FOAM DYNAMICS IN POROUS MEDIA AND ITS APPLICATIONS IN ENHANCED OIL RECOVERY: REVIEW

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ABSTRACT

The usage of foam in enhanced oil recovery (EOR) is either to reduce the gas/oil ratio in production wells or to control gas mobility in water-alternating-gas injection. Any project of foam injection needs laboratory experiments and simulation studies to optimize factors affecting foam behavior at the target reservoir. The study presents characteristics of foam dynamics in porous media, and a comprehensive review for the factors should be considered in planning for foam injection projects. Lessons learnt from field applications of foam in EOR have been presented. Mathematical modelling of foam in porous media is not the objective of this study and it has not been included. The present study is a useful reference for engineers and scientists interested in foam flow in porous media, and it provides a background for the laboratory research of foam injection projects.

Keywords: *Enhanced oil recovery; Flow in porous media; Foam dynamics*

1. INTRODUCTION

Foam has been extensively used in improved and enhanced oil recovery processes in the petroleum industry over decades (Mayberry et al., 2008). There are two uses for foam in the process of oil recovery. The first one is to control gas mobility in depth of oil reservoirs. In the applications of gas injection or water-alternating-gas (WAG) injection techniques, the high mobility and low density of the gas lead the gas to flow in channels through the high permeability zones of the reservoir and to rise to the top of the reservoir by gravity segregation. As a result, the sweep efficiency decreases and the residual oil in the reservoir will be more. Foam has been used to control the gas mobility and improving the sweep efficiency by increasing the effective viscosity and decreasing the relative permeability of the gas. The second use of foam is for gas shut off to reduce the gas/oil ratio (GOR) at the production wells.

Design of the foam injection project requires comprehensive laboratory experiments and reservoir simulation studies. The operating parameters that should be investigated by laboratory experiments are; formulation and concentration of surfactant, pressure gradient required for stable foam flow, and injection strategy either pre-prepared foam before injection, or co-injection of surfactant solution and gas, or surfactant solution-alternating-gas (SAG) injection. The reservoir simulation studies should be used to optimize locations of the injection wells, injection pressure, volumes of gas and surfactant solution, and number of cycles and period of each cycle if the SAG injection is the selected option.

The study presents characteristics of foam dynamics; mechanisms of generating, stability, and flow regimes of foam in porous media. Factors affecting dynamics of foam in porous media have been reviewed comprehensively and summarized. Problems and lessons from field applications of foam in EOR have been presented.

2. CHARACTERISTICS OF FOAM DYNAMICS IN POROUS MEDIA

Foam is a mix of gas, water and a foamer, and consists of liquid films/lamellae and Plateau borders (Schramm and Wassmuth, 1994; Vikingstad, 2006). A plateau border is the connection point of three lamellae, at an angle of 120° (Figure 1). Foam is a special case of two-phase (gas-liquid) flow. For gas-liquid flow in porous media without foam, the gas phase resides in the center of the large pores occupying the main paths of flow, while the liquid phase fills the small pores and coats walls of the large pores. Existence of foam affects this diffusivity mechanism. The gas phase in foam will be trapped by films of the liquid lamellae. As a result the gas velocity decreases and gas and liquid phases will move together at the same velocity if a case of stable foam has been achieved. This section briefs mechanisms of generating, stability, and flow regimes of foam in porous media.

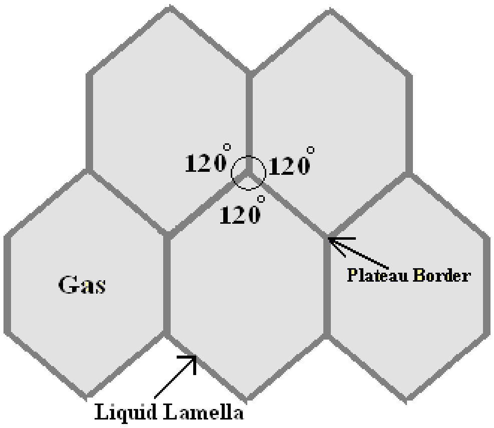

Figure 1. Sketch of a foam system

2.1. Generation of foam in porous media

Ransohoff and Radke (1988) observed three mechanisms lead to foam generation in porous media; snap-off, leave-behind, and lamella division. Figure 2 shows these mechanisms.

