam process is the objective of this project, water flooded situation should be considered as an initial condition. In real cases for water flooding, seawater is used to inject especially in the offshore oil field. Therefore, the synthetic brine which was used in this work is seawater.

On average, seawater in the world's oceans has a salinity of about 3.5% (35000 ppm), which is a specific gravity and viscosity of about 1.025 and 1cp in ambient condition, respectively [12].

The surfactant was used in this study to generate foam was an IOS surfactants (ENORDET. TM) with CMC around 0.003 wt%. The surfactant solution was prepared in sea water brine with the concentration of 1 wt%.

The Nitrogen was used as the injecting gas because this gas is inert, noncorrosive and immiscible in low pressure compared to CO2. Moreover, this gas has been employed in previous foam's studies [13], [14].

2.2 Core Flooding Procedure

As mentioned before, the main aim of this study is to investigate the flow rate's effect on foam flow. In order to achieve this objective, the pressure drop in different injection flow rates for gas, in the absence of foam and in the presence of foam, was examined. These flow rates should be large enough to overcome the end capillary effect, therefore the selected rates for this set of experiments are 2, 5, 10, 20 cc/min. The flow rate is adjusted by gas flow controller in this experimental setup. The core flooding procedures were conducted as following; First, The core was saturated by brine via vacuum apparatus (evacuating air from core) and placed in core holder. Second, the brine was injected into the core to measure the liquid permeability of brine and filling up small pores if remained. Third, the gas was injected under certain flow rate, meanwhile the pressure drop and liquid recovery were recorded. After each gas flooding, we injected the 5 pore volume of brine with low flow rate (0.5 cc/min) to saturate the core and prepare the core for the next run. Fourth, the amount of 5 pore volume surfactant solution with low flow rate (0.5 cc/min) was injected into core to saturate the core by surfactant as well as to equilibrate the adsorption of surfactant on the pore surfaces. Also, the pressure drop was measured to examine the adsorption phenomena. Fifth, the gas was injected into the core saturated with surfactant solution under certain flow rate. The pressure drops and liquid recovery were measured throughout the test. After each flooding, the core was saturated with surfactant solution and prepare for the next gas flooding.

3.0 RESULTS AND DISCUSSION

3.1 Liquid Recovery

At first set of experiments, the liquid recovery for the gas injection in brine solution and surfactant solution has been compared with each other at different gas flow rates. Results of these experiments were illustrated in

Figure **2** and

Figure **3**.

