

## An Overview of the Present Stability and Performance of EOR-Foam (Gambaran Keseluruhan Kestabilan Semasa dan Prestasi EOR-Buih)

MOHAMMED FALALU HAMZA, CHANDRA MOHAN SINNATHAMBI\*, ZULKIFLI MERICAN ALJUNID MERICAN,  
HASSAN SOLEIMANI & STEPHEN KARL D.

### ABSTRACT

*Foam flooding technique, commonly known as foam assisted water alternating gas method (FAWAG) has been identified as an effective chemical enhanced oil recovery (CEOR) technique. The ability of EOR-foam to sweep oil in low permeable zones makes it important displacement fluid in the oil industry. However, extreme reservoir conditions such as temperature, pressure and salinity have detrimental effects on the stability and the overall performance of the EOR-foam. Consequently, understanding foam stability and performance under different conditions is crucial for long term oil field application. This paper discusses the current status of the EOR-foam stability, performance and challenges from laboratory studies to field application perspective. The paper also highlights the knowledge gaps which require further research for successful field application.*

*Keywords: EOR-foam; foam application; foams performance; foam stability*

### ABSTRAK

*Teknik banjir buih, biasanya dikenali sebagai kaedah air berselang-seli gas berbantu buih (FAWAG) telah dikenal pasti sebagai satu teknik pemulihan (CEOR) minyak tertingkat kimia yang berkesan. Keupayaan EOR-buih untuk menyapu minyak di zon rendah boleh telap menjadikan ia cecair anjakan penting dalam industri minyak. Walau bagaimanapun, keadaan melampau takungan seperti suhu, tekanan dan kemasinan mempunyai kesan yang memudaratkan terhadap kestabilan dan prestasi keseluruhan EOR-buih itu. Oleh yang demikian, kefahaman tentang kestabilan buih dan prestasi di bawah keadaan yang berbeza adalah penting untuk jangka masa panjang bidang aplikasi minyak. Kertas ini membincangkan status semasa kestabilan EOR-buih, prestasi serta cabaran daripada ujian makmal bidang kepada perspektif aplikasi lapangan. Kertas ini juga menyerlahkan jurang pengetahuan yang memerlukan kajian lanjut untuk aplikasi lapangan ini berjaya.*

*Kata kunci: Aplikasi buih; EOR-buih; kestabilan buih; prestasi buih*

### INTRODUCTION

Tertiary oil recovery, alternatively known as enhanced oil recovery (EOR) method was developed to further increase oil production after exhausting primary and secondary methods (Alvarado & Manrique 2010; Tunio et al. 2011; Tzimas et al. 2005). The EOR techniques involve the injection of specific fluids by any method to displace oil toward producer wells (Hou et al. 2016; Nagy et al. 2015; Shedid 2015; Verma 2015). The injected fluids promote the sweep efficiency by altering the reservoir rock/fluid or fluid/fluid phase properties (Nagy et al. 2015; Touray 2013;). Example of EOR injection techniques involve polymer flooding, surfactant flooding, alkali-surfactant-polymer flooding (ASP), steam flooding, microbial flooding and water alternating gas injection (WAG). Among these processes, water alternating gas (WAG) method has been widely recognized and successfully utilized because of its ability to tackle early gas breakthrough (Hamza et al. 2016; Nangacovié 2012; Tunio et al. 2012). However, recent technology utilizes the applications of foams to assist the WAG method and is called foam assisted water alternating

gas method (FAWAG). The FAWAG method reduces the gas mobility as well as minimizes the production of gas cap (Ahmadi et al. 2015). However, foam behaviour and stability at higher temperature and in contact with oil remain a challenge in oil field, as a result, understanding foam behaviour in oil contact under a harsh reservoir conditions (higher temperature) is important. The stability of foam could be improved by modifying the properties of foaming agents (EOR-surfactants) using either nanoparticles or polymers or sometimes the mixture of both (Shedid 2015). Nanoparticles have greater adsorption energy, which enable them to be irreversibly adsorbed to the fluid/fluid interface and increase foam stability (Worthen et al. 2014). Similarly, by incorporating viscoelastic polymers to the EOR-surfactant solution, the thermal and shear resistance of EOR-foam could also be improved, especially when attractive interactions are formed between their charges (Xue et al. 2016). In this paper, a literature survey on the stability and performance of EOR-foam has been conducted and various factors responsible for its instability have been outlined and discussed, and measures to resolve these issues are also detailed.