2.1.1. Snap-off mechanism

Roof (1970) showed that when oil emerges from a water-wet constriction into a water-filled pore, the interfacial forces are such that a leading portion of the oil may separate into a droplet (snap off). The same mechanism occurs during invasion of gas to pores filled with liquid. It takes place regardless of the presence or absence of surfactant, but if a stabilizing surfactant is not present, snapped off bubbles quickly coalesce (Kovscek and Radke, 1993). The snap-off process is a result of the difference in the capillary pressure between the pore body and pore throat. Thus occurrence of the process is a function of ratio of the body-to-throat equivalent diameters. Kovscek and Radke (1993), and Li (2006) presented details of the snap-off process.

2.1.2. Leave-behind mechanism

The leave behind mechanism also occurs during invasion of a gas phase to a porous medium saturated with a liquid phase. Foams generated solely by leave-behind give approximately a five-fold reduction in steady-state gas permeability (Ransohoff and Radke, 1988; Kovscek and Radke, 1993), whereas discontinuous-gas foam created by snap-off resulted in a several-hundred fold reduction in gas mobility (Persoff et al., 1991; Ettinger and Radke, 1992; Kovscek and Radke, 1993). This indicates that the strength of foam (i.e. number and stability of lamellae) is affected by the dominant mechanism of foam generation.

2.1.3. Lamella division mechanism

Increasing number of lamellae or bubbles by lamella division mechanism can be existed when mobile foam bubbles are pre-existed in the porous medium. When a moving lamella train encounters a branch in the flow path, it may split into two, one in each branch of the path (Tanzil et al., 2002). Lamella division is thought to be the primary foam-generation mechanism in steady gas-liquid flow (Gauglitz et al., 2002; Li, 2006).

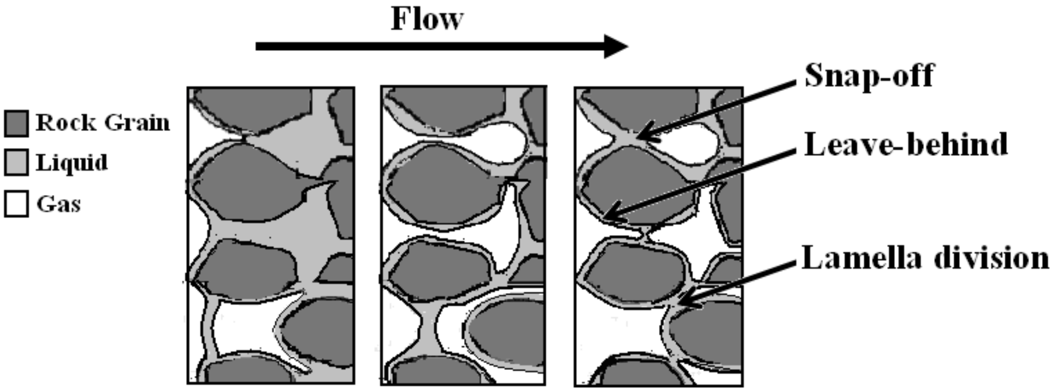

Figure 2. Mechanisms of foam generation in porous media

2.2. Stability of foam in porous media

Foam in porous media can be in a stable state at a certain value of the capillary pressure, called the limiting capillary pressure (Pc*) (Khatib et al., 1988). The limiting capillary pressure is a function of the surfactant formulation and concentration, gas velocity, permeability of the porous medium, and presence of oil. The corresponding liquid saturation of (P_c^*) is (S_w^*).

