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Study of Unsteady State Behavior of Foam in Surfactant-Alternating-Gas Process

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Abstract

Background/Objectives: In order to derive foam model's parameters for simulation, steady state experiments should be conducted because it can satisfied local equilibrium condition for modeling. Although this method is commonly used, it is time-consuming. Unsteady state experiment is one of the alternative approaches. In order to utilize this approach, it is required to be proven whether can satisfy local equilibrium or not. **Analysis:** In this study, the condition of local equilibrium in unsteady state experiment was investigated. All governing equations in foam process were utilized to show whether in unsteady state experiments there is local equilibrium or not. In order to achieve the goal of this study, Various Assumptions were considered to simplify the model. **Finding:** As results, it has been proven that the local equilibrium condition can be applied to the front zone in unsteady state foam flooding. Regarding this result, it can be concluded that to drive model parameters of foam assisted process, unsteady state experiments can be performed instead of the steady state. **Novelty:** Accordingly, this study aims to prove that whether the unsteady state data can be utilized to in foam modeling or not.

Keywords: Unsteady State, Steady State, Foam Flooding, Foam Models, Local Equilibrium

1. Introduction

Recently, the upgrading routines Enhanced Oil Recovery (EOR) methods turned into the focal point of consideration in the petroleum business. Because numerous hydrocarbon fields came to downturn period in their life span. The EOR processes also have called the tertiary oil recovery in several kinds of literature. Generally, the EOR process includes the process which injects materials that are not existed in the reservoirs to build up the recovery of hydrocarbon phases. The utilizing the gas as an injection phase in EOR process is one of the frequent mechanism to grow the recovery of oil reservoirs. However, implementation of gas phase accompanies by some changelings issues. The viscous channeling and overriding the gas phase are more probable due to low viscosity and low density of gas phase compare to liquid phases, respectively. Therefore, the implementation of foam phase has been introduced to conquer those disadvantages of gas injection.

The basic concept of foam phenomena is the dispersion of gas phase into the liquid phase in such a way that, in spite of, the fluid phase keeps its ceaseless form in a few sections, the gas phase results in the disjointedness form and create thin liquid films. The thin liquid films that are generated during the foaming process is denominated "lamellae" [1]. Once the foam exists in permeable medium, it parts into more than one phases: the liquid phases contains the surfactant which possessing small size pores and also gas phase which is encompassed by lamellae which occupying larger pores.

The texture of foam can be characterized by the quantity of lamellae films in unit volume which is illustrated by "n_f". Although the foam texture is critical to decide the rheology of foam, there is no solid procedure to quantify it specifically. With respect to the texture of foam (numbers of lamellae), foam has been categorized into two different types: the weak type which refers to the foam with the lower number of lamellae in their texture and strong type which refer to the foam with the high

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number of lamellae in their texture. The lower number of lamellae leads to generate the large bubbles (coarse texture), consequently, the small reduction in mobility of gas phase. On the other hand, the higher number of lamellae leads to generate the small bubbles (fine texture), consequently, the larger reduction in mobility of gas phase. Therefore, the foam also can be portrayed by evaluating by bubble size[2]. Moreover, the foam quality is another parameter to evaluate the foam strength and behavior. The foam quality is the portion or rate of gas to aggregate volume:

$$foam\ quality = \frac{\mathbf{V_g}}{\mathbf{V_l + V_g}} \tag{1}$$

Where the gas volume in the foam is denoted by V_g, and the liquid volume in the foam phase is denoted by V_l.

In order to achieve a successful foam process, an appropriate model is required to predict the behavior of foam through porous media, correctly. There are several approaches for foam flow modeling through porous media[3].These approaches are categorized into three groups; Mechanistic, semi-empirical and empirical. The mechanistic approach is the most confused one in light of the fact that it is hard to get its parameters compares to other approaches. In spite of, the presence of diverse thought regarding the best method, there are a few ideas which have been acknowledged for all methodologies; the function of mobility of water has the same behavior in both circumstances; presence of foam or presence of gas, the behavior of foam is considered as a one phase through permeable medium and the texture of foam has primary impact on gas portability control. STARS™ is one of the commercial foam simulators which widely is utilized. It is able to fit the behavior of foam with high quality as well as low quality reasonably well. The STARS™ simulator, equipped with the population balance simulation package to simulate the foam behavior. It also includes a local equilibrium model which can simplify the population balance model to predict the foam behavior in the porous medium. In STARS™, the empirical foam model tends to modify the relative permeability of gas phase to apply the effect of foam by multiplication by a factor FM which is inversely proportional to several other factors as shown in (2) and (3).