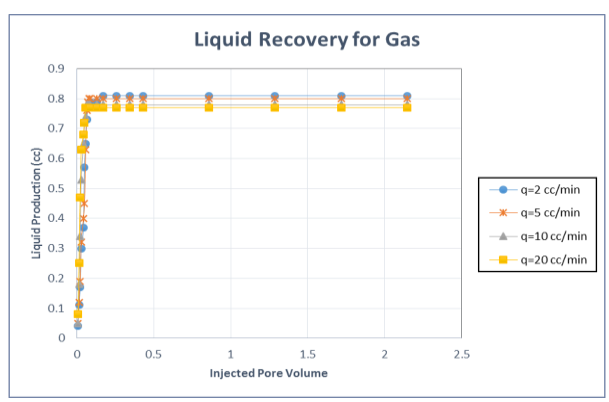


Figure 2 Liquid recovery for gas

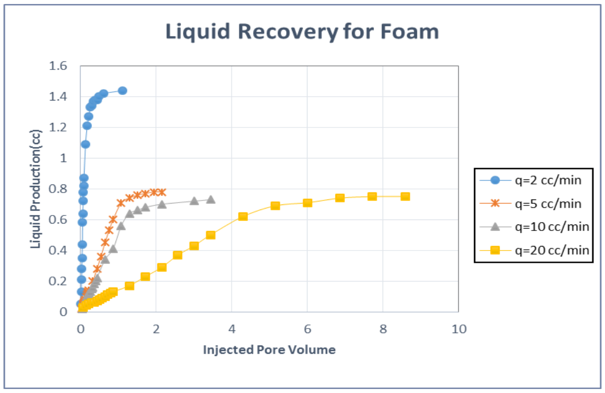


Figure 3 Liquid recovery for foam

As the
Figure **2** shows, the ultimate recovery doesn't change significantly by changing the gas flow rate in the absence of a foaming agent, more over the breakthrough time changes is also hardly noticeable in this figure. Increasing the flow rate leads to decreasing in breakthrough time as well as ultimate recovery.
The
Figure **3** depicts that liquid recovery highly depends on gas flow rate in the presence of the foaming agent. It shows that the low flow rate provides the better condition to generate the foam, consequently, increase the sweep efficiency as well as liquid recovery.

3.2 Surfactant Adsorption

In order to realize the surfactant adsorption's effect on pressure drop, the pressure drop of initial brine flooding, surfactant solution flooding and brine flooding after surfactant solution were analyzed [15]. The results shows that the surfactant adsorption is hardly noticeable because it increase the pressure drop very slightly (
Figure **4**).

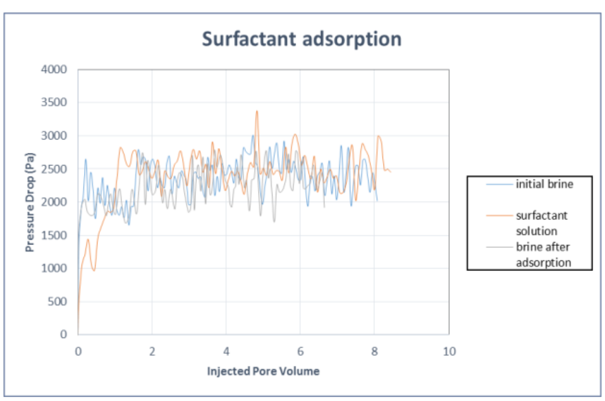


Figure 4 Adsorption of surfactant

3.3 Pressure Drop in SAG

As mentioned above, pressure drop is appropriate indicator to show the strength of the foam, results of these experiments are described in this section.
Figure **5** to Figure 9 illustrate the difference between pressure drops in both cases of presence of foam and absence of foam.