2.3. Flow regimes of foam in porous media

Osterloh and Jante (1992) showed that two flow regimes of foam in porous media can be identified; high-quality (dry) regime in which steady-state pressure gradient is independent of gas flow rate and low quality (wet) regime in which pressure gradient is independent of liquid flow rate. The transition zone between the two regimes was characterized by a specific value of gas fractional flow (gas velocity divided by total velocity) (fg*). Alvarez et al. (1999) confirmed conclusions of Osterloh and Jante (1992) and showed that this behavior of foam flow is general by using data of foam flow with a variety of porous media and surfactant formulations, over a range of flow rates. There is a critical pressure gradient that must be exceeded to generate a high-quality regime of foam during the flow of surfactant solution and gas through homogeneous porous media (Li et al., 2008). Figure 3 shows a schematic plot of parameters of the foam flow in porous media.

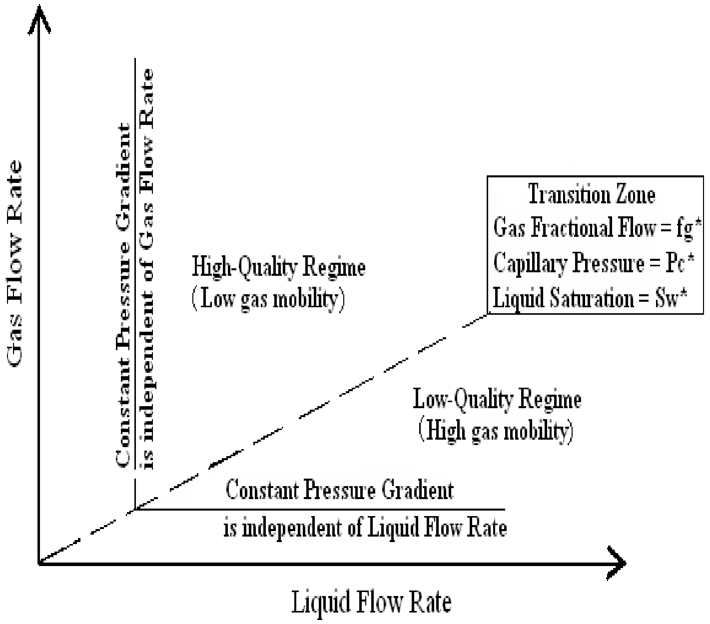

Figure 3. Schematic plot of parameters of the foam flow in porous media

3. FACTORS AFFECTING FOAM DYNAMICS IN POROUS MEDIA

Experimental studies that investigated factors affecting foam dynamics in porous media have been reviewed and their important conclusions have been highlighted. The studies investigated different types of surfactant (anionic, nonionic, cationic, and amphoteric surfactants) with types of porous media consisted of steel wool packs, sand packs, crush cores, and sandstone and carbonate cores. The used methodologies included static and flow tests (pre-prepared foam injection, co-injection of surfactant solution and gas, and SAG injection) at conditions ranged from room to reservoir conditions and in absence and presence of oil. The progress of foam front was monitored by measuring of the differential pressure. To identify the liquid saturation and propagation of foam in porous media, some studies used X-ray computed tomography e.g. Apaydin and Kovscek (2000) and Nguyen (2004), or Gama ray e.g. Persoff et al. (1991). The investigated factors include; surfactant, injection parameters, permeability and heterogeneity of porous media, and presence of oil.

3.1. Surfactant

The surfactant has an important role in generation and stability of the foam in porous media. It affects the interfacial forces between the gas and liquid which in turn affects value of Pc^*. The proper surfactant should have the following properties: be capable of generating ample, lasting foam at the reservoir conditions, should have low adsorption and decomposition losses, should increase the sweep efficiency and the oil recovery, in addition it should be commercially available and inexpensive (Casteel and Djabbarah, 1988). Foam is readily formed during a drainage process (displacing the liquid phase by the gas phase) whenever the porous medium is pre-saturated with a surfactant solution (Chou, 1991). The reduction of surfactant concentration below the Critical Miscelle Concentration (CMC) caused a shift of the transition zone of the flow regimes to lower values of fg^* and Pc^* (Alvarez et al., 1999). Foam coalescence forces are inversely proportional to surfactant concentration, thus the foam weakens and the displacement efficiency decreases as the surfactant concentration decreases (Apaydin and Kovscek, 2000). Friedmann and Jensen (1986) showed that size of foam bubbles inside porous media slightly decreases with increasing of the surfactant concentration. Li (2006) found that higher velocity is required to create foam when the surfactant concentration is reduced.

