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Foam Modeling Approaches in Enhanced Oil Recovery: A Review

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Abstract

Background/Objectives: Nowadays, gas injection is one of a convenient method to increase oil recovery. The drawbacks of gas injection have been solved, to some extent, via introducing the foam assisted process. In order to accomplish an advantageous foam flooding a suitable model for foam is required to be able to predict the foam behavior appropriately. **Analysis:** This paper describes the basic concept of foam as well as different foam model approaches for foam assisted process in Enhanced Oil Recovery. In addition, pros and cons of each approach has been tabulated and discussed. **Finding:** We able to provide the advantages and disadvantages of each modeling approach as well as those parameters which have a significant effect on each model. The result depicted that, the best way to simulate the foam flooding in the commercial simulator is the Empirical approach. However, this model is not able to predict the behavior of foam in unsteady state properly. **Novelty:** The lack of a brief and informative study about basic of foam modeling approaches is the motivation of this study. Accordingly, this study presents the general overview in foam models which has been developed in the past three decades.

Keywords: Empirical Approach, Foam Flooding, Foam Modeling, Gas Mobility Reduction, Mechanistic Approach

1. Introduction

Foam is defined as dispersed gas phase in liquid phase[1]. The concept of foam assisted process has been introduced at 1958 for the first time[2]. At that time, only the application of foam in gas drive mechanism has been investigated. The main phenomena which has been focused for foam flooding was mobility control of gas injection process. In despite of introducing other applications for foam in oil industry such as matrix acidizing treatment[3–5], contaminated aquifer remediation[6,7] and gas blockage[8,9], still the prominent implementation of foam is Enhanced Oil Recovery. The injection of a material that is not initially existed in the reservoir to increase the oil recovery is called Enhanced Oil Recovery (EOR)[10]. The gas injection process is one of the common method to increase oil recovery especially in carbonate reservoir however the low sweep efficiency due to high mobility as well low density of gas phase is considered as drawback of gas injection. In order to overcome this draw of gas injection several methods has been introduced such as Water Alternating Gas (WAG), Simultaneous Water And Gas injection (SWAG)[11,12]. Although these mechanisms shows the better performance compare to gas injection due to mobility control, foam assisted process leads to higher recovery compare to these methods[13].

Foam assisted processes are implemented in four different ways: (1) pre-generated foam injection which foam is generated on the surface and then inject into the reservoir. (2) Surfactant Alternating Gas (SAG) which the surfactant solution slug follows by gas slug and when gas meet the surfactant phase the foam will be generated inside the reservoir[14]. (3) According to recently studies[15], some surfactant can be dissolved in

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supercritical CO_2, therefore injecting this solution under the special circumstances leads to foam generation inside the reservoir. (4) Both gas phase and surfactant solution can be injected simultaneously but in different layers to generate the foam through the reservoir[16].

2. Basics of Foam

Foam is not thermodynamically stable therefore; it is not considered as one phase. The thin liquid layer which separate the gas bubbles is called "lamella"[17]. The force which is required to sustain the lamella is called "disjoining pressure". The disjoining pressure is the combination of three forces: van der Waals force, adsorption and protrusion and/or hydration forces. The number of lamella per unit area is known as "foam texture" and is shown by "f_g". Although this parameter plays the main role in foam characterization, there is no direct method to measure foam texture inside porous media during the displacement process. Therefore, the pressure gradient is utilized to characterize the foam in porous media. Generally, the foams are categorized in two groups: weak foam and strong foam. In weak foam the foam texture is low, in other word, the weak foam has coarse texture and leads to low pressure gradient. On the other hand, the strong has high foam texture i.e. it has fine texture and leads to high pressure gradient. Figure 1 illustrates types of foams.