$$K_{rg}^{f} = K_{rg}^{0}(S_w)FM \tag{2}$$

$$FM = \frac{1}{1 + fmmob\,.F1.F2.F3.F4.F5.F6.fdry} \tag{3}$$

$fmmob$ describes the normalized resistance to the flow of foam with minimum-size bubbles, in the absence of factors increasing bubble size. K_{rg}^{f} is the gas relative permeability in the presence of foam and K_{rg}^{0} is the gas relative permeability in the absence of foam. F1 represents the effects of surfactant concentration; F2 describes the effect of oil saturation. F3 represents the shear-thinning effect of pressure gradient on gas mobility in the low-quality regime, F4 shows critical generation capillary number effect on gas mobility, F5 illustrates the effect of critical oil mole fraction on gas mobility, F6 presents the salt effect on gas mobility The effect of foam dry out at the limiting capillary pressure is accounted for by *fdry*. *fdry* as shown in equation (4) controls gas mobility as water saturation decreases in the vicinity of *sfdry*. *sfbet* controls the abruptness of the increase of gas mobility in the vicinity of water saturation *sfdry* :

$$fdry = 0.5 + \frac{\arctan\left(sfbet(S_w - sfdry)\right)}{\pi} \tag{4}$$

This model is an empirical model where the local equilibrium condition has been applied to it. The local equilibrium condition means that the rate of foam generation and destruction be the same. Therefore to employ STARS™ for foam simulation, it is crucial to ensure that our experimental data follow local equilibrium condition. One of the ways to be assured that it can satisfy local equilibrium condition is conducting steady state experiments. Different studies have been conducted to obtain the parameters of this model using steady state data. There are several methods for obtaining model parameters by steady state data which all of them employ the fitting method for foam quality and apparent viscosity plot[4,5,6].

This study aims to prove the existence of local equilibrium condition in unsteady state experiment because it is a crucial condition for utilizing these data to obtain the model parameters of STARS™.

2. Method

In this section, the simple model of foam flooding has been developed. In order to generate a simple model several assumptions are required: all phases are considered as incompressible, Newtonian fluids, there is only one direction to flow and the effect of dispersion, as well as capillary pressure gradient, are neglected. Although there are various approaches to foam flooding [5], the Surfactant Alternating Gas (SAG) have been investigated in this study. In this approach, dry gas is injected after one slug of surfactant solution. To achieve this, a simple model has been considered as shown in Figure 1. In this model the shock front has been considered as foam zone.

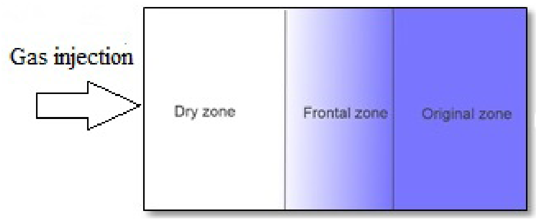

Figure 1. A simple model of foam flooding.

The governing equation for an immiscible two-phase, incompressible displacement and linear flow through porous media is given by Rapoport-Leas equation [7]

$$\varphi \frac{\partial S_w}{\partial t} + u\frac{\partial f_w}{\partial x} + \frac{\partial}{\partial x}\left(\left(\frac{\lambda_w \lambda_g}{\lambda_w + \lambda_g}\frac{dP_c}{dS_w}\right)\frac{\partial S_w}{\partial x}\right) = 0 \quad (5)$$

Where f_w and S_w are fractional flow and water saturation respectively, u is total superficial velocity ($u_w + u_g$), and mobilities of water and gas are shown by λ_w and λ_g. However f_w is dependent on S_w it also depend on foam texture in foam process. For instance it may rely on surfactant concentration but in this study for straightforwardness, we assume full strength concentration in aqueous phase throughout of our model.