## EOR-FOAM

EOR-foam was first introduced by Bond and Helbrook in 1958 as a mobility control (Salehi et al. 2014). Foam is generated using EOR-surfactants (Farzaneh & Sohrabi 2013; Nezhad et al. 2013). EOR-surfactants are classified into anionic (Sodium dodecyl benzene sulfonate-  $\text{CH}_3(\text{CH}_2)_{11}\text{C}_6\text{H}_4\text{SO}_3^- \text{Na}^+$ ), nonionic (Ethyleneoxy- $\text{C}_n\text{H}_{2n+1}(\text{OCH}_2\text{CH}_2)_n\text{OH}$ ), cationic (Trimethyldodecylammoniumchloride- $\text{C}_{12}\text{H}_{25}\text{N}^+(\text{CH}_3)_3\text{Cl}^-$ ) and amphoteric (Lauramidopropyl betain- $\text{C}_{11}\text{H}_{23}\text{CONH}(\text{CH}_2)_3\text{N}^+(\text{CH}_2)\text{CH}_2\text{COO}^-$ ) (Schramm 2000). Usually, the dissolved gas in a surfactant solution forms the foam as the gas moves from lower to higher permeable regions in the porous media (Ahmadi & Sheng 2016; Shabib-Asl et al. 2014). Generally, there are two ways to generate EOR-foam, either by alternating injection of surfactant solution and gas or by simultaneous injecting gas into the lower region and surfactant solution into the upper region (Tunio et al. 2012). The application of foam in EOR has been increasingly studied and demonstrates good effect for sweep conformance and oil recovery (Kapetas et al. 2016; Talebian et al. 2015). For successful utilization of EOR-foam in oil fields, its stability is one of the fundamental requirements. The instability of EOR-foam is mainly due to decrease in the viscosity of foaming solution, precipitation and decomposition of foaming agents due to increase in temperature, diffusion of gasses through the foam film due to increase in kinetic energy, foam/oil contact (oil acts as defoamer) (Tyrode et al. 2003).

However, many additives like nanoparticles and polymers, have been reported to improve foam rheological properties and thermal stability in contact with the oil (Sun et al. 2015). The action mechanisms of nanoparticles and polymers have been explained in a separate section in this paper. Furthermore, the performance of these additives in improving foam thermal stability could be evaluated by understanding various stability coefficients which include the entering coefficient (E), spreading coefficient (S), bridging coefficient (B), lamella number (L) as well as pseudo-emulsion film. These can be predicted according to the expressions given below (Sun et al. 2015).

$$\text{Entering coefficient (E)} \quad (\gamma_{\text{gw}} + \gamma_{\text{ow}} - \gamma_{\text{og}}).$$

$$\text{Spreading coefficient (S)} \quad (\gamma_{\text{gw}} - \gamma_{\text{ow}} - \gamma_{\text{og}}).$$

$$\text{Bridging coefficient (B)} \quad (\gamma_{\text{gw}}^2 + \gamma_{\text{ow}}^2 - \gamma_{\text{og}}^2).$$

$$\text{Lamella No. (L)} \quad (0.15 \gamma_{\text{gw}} / \gamma_{\text{ow}}).$$

where  $\gamma$ : interfacial/surface tension

go = gas/oil phase

ow = oil/water phase

g/w = gas/water phase

If the value of the stability coefficient above is found to be negative, the foam is stable, otherwise is not stable. Various stability experiments from the work of different researchers are presented in Table 1. From the table, the stability criteria were used to assess the thermal stability of foam in contact with the oil.

## MECHANISMS OF EOR-FORMS GENERATION

*Snap-off mechanism* In snap-off mechanism, which is regarded as a mechanical process, it involves the formation of collars in the pore throat by the wetting phase due to the movement of gas bubbles through the pore throat (Vasshus 2016). For snap-off to occur, a capillary pressure at the throat must be greater than the capillary pressure at the front of the interface. This could only occur if the ratio of the pore throat to the pore body is 1:2.67. Figure 1 describes the snap-off mechanism in the porous body. A snap-off mechanism has been reported as the dominant mechanism of foam generation (Morin et al. 2016; Vasshus 2016).