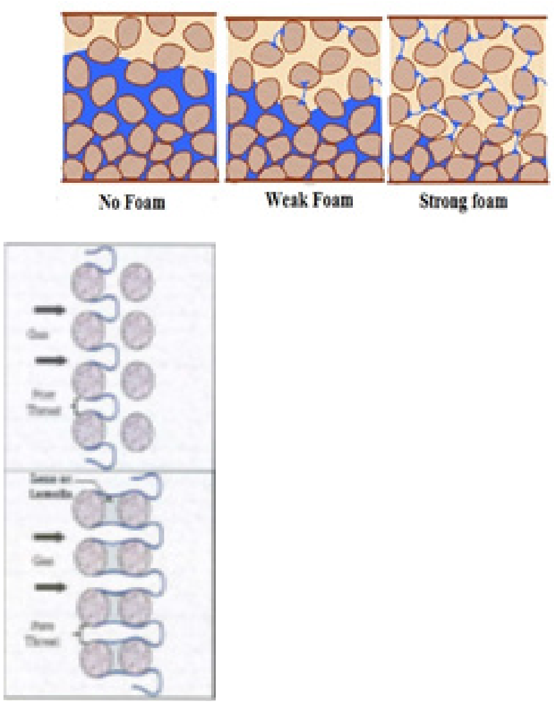
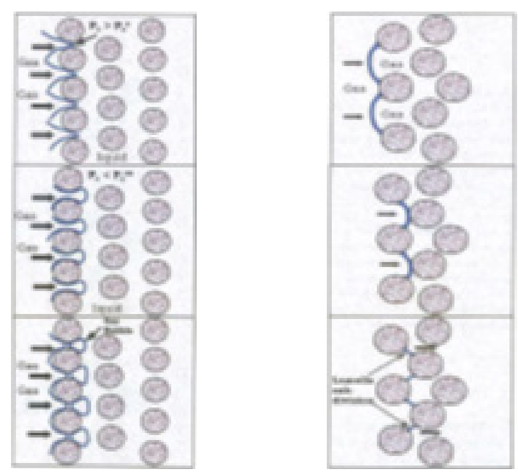


Figure 1. Types of foam textures[18].

The "foam quality" is defined as the ratio of gas volume over total volume which normally is shown by "". This parameter also is an indicator to characterize the foam, the high foam quality and low foam quality. The foam quality corresponding to maximum value of pressure gradient is called "transition foam quality" (f_g) which is depend on surfactant type, surfactant concentration, rock type and permeability.

The mechanisms of foam generation are categorized in three; first, leave behind, in which lamella deserted behind during the invasion of gas into surfactant solution i.e. drainage process, second, snapped-off, in which the driving force of gas on interface of gas-liquid leads to bubble generation, also the capillary fluctuation cause the bubble generation, third, lamella division, in which the preexisting bubbles are divided into many at pore junction due to pressure gradient[18]. These three different mechanisms are shown in Figure 2.



1.1.1.1 Leave behind 1.1.1.2 Snapped-off 1.1.1.3 Lamella Division

Figure 2. Mechanisms of foam generation[14].

As mentioned before foam is not thermodynamically stable, hence the lamella is unstable. The lamella coalescence leads to destruction of the foam. This coalescence of lamella is the consequence of changing the surface free energy by alternating interfacial area between immiscible phases[19]. As it was mentioned before disjoining pressure sustain the lamella and whenever this pressure reach to maximum value the lamella will ruin. This maximum value for disjoining pressure is related to a capillary pressure which is called "limiting capillary pressure" *(p_c*)*.

3. Foam Modeling through Porous Media

In order to model the foam through porous media many different models have been developed during past three decades. Generally, three different modeling approaches have been describe in literature: Empirical models, Semi-empirical models and Mechanistic models[18]. In another categorization, modeling approaches have been divided in two main groups: Local equilibrium models and Population balance models[20]. The main aim of all models is to reduce gas mobility in presence of foam. Therefore, all models focus on reduction of gas mobility whether by modifying the relative permeability of gas or gas viscosity or both. In all models the relative permeability of water phase was considered as constant. In other word, the water permeability does not changed in the presence of foam[21,22]. Furthermore, the proper foam model should be able to model the gas mobility reduction, the non-Newtonian behavior of foam, changing the foam behavior by surfactant concentration changing and surfactant flow (adsorption phenomena)[23]. The last part of foam model, the surfactant flow needs additional material balance and diffusivity equation[24], hence, it is out of the scope of this study. In the following sections the different foam model approaches has been explained in details. In this study, the first categorization has been followed.