Adsorption of the surfactant on the reservoir rock reduces the surfactant concentration in the injected fluid. The adsorption is a function of the surfactant formulation, reservoir fluids, reservoir lithology, and reservoir conditions (Casteel and Djabbarah, 1988). For unconsolidated sand cores at temperatures ranging from 50 ^{o}C (122 ºF) to 150 ^{o}C (302 ºF) it was found that the surfactant adsorption decreases with increasing the temperature, and increases with the presence of clays in the core (Novosad et al., 1986). Grigg and Mikhalin (2007) showed that the adsorption is a function of state of the fluid movement beside the other parameters, and the density of adsorption of the surfactant on the rock is best described as a function of the surfactant available in the system (concentration plus volume), rather than by surfactant concentration only. In experiments on carbonate cores, Liu et al. (2006) observed that the presence of gas with the surfactant solution in the rock does not affect the surfactant adsorption.

3.2. Injection parameters

3.2.1. Pre-prepared foam injection and co-injection of surfactant and gas

The injection flow rate affects foam dynamics strongly. Faster flow rate produces foam with smaller and more uniform bubble sizes, and the foam formed at the higher pressure is more stable (Friedmann and Jensen, 1986). The relationship between the gas fractional flow (also called foam quality, fg) and gas mobility is characterized by two straight lines intersecting at a critical foam quality (fg^*) (Khatib et al., 1988; Liu et al., 2006), as shown in Figure 4. At values of fg slightly below fg^*, gas mobility slightly decreases or remains constant with increasing of fg, which indicates a stable state of foam texture (high-quality regime). While at higher fg (above fg^*) the gas mobility increases with increasing of fg which indicates an unstable state of the foam texture (low-quality regime). Persoff et al. (1991) found that during the transient foam flooding, the flow characteristics vary from characteristic of free gas to that of strong, fine-textured foam. Nguyen (2004) showed that before the breakthrough the foam displaces the liquid in a piston-like manner and after the breakthrough a stage of strong secondary liquid de-saturation initiates in central portion of the porous medium and propagates towards the inlet and the outlet.