Regarding our assumption in this model we neglect capillary pressure gradient ($\frac{dP_c}{dS_w} = 0$) in large scale for water velocity in equation (5); consequently, displacement fulfil the following equation:

$$\varphi \frac{\partial S_w}{\partial t} + u\frac{\partial f_w}{\partial x} = 0 \quad (6)$$

By solving this equation, the velocity of portion in vicinity of shock front can be derived by:

$$v = \frac{u}{\varphi}v_s = \frac{u}{\varphi}\frac{f_w^D - f_w^U}{S_w^D - S_w^U} \quad (7)$$

Where v_s indicates the slope of shock line the downstream and upstream sections of the front are indicated by the D and U, respectively.

On the small scale of within shock front, there is a region where the capillary pressure gradient is equal to the pressure gradient of viscous forces to generate the unceasing profile of saturation [8,9]. To make our model easier, the new coordinate was defined through the shock front:

$$\theta = vt - x \quad (8)$$

Where ν is the shock velocity which can be determined by equation (7). The new coordinate means that if θ tends to +∞ then we approach to downstream zone of front with water saturation as S_w^D and foam texture as n_D^D. Also if θ tends to +∞ then we approach to upstream zone of front with water saturation as S_w^U and foam texture as n_D^U.

By writing the equation (5) in new form ($S_w = S_w(x)$), the following equation was derived:

$$\varphi \frac{\partial S_w}{\partial x}\frac{\partial x}{\partial t} + u\frac{\partial f_w}{\partial x} + \frac{\partial}{\partial x}\left(\left(\frac{\lambda_w \lambda_g}{\lambda_w + \lambda_g}\frac{dP_c}{dS_w}\right)\frac{\partial S_w}{\partial x}\right) = 0 \quad (9)$$

Take integral respect to x in upstream zone of the front the following equation was obtained:

$$\varphi \frac{\partial x}{\partial t(S_w - S_w^U)} + u(f_w - f_w^U) + \left(\left(\frac{\lambda_w \lambda_g}{\lambda_w + \lambda_g}\frac{dP_c}{dS_w}\right)\frac{\partial S_w}{\partial x}\right) = 0 \quad (10)$$

Considering chain rules:

$$\frac{\partial x}{\partial t} = \frac{\partial x}{\partial \theta}\frac{\partial \theta}{\partial t} = -v = \frac{u}{\varphi}v_s \quad (11)$$

$$\frac{\partial S_w}{\partial x} = \frac{\partial S_w}{\partial \theta}\frac{\partial \theta}{\partial x} = -\frac{\partial S_w}{\partial \theta} \quad (12)$$

and afractional flow definition

$$f_w = \frac{\lambda_w}{\lambda_w + \lambda_g} \quad (13)$$

The following equation was derived.

$$\frac{dS_w}{d\theta} = \frac{u[f_w - v_s S_w - (f_w - v_s S_w)^U]}{f_w \lambda_g \left(\frac{dP_c}{dS_w}\right)} \quad (14)$$

This equation also can be derived for thedownstream zone of the front.

The gas properties in foam process depend on foam texture and thesaturation of water [10]. Hence, In order tomodel thefoam process additionalequation is required which called population balance equation:

$$\varphi\frac{\partial}{\partial t}(S_g n_D) + \frac{\partial}{\partial t}(U_g n_D) = \frac{\varphi}{n_{max}}S_g(r_g - r_c) \quad (15)$$

Where $n_D = \frac{n_f}{n_{max}}$ is the dimensionless bubble texture and n_{max} is the upper limit for foam texture. r_g and r_c denote the rate of bubble generation and destruction, respectively. These parameters are related to net foam generation. Wherever local equilibrium is presented these two rates will be equal and the net foam generation will be zero. In both sides of the front, the local equilibrium condition exists because there is no foam in both sides. Accordingly, this condition should be investigated through the front zone.