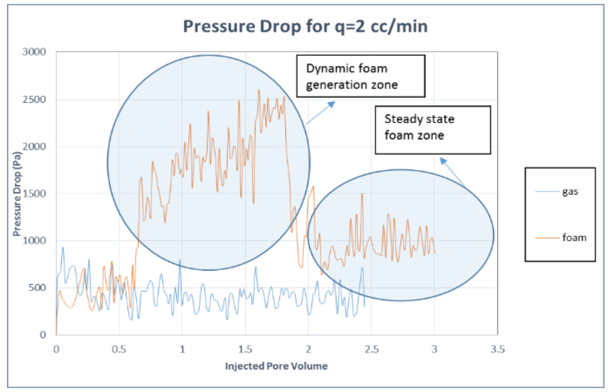


Figure 5 Pressure drop for q=2 cc/min

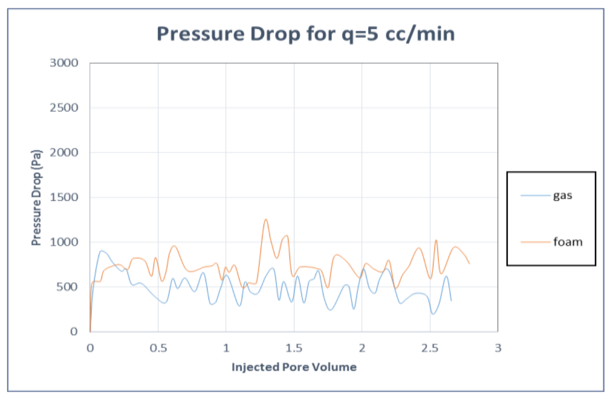


Figure 6 Pressure drop for q=5 cc/min

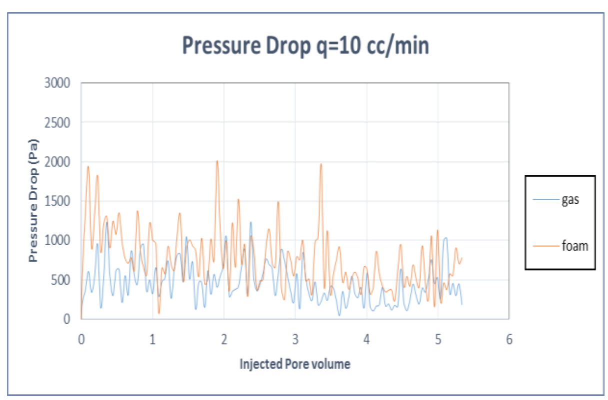


Figure 7 Pressure drop for q=10 cc/min

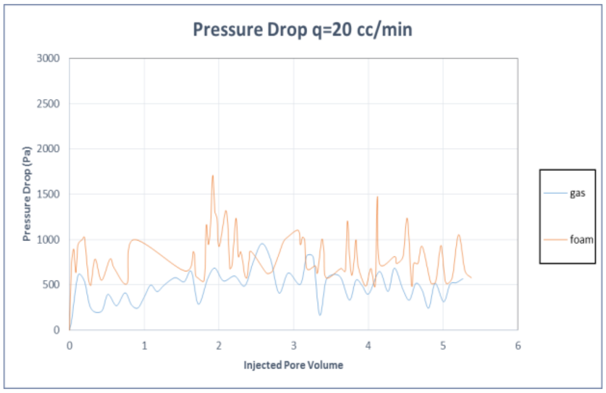


Figure 8 Pressure drop for q=20 cc/min

These figures show that the injection flow rate affects the foam flow through porous media. Among all tested flow rates, the flow rate of 2min/cc can be representative of the foam generation inside the core. Although rest flow rates show the slightly increasing in pressure drop, this mounting in pressure drop is because of slightly adsorption of surfactant on pores' surfaces (
Figure ***4***).

The results elucidated the low value of the reduction in mobility even in q=2 cc/min.

Figure ***5*** shows that the maximum MRF is around 8.5 in dynamic foam generation zone and 3.3 when foam reaches to steady state. This result can be expressed by foam generation mechanism. As mentioned before, there are three mechanisms to generate the foam. The dominant mechanism for these experiments is left behind mechanism because the capillary pressure is negligible in this core due to its large pore size (Figure 1) also there was no pre-generated foam inside the core. The left behind mechanism has the low reduction in mobility compared to other mechanisms. Additionally, the large pore size allows the foam's bubbles to grow, consequently, the foam with coarse texture were created. As said before, coarse texture foam has the low mobility reduction factor.

In high flow rates injections of gas, the dragging force were increased so it overcame the disjoining pressure of lamellae, consequently, lamellae became instable. This instability caused lamellae's rapturing and gas channeling, therefore, the foam cannot be generated in these cases.

4.0 CONCLUSION

In this study, the gas was injected under different flow rates into surfactant saturated core to investigate the gas flow rate's effect on SAG foam process. Analyzing the results came up with the following conclusions;

1) The injection flow rate has a remarkable effect on foam generation and destruction mechanism, this can be explained by the sweep efficiency (liquid recovery) and the pressure drop. The liquid production increased to 1.44 cc and pressure drop reached to 2527 Pa. under foam generation condition.
2) The Increasing in pressure drop during gas flooding into surfactant saturated medium can be results of either surfactant adsorption or foam generation. If pressure drops increased to a peak and fell after that, this behavior shows the foam generation and increasing in mobility reduction factor. In this study, The MRF reached to 8.5 under foam generation condition.
3) The gas injection above a certain flow rate (2 cc/min) leads to destruction the lamellae, consequently, destruction of foam.
4) The governing mechanism of foam generation in large pore size medium is left behind and the foam texture tends to be coarse which results in a low value of mobility reduction factor.
5) In SAG foam process, two different zones were observed, dynamic foam generation zone and steady state zone. In first zone, the pressure raised to maximum value and suddenly drop to steady state pressure drop and remains constant in second zone.