3.1 Emprical Approch

This kind of approach was developed only based on reduction factor of mobility of gas phase. These models do not directly include the foam texture in the calculation, only based on observed data and effective parameters were developed. All of these models have been developed based on the local equilibrium's concept for foam, i.e. the number of generated foam is equal to the number of destructed foam since there are two factors which can modify the mobility (relative permeability and viscosity of foam phase), two different types of empirical model have been developed: relative permeability modifier, viscosity modifier. The first model for viscosity modifier utilizes the gas velocity, water saturation and surfactant concentration to modify the viscosity of gas in the presence of foam[25]:

$$\mu_g^f = \mu_g\left[1 + RC_s(S_w - S_{wc})f(u_g)\right] \quad (1)$$

where, is constant and normally considered as 0.01. This model was modified by [26] and the new function for surfactant concentration, pressure gradient and oil saturation have been included in this model.

$$\mu_g^f = \frac{\mu_g[1 + Df_c(C_s)(S_w - S_{wc})f_k(k) + f_p(\nabla p)]}{1 + ES_o^2} \quad (2)$$

The first model which considered the modification on both relative permeability and viscosity was developed by Chang and co-workers [27]. In this model the total mobility has been modified in the presence of foam, this model includes interstitial gas velocity (), fractional flow of gas (), surfactant concentration () and phase saturations (oil and water).

$$\frac{kk_{rg}^f}{\mu_g^f} = (k_1 f_g + k_2 u_g^n)[1 + k_3 C_s(S_w - S_{wr})][1 + k_4(S_o - S_{or})] \quad (3)$$

where, K values are fitting parameters and should be determined using experimental data.

Many empirical models have been developed to modify the relative permeability of gas in presence of foam. However, the common models have been reviewed in this study[28], for the first time introduced the new model to only reduce the gas relative permeability which includes the surfactant concentration and pressure gradient as shown in Equation 4.

$$\begin{cases} FM = \left[1 + \dfrac{\nabla p_{foam}}{\nabla p_{nofoam}}\left(\dfrac{C_s}{C_s^{max}}\right)^{e_s}\right]^{-1} \\ k_{rg}^f = k_{rg} \times FM \end{cases} \quad (4)$$

This model has been utilized in reservoir simulator (STARS) at that time. This model has been modified and improved and utilized in different reservoir simulators:

$$\begin{cases} FM = [1 + fmmob . f_w \cdot f_s \cdot f_o \cdot f_c \cdot f_{salinity}]^{-1} \\ k_{rg}^f = k_{rg} \times FM \end{cases} \quad (5)$$

This model includes the pressure gradient function (f_{mmob}), dry out function (f_w), surfactant concentration function (f_s), oil saturation function (f_o), capillary number function (f_c) and salinity function ($f_{salinity}$)[29]. Therefore, to employ these model there are many parameters to be determined, consequently, required many experiments to be conducted. These models are not able to predict unsteady state foam data especially for surfactant alternating gas which is unsteady. The reason is that these models have been developed biased on the local equilibrium concept.