The equation (6) was written for gas phase and solved to reach following equations:

$$v_s = \frac{f_g - f_g^U}{S_g - S_g^U} = \frac{1}{u}\frac{u_g - u_g^U}{S_g - S_g^U} \quad (16)$$

$$u_g = u v_s (S_g - S_g^U) + u_g^U \quad (17)$$

The population balance in equation (15) was rewritten in new coordinate and chain rule was applied to obtain equation (18).

$$u v_s \frac{d}{d\theta}(S_g n_D) - \frac{d}{d\theta}(u_g n_D) = \frac{\varphi}{n_{max}} S_g (r_g - r_c) \quad (18)$$

By Substituting u_g (equation (17)) in equation (18) and rearrangement the following equation was obtained.

$$\frac{d}{d\theta}\left(u v_s \left(S_g^u n_D\right)\right) - \frac{d}{d\theta}\left(u_g^u n_D\right) = \frac{\varphi}{n_{max}} S_g (r_g - r_c) \quad (19)$$

or equally

$$\frac{d}{d\theta}\left[n_D u \left(v_s S_g^u - \frac{u_g^U}{u}\right)\right] = \frac{\varphi}{n_{max}} S_g (r_g - r_c) \quad (20)$$

By utilizing S_w instead of S_g the following equation was obtained

$$\frac{d}{d\theta}\left[n_D u \left(v_s 1 - S_w^U\right) - 1 + f_w^U\right] = \frac{\varphi}{n_{max}} S_g (r_g - r_c) \quad (21)$$

By rearranging equation (21), we have:

$$\frac{dn_D}{d\theta} = \frac{\varphi}{n_{max} u\left[\left(1 - S_w^U\right) - 1 + f_w^U\right]}(1 - S_w)(r_g - r_c) \quad (22)$$

As a conclusion for this section, there are two equations (14) and (22) to determine water saturation and foam texture within the front zone, respectively.

3. Result and Discussion

A various number of studies have been conducted about population-balance foam modeling in thecase of no gas initially present [9,11,12,13]. According to our model, considering no gas in front of foam, i.e., injection of gas into a fully saturated surfactant solution porous media, the initial state I would be $S_w = 1$ and $f_w = 1$. Substituting the initial state in equation (7) results in following equation;

$$v_s = \frac{f_w^U - 1}{S_w^U - 1} \quad (23)$$

By substituting equation (23) in (21), the left side of becomes zero, therefore, the right side also should be zero. In the right side because the φ and S_g are not zero within the front zone so (r_g - r_c) should be zero. Therefore $r_g = r_c$ within the front zone, it means that local equilibrium condition exists through the front zone. In the physical point of view, this outcome is consistent with the physical concept of fluid flow in porous media because the gas moves at the same speed of front moves in the absence of gas in original zone. This cannot be conceivable unless the total number of generated bubbles becomes equal to the total number of destroyed bubbles in the front and the net value be zero.

In SAG foam injection, the similar situation exists, because there is no foam behind the front zone and there is no gas ahead of it. So, these results prove that the foam in front zone moves at local equilibrium.

4. Conclusion

In order to simulate foam flooding the population balance model is used in simulator software in which local equilibrium condition has been applied to it. Therefore for calculating model's parameters, the local equilibrium condition should be considered in experiments. Although in steady state there is no doubt for local equilibrium condition and we can consider everywhere under equilibrium condition, in this study we focused on unsteady state experiment. The basic model for the unsteady state has been developed and related equations have been derived. The derivation showed that there is equilibrium condition (zero net bubble generation) within the front zone of flooding. Accordingly, it was proven that unsteady state experimental data can be utilized to determine model parameters of simulation software. In another word instead of steady state experiment which is time-consuming, the unsteady state experiment can be conducted to obtain model's parameters.Performing the both steady state and unsteady state foam flooding and comparing the results of foam quality and apparent viscosity can be an appropriate recommendation for future studies. Also, comparison studies on foam fronts behavior under unsteady state condition, utilizing the population balance models, can bring the opportunity for future studies.

5. Nomenclature

f	Foam Quality	λ	Mobility
$\mathbf{V_g}$	Gas volume	v	shock velocity of flow
$\mathbf{V_l}$	Liquid volume	u	velocity
K_{rg}^{f}	Foam relative permeability	n_f	Foam texture
FM	Mobility Factor	n_{max}	Max. foam texture
S_w	Water saturation	n_D	Dimensionless foam texture
S_g	Gas saturation	r_g	Foam generation rate
φ	Porosity	r_c	Foam coalescence rate
f_w	Water fractional flow	P_c	Capillary pressure

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