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Refrences

[1] Schramm, L. L. 1994. Foams: Fundamentals and Applications in the Petroleum Industry. *ACS Adv. Chem. Ser. No. 242.*

[2] D. C. Bond and C. C. Holbrook. 1958. Gas Drive Oil Recovery Process. Patent Number: 2,866,507.

[3] Afsharpoor, G. S. Lee, and S. I. Kam. 2010. Mechanistic Simulation Of Continuous Gas Injection Period During Surfactant-Alternating-Gas (SAG) Processes Using Foam Catastrophe Theory. *Chem. Eng. Sci.* 65(11): 3615-3631.

[4] Ashoori, E., van der Heijden, T., and Rossen, W. 2010. Fractional-Flow Theory of Foam Displacements With Oil. *SPE J.* 15: 20-22.

[5] Le, V. Q., Nguyen, Q. P., Sanders, A. W., and Dow, T., 2008. A Novel Foam Concept with CO 2 Dissolved Surfactants. *The SPE/DOE Improved Oil Recovery Symposium held in Tulsa, Oklahoma, 19-23 April*. 1-15.

[6] Stone, H. L. 2004. A Simultaneous Water and Gas Flood Design with Extraordinary Vertical Gas Sweep. *Proceedings of SPE International Petroleum Conference in Mexico*.

[7] Rossen, W., van Duijn, C., Nguyen, Q., Shen, C., and Vikingstad, A. 2010. Injection Strategies To Overcome

Gravity Segregation in Simultaneous Gas and Water Injection Into Homogeneous Reservoirs. *SPE J.*15.

[8] Hirasaki, G. J. 1989. The Steam-Foam Process--Review of Steam-Foam Process Mechanisms. *Soc. Pet. Eng.* SPE–19518–MS.

[9] H. Hematpur, M. Karimi, and M. Rashidi. 2014. A Brief Review On Foam Flow Modeling Through Porous Media. *Int. J. Pet. Geosci. Eng.* 104-119.

[10] Rosman, A. and Kam, S. I. 2009. Modeling Foam-diversion Process Using Three-phase Fractional Flow Analysis in a Layered System. *Energy Sources, Part A Recover. Util. Environ. Eff*. 31(11): 936-955.

[11] Rossen, W. R. and Boeije, C. S. 2015. Fitting Foam-Simulation-Model Parameters to Data : II . Surfactant-Alternating-Gas Foam Applications. *SPE Reserv. Eval. Eng.* 273-283.

[12] 2015. Seawater. *Wikipedia, The Free Encyclopedia*, [Online].Available:https://en.wikipedia.org/wiki/Seawater#cite_note-1.

[13] Fergui, O., Bertin, H., and Quintard, M., 1998. Transient Aqueous Foam Flow In Porous Media: Experiments And Modeling. *J. Pet. Sci. Eng.* 20: 9-29.

[14] Ma, K., Lopez-salinas, J. L., Puerto, M. C., Miller, C. a, Biswal, S. L., and Hirasaki, G. J. 2013. Estimation of Parameters for the Simulation of Foam Flow through Porous Media. Part 1 : The Dry-Out Effect. *Energy Fuels*. 27(5): 2363-2375.

[15] Hematpour, H., Arabjamloei, R., Nematzadeh, M., Esmaili, H., and Mardi, M. 2012. An Experimental Investigation of Surfactant Flooding Efficiency in Low Viscosity Oil Using a Glass Micromodel. *Energy Sources, Part A Recover. Util. Environ. Eff*. 34(19): 1745-1758.