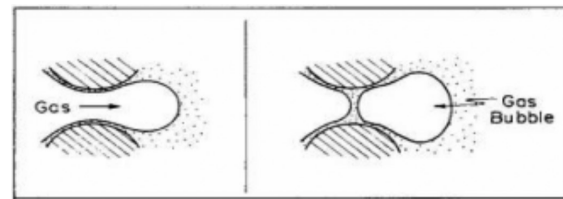


FIGURE 1. Schematic diagram of snap-off mechanism (Vanhus 2016)

TABLE 1. Below presents various laboratory foam stability test predictions

Stability criteria	Foam stability experiment	Reference
$E < 0$	Stable	Denkov et al. (2014)
$E > 0, B < 0$	Stable	Denkov et al. (2014)
$E > 0, B > 0, S > 0$	Unstable	Simjoo et al. (2013), Jones et al. (2016),
$E > 0, B > 0, S > 0$	unstable	Denkov et al. (2014)
$L < 0$	Stable	Schramm and Novosad (1990)
$1 < L < 5.5$	Intermediate	
$L > 5.5$	unstable	

**Lamella Division mechanism** Foam generation in this kind of mechanism requires pre-generated foam with bubble size larger than the pore body. A division of lamella occurs when lamella approaches the ‘branch point’ as seen in Figure 2.

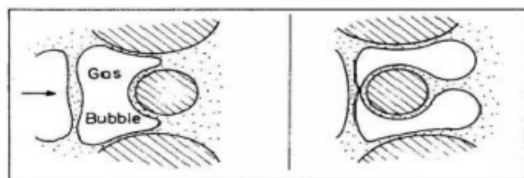


FIGURE 2. Schematic diagram of lamella division mechanism (Vanhuss 2016)

**Leave behind mechanism** Unlike snap-off and lamella division, this type of mechanism generates less stable and weaker foams, due to invasion of two or more gas fronts from different direction into a liquid saturated medium (Figure 3). These leads to generation of continuous gas bubbles which accumulate to form a parallel large number of lamellae and subsequently block the passage channels and result to dead-end pathways (Chen et al. 2004).

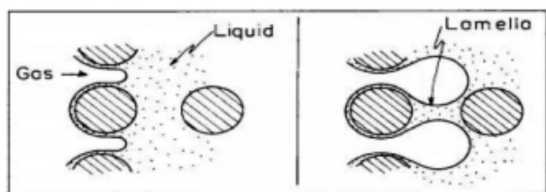


FIGURE 3. Schematic diagram of leave behind mechanism (Vanhuss 2016)

The examples of laboratory foams generated by the 3 mechanisms above using different types of foaming agents are presented in the Table 2.

## PROPERTIES OF EOR-FOAM

**EOR-foam quality** Foam quality is the percent volume of a gas in foam bubbles under certain condition of pressure and temperature. In reservoir conditions, foam quality plays an important role because of foam mobility and foam resistance factors depend directly on the foam quality (Buchgraber et al. 2012; Tyrode et al. 2003). Approximately, foam qualities can reach up to 97%, but most oilfield foams used for conformance improvement have quality typically in the range of 75 to 90% (Kalyanaraman et al. 2017). Apparent foams viscosity ( $\mu_{app}$ ) is one of the important properties that is used to assess the foam quality, which describe the relative foams stability. The  $\mu_{app}$  is usually calculated according to (1) as follows;

$$\mu_{app} = k\nabla P / (u_l + u_g), \quad (1)$$

where  $k$  is the permeability ( $m^2$ );  $u_l$  and  $u_g$  are the liquid and gas superficial velocities respectively ( $m/s$ ); and  $\nabla P$  is the pressure gradient ( $Pa/m$ ) across the whole core.