3.2 Semi-emprical Approach

This model's approach also follows the local equilibrium concept for foam same as empirical approach. These models consider the bubble generation and destruction, however put them equal due to local equilibrium concept. One of the well-known models has been developed[30] and modified by others[14,31]" to reach the following equation:

$$\begin{cases} r_g = C_g S_w (\nabla P)^a \\ r_c = C_c n_f \left(\dfrac{1}{S_w + S_w^*}\right)^b \\ n_f = \left(\dfrac{C_g}{C_c}\right)(S_w - S_w^*)^b S_w (\nabla P)^a \\ q_f = \dfrac{k k_{rf}^0 \nabla P}{\mu_f} \\ \mu_f = \mu_g + \dfrac{C_f n_f}{q_f^{1/3}} \end{cases} \quad (6)$$

In this model the rate of bubble generation (r_g) was put equal to bubble destruction rate (r_c) so the foam texture (n_f) can be calculated. In this model are model parameters which should be determined by conducting experiments. Moreover, the concept of critical water saturation (S_w*), water saturation, below that the foam will be collapsed, has been employed in this model. Substituting the in viscosity formula gives foam viscosity, eventually, by performing the try and error procedure and substituting the foam viscosity in Darcy equation the flow rate of foam can be calculated. This model only modified the viscosity. Although these models appropriately fit to steady state foam data, they are weak in fitting the unsteady state behavior of foam flooding.

3.3 Mechanistic Approach

The models which have been developed based on mechanistic approach relied on the foam flow in physical point of view, also they include the foam texture. This approach was categorized in three sub groups' approaches; the first one is population balance approach, second is an approach based on catastrophic theory and third is the percolation approach.

3.3.1 Population Balance Approach

This model considers the bubble as a phase for transporting through the porous media, hence it includes the conservation equation, which has been written for foam bubble. The foam texture () is appropriate index for foam bubble, therefore it has been utilized to write the conservation equations and after that to modify the relative permeability of the gas. In [32] developed the first model based on this approach, after that many studies have been conducted on this approach, however, in the most recently studies [33, 34], the below conservation equation was followed:

$$\begin{cases} \dfrac{\partial}{\partial x}\left[\emptyset(S_{gf} n_f + S_{gt} n_t)\right] + \nabla.\left(u_g n_f\right) = \emptyset S_g \left(R_g - R_c\right) + Q_b \\ S_g = S_{gt} + S_{gf} = X_t S_g + X_f S_g \end{cases} \quad (7)$$

In this model the gas saturation (S_g) is divided to two part; trapped gas due to foam (S_{gt}) and flowing gas saturation (S_{gf}). Also, the foam texture for flowing foam (n_f) and trapped foam (n_t) has been considered in this model. The rate of foam generation and foam destruction shows by R_g and R_c, respectively.

In order to drive foam generation and destruction rate several models have been developed[23,33–37]. The model which was developed, was shown in the following equation[37];

$$\begin{cases} R_g = k_1 u_g^m \\ R_c = k_{-1} u_g^n n_f \end{cases} \quad (8)$$

where, k_1 and k_{-1} are constant coefficient and and are fitting parameters of model. Also the relative permeability and viscosity of foam are calculated from equation 9.

$$\begin{cases} k_{rg}^f = k_{rg}^0 \left(\dfrac{X_f S_g}{1 - S_{wc}}\right)^g \\ \mu_g^f = \mu_g + \dfrac{\alpha n_f}{u_f^c} \end{cases} \quad (9)$$

These kinds of models also called full-physic version of mechanistic models. These models are able to predict the unsteady state foam as well as steady state foam behavior. The difficulty in finding models parameters are disadvantages of these models. Moreover, these models need more calculation in their application because the conservation equation for foam texture also should be solved.

3.3.2 Catastrophic Theory Approach

Several studies have been conducted on foam's rheology in porous media[14,38,39] which is often referred to as surfactant-alternating-gas (SAG. All these studies have revealed that there is a suddenly change in foam's behavior in the certain water saturation. This dramatically change phenomena is called "catastrophic phenomena", this leads to mathematical singularity in the foam behavior. Some mechanistic approaches have considered this phenomena in their foam destruction rate models, the recently model which has been developed, was shown as following equation [14].