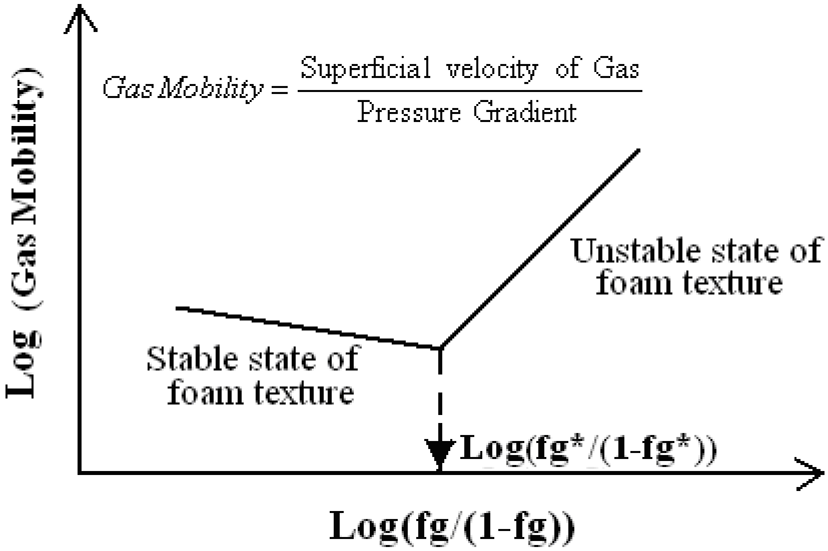

Figure 4. Schematic plot for the relationship between fg and gas mobility

3.2.2. SAG injection

Since foam is readily formed during drainage process whenever the porous medium is pre-saturated with a surfactant solution (Chou, 1991), thus SAG injection is a favorite method to create in-situ foam in porous media. (Xu, 2003) proved that the SAG injection can produce stable and persistent foam. Li et al. (2008) pointed that foam generated in situ by SAG injection can be a substitute for polymer drive in the alkaline-surfactant-polymer EOR process. Gas mobility in SAG injection is higher than that in co-injection of surfactant and gas (Li, 2006). This makes SAG injection more favorite than co-injection to overcome problem of the injectivity reduction that accompanies foam applications in EOR processes.

3.3. Permeability and heterogeneity of the porous media

The foam propagation rate in porous media is significantly affected by rock permeability (Friedmann and Jensen, 1986). The minimum pressure gradient required for triggering foam generation in steady flow through porous media varies with the permeability (Rossen et al., 2005). As permeability increases, the pressure gradient and gas velocity required for foam generation decrease (Li, 2006), and value of fg^* is much higher in the high-permeability medium (Alvarez et al., 1999). In SAG injection, gas breakthrough is much faster in a high-permeability bead-pack than in a low-permeability pack (Li, 2006). Khatib et al. (1988) concluded from their experiments on porous media with permeability range of 69.09 to 8882.31 μm^2 (70 to 9000 darcies) that Pc* decreases with increasing of the permeability, and there is a straight line relationship between Pc* and logarithm of permeability. This conclusion needs to be verified for low permeability porous media. Siddiqui et al. (1997) stated that the dependence of foam mobility on the injection parameters is different for the low-permeability porous media than that of higher-permeability porous media. (Rossen et al., 2005) showed that the relation between the minimum pressure gradient required for creating foam and permeability is more complex in consolidated media.

Casteel and Djabbarah (1988) conducted an interesting experiment to optimize oil recovery from parallel layers have different permeabilities. The result was the foam is more effective to improve oil recovery if it is conducted after the recovery by gas injection. This result agrees with findings of Apaydin et al. (1998) where they showed that in heterogeneous layers the foam fronts move at identical rates in all layers if the layers are in capillary communication and cross flow is allowable, but if the cross flow is prohibited between the layers, foam partially plugs the high permeability zone and diverts flow into the low permeability zone. Based on that, it can be concluded that the stage of using foam in EOR should be after a stage of gas flooding alone to get the maximum oil recovery. Thus foam injection must be the fourth stage of the recovery after primary recovery, water flooding, and gas flooding.

3.4. Presence of oil

For simplicity most of the experimental studies have been conducted in the absence of oil (Sayegh and Girard, 1989; Liu, 1991; Persoff et al., 1991; Apaydin et al., 1998; Schramm and Kutay, 2000; Apaydin and Kovscek, 2000; Dong, 2001; Xu, 2003; Nguyen, 2004; Xu and Rossen, 2004; Kutay and Schramm, 2004; Du et al., 2005;Kim et al., 2005; Li, 2006; Liu et al., 2006; Li et al., 2006; Li, 2008). Success without oil is a precondition to success with oil (Ashoori and Rossen, 2010). But presence of oil has important effects on foam flow in porous media. Presence of oil represents an additional phase to the gas phase and the surfactant solution phase in the porous medium. This will affect the interfacial tension between phases and the saturations of the phases in the porous medium. Nikolov et al. (1986) showed that brine concentration, and surfactant type and concentration affect directly the stability of emulsion and foam films. Oil saturation has a stronger effect on foam than the variances in properties of oil (Jensen and Friedmann, 1987), and behavior of foam to displace oil is not the same for all the surfactants (Novosad et al. 1989). Effect of the presence of oil on the propagation of foam in porous media is strongly surfactant-specific, this was confirmed by Jensen and Friedmann (1987), Novosad et al. (1989), Mannhardt et al. (1998), and Vikingstad and Aarra (2009). For instance Friedmann and Jensen (1986) found that presence of oil greater than 20% saturation is detrimental to both foam generation and to propagation of preformed foam, while with different porous medium, oil, and surfactant Vassenden et al. (2000) showed that in presence of oil even at very low saturation (5%), gas and surfactant solution were found to flow together without forming foam, and a low-mobility foam zone was found to propagate from the inlet significantly slower than the gas and surfactant fronts. This high difference in the critical oil saturation at which presence of oil be a detrimental factor for propagation and stability of foam indicates that results of experiment of the foam flooding are very restricted to the used type of porous medium, type and saturation of oil, and type and concentration of surfactant, i.e. it is difficult to develop generalized correlations for predicting performance of foam in oil reservoirs.