Jones et al. (2016) studied the  $\mu_{app}$  of six different foaming solutions (solution 1-6) to describe the foam quality as the parameter index for stability in the absence and presence of oil. The results are presented in Figure 4, which is a plot of  $\mu_{app}$  as a function of the foam quality. From the figure, the authors reported that the curves appearing at the left represent low foam-quality regime because of the trapping and releasing of foam bubbles which affects the  $\mu_{app}$  (which is dependent on the gas flow rate). However, at the right side of the curves, high foam-quality were observed due the foam behaviours were dominated by coalescence. They concluded that, presence of oil has less destabilizing effect on foams in the low foam-quality regime compared to the foams in the high foam-quality regime. Similar phenomena have been described in (Batôt et al. 2016; Zeng et al. 2016).

Derikvand and Riazi (2016) experimentally studied the qualities of four aqueous EOR-foams after modifying their viscosity using a cost effective polymer (carboxymethyl

TABLE 2. Laboratory generation of foams using different mechanisms

Primary mechanisms	Type of foamers used	Reference
Snap-off	polydimethylsiloxane functionalized	Morin et al. (2016)
	with polyethylene glycol	Gautepllass et al. (2015)
	Alpha olefin sulphonate	Ferno et al. (2016)
Lamella division	Sodium dodecyl sulphate	Géraud et al. (2017)
	Sodium dodecyl sulphate	Géraud et al. (2016)
	Alpha olefin sulphonate	Getrouw (2016)
Leave behind*	Sodium dodecyl benzene sulfonate and Sodium dodecyl sulfate	Ransohoff and Radke (1988)

\*Foam generation by this mechanism is not recommended because it results in the generation of weak and unstable foam, as such data from the literature are limited

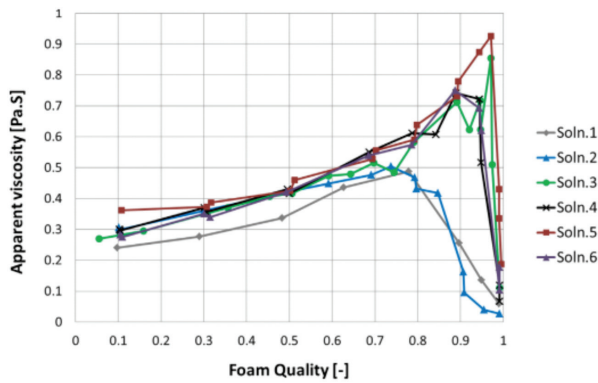


FIGURE 4. Apparent viscosity as a function of foam quality

cellulose gum). They found out that by increasing the polymer concentration, the foam viscosity increased and the foam quality was improved. Furthermore, they noticed that the foam quality is mainly dependant on the foam bubble, bubbles size, shape and viscosity of lamellae.

Similarly, Guo and Aryana (2016) determined the foam quality in terms of the foam density. Foam density is defined as the total number of bubbles formed per area. The authors noticed that, initially large number of bubbles were formed in the porous body and started to decay as a result of drainage and coalescence, thus resulting in fewer number of bubbles per area. They suggested that foam with low density reduction rate are more stable.

EOR-FOAM HALF-LIFE

Foam half-life is considered as the time taken by the generated foam to reach half of its initial volume upon decayed as described in Figure 5. It is not possible to count the number of bubbles, but the level of foam which decreases by the decadence of bubbles can be easily measured over time. In most of the EOR-foam studies, the foam half-life play important role to determine the foam quality and stability, thus, the longer the half-life the better the quality and the greater the stability.

The work of Jones et al. (2016) described the relationship between the foam half-life and IFT to measure the foam stability. They found that, foam stability assessment could not be established from the plot of foam

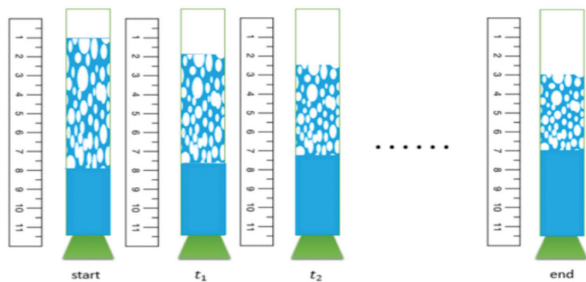


FIGURE 5. Schematic diagram to measure the foam half-life (Derikvand & Riazi 2016)

half-life against the IFT in the absence of oil. However, in the presence of oil, a clear relationship describing foam stability was observed. Their result indicated that the high IFT value between the oil and foam bubbles could prevent oil to enter the foam, thus the slower the decay rate. This conforms with the principle of the entry barrier stability coefficient (E) described in the Table 1.