$$\begin{cases} R_g = \frac{C_g}{2}\left[erf\left(\frac{\nabla p - \nabla p_0}{\sqrt{2}}\right) - erf\left(\frac{-\nabla p_0}{\sqrt{2}}\right)\right] \\ \begin{cases} R_c = C_c n_f \left(\frac{1}{S_w - S_w^*}\right)^n \text{ if } S_w < S_w^* \\ R_c = C_c n_f \left(\frac{S_w}{S_w - S_w^*}\right)^n \text{ if } S_w > S_w^* \end{cases} \end{cases} \quad (10)$$

In this model the critical capillary pressure was considered in the form of corresponding critical water saturation which below that foam will be destructed. These types of models same as rest mechanistic models need many calculations hence they are time consuming. Theme models can be an appropriate alternative for the empirical models which were developed based on fractional flow theory because these models are able to predict the behavior of foam in unsteady state condition and near the critical water saturation.

3.3.3 Percolation Approach

This approach also can be considered as a mechanistic approach because it focuses on physical modeling of fluid flow in porous media. In this approach, the porous media are considered as a bunch of capillary tubes as pore throat and pores. The percolation approach is utilized to simulate the foam process at the scale of the network of throats and pores in porous media due to its ability to quantify connection of volumes, areas or line segment[40]. Therefore, the ability of this approach to quantify the heterogeneity of porous media is one of the advantages of this approach. This approach can be utilized for foam studies to recognize the spatial distribution's effect on foam generation and destruction. For instance, this approach was employed in the studies to find out there is the minimum value of pressure gradient to mobilize the foam lamella[41]. Moreover, some theoretical models have been developed on the role of formation permeability on foam mobility[35]. Although some parameters which are difficult to be obtained in other mechanistic approaches can be derived by this approach[42], the main drawback of using this approach for foam modeling is the large computational time and cost of this model[43].

4. Conclusion Recommendations for Future Research

In order to model foam flow through porous media, three different approaches exist; Empirical, Semi-empirical and Mechanistic. In the empirical approach to derive gas mobility, the foam texture hasn't directly affect it but

Table 1. Summary of approaches

	Number of model parameters to be determined	Difficulty of method for determining model parameters	Accuracy to fit experimental data	Time consumption for simulation	Commercial simulator software
Empirical Approach	large number of model's parameter should be determined	easy	good fit for steady state experiment but weak for unsteady state	short time	widely used
Semi-Empirical Approach	large number of model's parameter should be determined	difficult	good fit for steady state experiment but weak for unsteady state	short time	not used
Mechanistic Approach	few number of model's parameter should be determined	difficult	good fit for both steady and unsteady state experiment	long time	rarely used

the gas mobility can be a function of flow rate and surfactant concentration. In semi-empirical approach, the foam transport is expressed like mechanistic approach, however, to simplify this approach some assumptions are considered. The modeling of the fractional flow curve, in the presence of foam, is the goal of this approach. Mechanistic approaches can be complete in principle, but it may be difficult to obtain reliable parameters whereas empirical and semi-empirical approaches can be limited by the detail used to describe foam rheology and mobility. In the general point of view, the selection of foam model's approach depends on several factors. Since each approach has advantages and disadvantages, an appropriate approach could be chosen for foam process modeling. These features were summarized in Table 1.

As a recommendation for future study, a new model is required to be developed to combine the mechanistic and empirical approaches. This model should be able to fit both steady state and unsteady state foam flooding, using fewer model parameters. Moreover, this model should be able to illustrate the catastrophic phenomena in foam flooding, when the water saturation reach to the critical value.

5. Nomenclature

μ_g^f	Foam viscosity	∇p	Pressure gradient
μ_g	Gas viscosity	S_o^*	Critical water saturation
C_s	Surfactant concentration	S_o	Oil saturation
S_w	Water saturation	S_{or}	Residual oil saturation
S_{wc}	Initial water saturation	k_{rg}^f	Foam relative permeability
U_g	Gas velocity	k_{rg}	Gas relative permeability
f_g	Foam quality	P_c^*	Critical capillary pressure

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