4. LESSONS LEARNT FROM FIELD APPLICATIONS

Important lessons can be learnt from previous field applications. From review of forty two foam applications, Turta and Singhal (1997) found that the most serious problem is the excessive reduction of injectivity. Kuehne et al. (1990) presented a study for a trial of applying of nitrogen-foam injection to reduce the gas channeling at a dual injector/producer. The trial was unsuccessful. The reasons were; (1) wrongly estimation of the injectivity led to use an injection pressure close to fracturing pressure which may caused to open new gas channels, and (2) wrongly estimation of the required foam volume to be injected. It raises here importance of selecting the proper method for foam injection to overcome problem of the low injectivity. May be the SAG injection is more suitable than co-injection of gas and surfactant that was used in this field trial.

Wong et al. (1997) described a foam treatment conducted on two production wells were experiencing increasing of gas coning and declining of oil productivity. The treatment was successful for one well while unsuccessful for the second well. The successful well was treated by preformed-foam injection. Injecting a surfactant solution alone and injecting preformed-foam were used in the unsuccessful well. For injection a surfactant solution alone in a porous medium saturated with gas does not create foam, because foam can be created by a drainage process but not by imbibition process. Fail of the preformed-foam injection is attributed to the wrongly estimation of the minimum size of foam slug required to improve the well performance significantly.

Blaker et al. (1999), Aarra and Skauge (2000), Skauge et al. (2002), and Blaker et al. (2002) presented details about the world's largest application of foam in the oil industry: Foam assisted WAG (FAWAG) project in Snorre Field/Norway. Two foam pilot projects have been conducted in this field. One project was to reduce the GOR at a production well and the second project was to control the gas mobility in depth of the reservoir by FAWAG. Both of the projects were successful to improve the oil recovery. For the project of FAWAG, the field application started after two years of planning and many years of active research (Blaker et al, 1999). The important lesson from this project is the good understanding for behavior of foam at the target reservoir conditions led to good planning and successful field application.

5. CONCLUSIONS

The study reached to the following conclusions:

1. Foam dynamics in porous media has been studied extensively and all the possible factors that affect propagation and flow of foam in porous media had been investigated.
2. The experimental studies have led to good understanding for the effects of surfactant, injection parameters, permeability and heterogeneity of the porous media, and presence of oil.
3. The foam can be generated during the drainage process and can not be generated during the imbibition process.
4. The foam strengthens as the surfactant concentration increases.
5. The minimum pressure gradient required to create foam decreases as the permeability increases.
6. Presence of oil destabilizes foam in porous media.

7. It is difficult to develop generalized correlations for predicting performance of foam in oil reservoirs.
8. Foam has been approved as a successful technology to improving EOR if there is a thorough understanding for foam behavior at the target reservoir.
9. The optimum stage to implement foam injection is after becoming gas injection alone fruitless.

6. NOMENCLATURE

fg = fractional flow of gas
k = permeability
P_c = capillary pressure
P_c^* = limiting capillary pressure
S_w = water saturation
S_w^* = water saturation corresponding to the limiting capillary pressure
φ = porosity

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