Pu et al. (2017) also studied the relationship between the foaming concentration, surface tension, foam height and half-life. In their result (Figure 6), it can be observed that as the concentration of foaming agent increases, the foam height and foam half-life increased considerably, while the surface tension lowered. From the figure, it can also be observed that the IFT values are in direct relationship with the half-life value, hence this clearly supports the findings of Jones et al. (2016) above with respect to foam stability. Therefore, the plot of IFT and foam half-life could serve as a method to describe the foam quality and the stability.

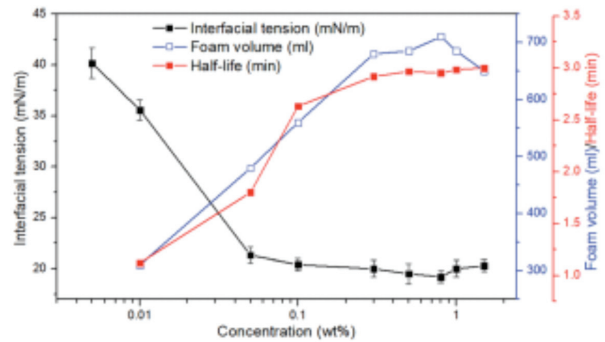


FIGURE 6. Foam volume, half-life and surface tension of CHSB at different concentrations

EOR-FOAM BUBBLE SIZE AND DISTRIBUTION

Foam bubble size and distribution constitute the foam texture, which is the main principle behind the foam mobility control. The foam with finer texture are believed to contain the smaller bubble size and has a higher resistance to flow than the bigger bubbles in the porous medium. However, dry foam with bigger bubbles in most cases have a higher viscosity than the wet foam with smaller bubbles. This statement conforms to the experimental work conducted by Osei-Bonsu et al. (2016), where the authors compared the apparent viscosities of the dry and wet EOR-foams with the bubble size. Though, the authors had pointed out that various thermodynamic parameters such as the foam generation mechanisms, bubble velocity, capillary pressure and injection rate affect the foam texture. Sun et al. (2015) has taken the research further to study the deformational stress the foam bubbles usually undergo while flowing in the porous media. The authors observed that foam bubbles generated from pure surfactant are more prone to deformation than those from the mixture of surfactant and additive as described in the Figure 7.



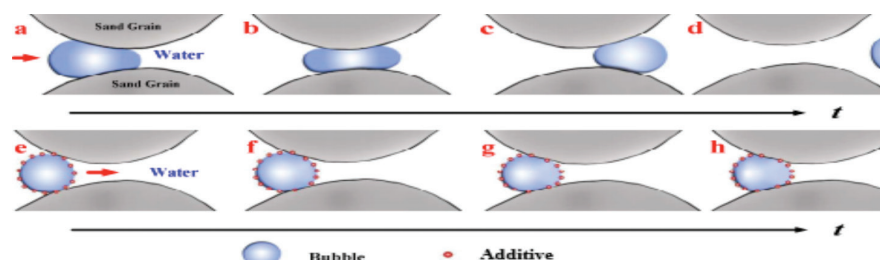


FIGURE 7. The different migration behaviors of surfactant foam (a to d) and surfactant/additive foam (e to h) in pore-throat

In addition to that, Wang et al. (2016) observed that pressure drop influenced the resistance of the bubble to deformation. That is, if the pressure drop is large, the resistance of the bubble to deformation would be stronger and the bubbles would encounter difficulties to pass between the grains.

#### EOR-FOAM STABILITY IMPROVEMENT USING ADDITIVES

In many literature reported to-date, the use of additive to improve surfactant properties and to obtain stable EOR-foam is gaining popularity. Additives such as nanoparticles and polymers are essential to obtain an efficient and successful oil recovery. They serve as promoters to provide optimal conditions with respect to temperature, pressure and salinity (Fathi & Ramirez 1984). Figure 8 typically describes an example of nanoparticles (silica nanoparticle) which has the ability to form a definite bond with the amphiphilic head of a foaming agent, thereby improving its thermal properties (Hesemann et al. 2014) as well as increase the oil recovery (Montoya et al. 2016).

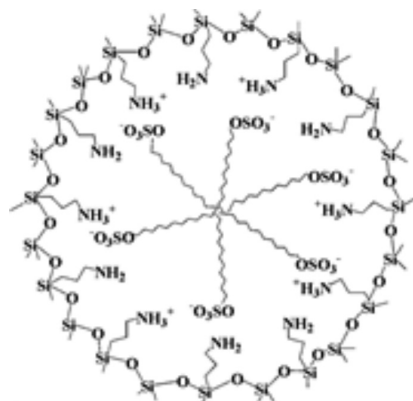


FIGURE 8. Effect of nanoparticles to improve surfactant properties

The composite of SDS/silica nanoparticles in the study of Sun et al. (2015) indicated that silica nanoparticles showed the ability to improve foams thermal stability by adsorbing at the surface of the liquid foam film.

Similarly, Al-Hadhrami and Blunt (2000) studied the effect of silica nanoparticles on wettability alteration and

concluded that silica nanoparticles were a good agent to increase the hydrocarbon recovery rate which is also in agreement with the finding of Ahmadi and Shadizadeh (2013).

Worthen et al. (2014) reported that nanoparticles have greater adsorption energy, which enable them to be irreversibly adsorbed to the fluid/fluid interface and improved EOR-foam stability, even though, their studies were only limited to a 50°C experimental condition.

The polymers usually increase the foam viscosity, thus enhancing mobility control and improving the oil sweep (Levitt et al. 2006). Similarly, polymers have greater impacts to protect foaming agents against shear stress between rock pores (Figure 9(a)-9(c)). From Figure 9(a), it can be seen that the arrangement of surfactant micelles are destabilized due to shear stress in the rock pores, hence additional time is required for them to reunite and form micelles again. However, Figure 9(b) typically describes the elasticity of the polymer after subjected to shear and stress. Meanwhile, Figure 9(c), demonstrates that polymers as additive can assist and prevent surfactant from the effect of shear and stress in rock pores and ultimately enhanced oil recovery (Zhu et al. 2013).

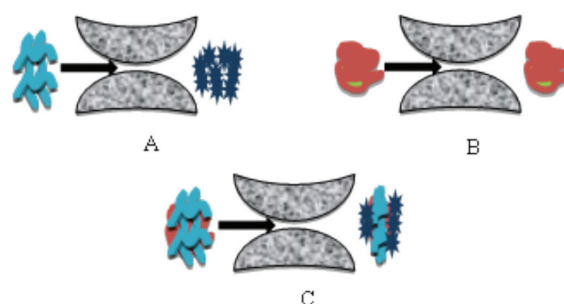


FIGURE 9. Graphical representation of the migration of surfactant (a), polymer (b) and surfactant and polymer mixture (c) through rock pores (Zhu et al. 2013)

Many core flood experiments show the benefits of adding polymers in the surfactant systems. Among the commonly employed polymers as additives include hydrolyzed polyacrylamide (HPAM), Xanthan gum and Schizophyllan (Levitt et al. 2006).

Kapetas et al. (2016) studied the effect of high temperature in a sandstone porous medium using Alpha Olefin Sulphonate (AOS) as foaming agent. The authors provided significant information of foam generation between 20-80°C. However, their findings showed that as the temperature reached 80°C in the core flood, the foams viscosity decreased by half, surface tension lowered and coalesced faster. They concluded that, with co-injection of foams, understanding foams behaviors and stability at elevated temperature is most important.

The studies of Zhao et al. (2015) provided other alternative means of maintaining foam stability up to 100°C using a polymer as additive.

Xue et al. (2016) in their investigation to stabilize EOR-foam using a hybrid composite in a water-less hydraulic fracturing fluid had found out that the composite material consists of a polymer (HPAM), a surfactant (LAPB) and silica nanoparticles had the ability to stabilize the EOR-foam.

#### UNSWEPT OIL IN THE LOW PERMEABLE RESERVOIR ZONES

Various recovery enhancements have long been identified and applied in oil industries (Fathi & Ramirez 1984). Most of the EOR processes have an increased recovery to about 30-40% or more of the original oil in place (OOIP) as compared with just 15-40% recovery through primary and secondary methods (Sakthipriya et al. 2015). Because of microscopic and macroscopic factors, about 60% of crude oil (OOIP) is left unswept in the reservoirs. The effects of wettability (rock-fluid interaction) and fluid/fluid interfacial or surface tension (IFT) attributed to microscopic factors, which resulted oil to remain in the rock pores unswept even at higher pressure (Meybodi et al. 2011). On the other hand, the macroscopic factor is due to reservoir rock permeability variations, where oil is easily displaced in high permeable regions, leaving unswept oil in the low permeable regions. Additionally, the negative capillary force in oil-wet formation is another factor of oil remaining in the rock pores unswept (Meybodi et al. 2011). To recover more oil, understanding sweep efficiencies of various fluids (foam) is crucial. Although various studies have demonstrated sweep efficiencies of some fluids yet it is difficult to maintain sweep conformance in reservoirs because of the rock heterogeneity or anisotropy. The total sweep efficiency can be improved by increasing the capillary number as well as improving the mobility ratio in any EOR processes.

#### SWEEP EFFICIENCY IMPROVEMENT

Three most important methods to improve sweep efficiency have been developed and implemented, these are: The blockage of high permeability regions using polymers; Injection of IFT reduction agents (surfactants) which is micro phenomenon; and Injection of foam.

For the blockage of high permeability regions using polymers, Murata et al. (2010) in their water flooding experiment reported that the sweep efficiency could be improved by blocking high permeable zones in the

reservoir using polymers, but found out that total sweep efficiency would be difficult to achieve because injected water apparently bypassed the blocked zones. In addition, Lalehrokh et al. (2008) observed that the crosslinking behaviour of blocking polymers was difficult to control, particularly at elevated reservoir temperature.

For the injection of IFT reducing agents, different types of EOR surfactant with respect to their compositions and concentrations have been developed and widely applied in various oil fields, however, surfactants were found to be highly sensitive to extreme reservoir conditions (temperature, pressure and salinity) and tend to be adsorbed or deposited on the reservoir rocks leading to economic loss (Fathi & Ramirez 1984).

Lastly, the foam injection was found to be more effective than the first two cases because of the apparent low foam's viscosity. Foam control gas mobility and spontaneously diverts a gas to the lower permeable zones leading to the sweep conformance and enhanced recovery (Ferno et al. 2016). Detail information on diversion of gas by foam have been reported (Casteel & Djabbarah 1988; Kovscek & Bertin 2003; Llave et al. 1990; Nguyen et al. 2005; Zerhoub et al. 1994) and its visual evidence has been provided by Guteplass et al. (2015).

#### EOR-FOAMS MOBILITY REDUCTION FACTOR

To reduce the mobility of injected gases in the porous media, strong and stable foam is required, which can be generated at high oil saturations (Memon et al. 2016). This could be achieved by mobility reduction factor (MRF). The ratio of pressure drop as a result of injecting gas and liquid simultaneously through the porous body in the absence and presence of foaming solution is called MRF (Batôt et al. 2016). The MRF has the range value of 1-10,000 which is used as a correlation of foam reduction mobility. Under the reservoir conditions, if the MRF value is greater than 1, it indicates the presence of foam in the porous body, while if it is less than 1, the foam is absent in the porous body (Sheng 2013).

Memon et al. (2016) comparatively studied the MRF of foams from pure surfactant (0.6% AOS) and surfactant blend of (0.2% AOS + 0.2% TX-100) and (0.6% AOS + 0.6% LMDO) in the three different Barea core samples. The authors found out that due to the synergistic action of the blend's component, the foam generated by the surfactant blends demonstrated good MRF than the foam from the single surfactant slug and the maximum MRF was recorded by the surfactant blend of 0.6% AOS + 0.6% LMDO. Similarly, Etminan et al. (2016) experimentally proved the possibility to generate quality foam (50% performance) using a steam gas and arylalkyl sulfonate surfactant. In Figure 10, it can be seen that the authors showed the maximum MRF could reach more than 40, which is sufficiently enough to ensure high degree of mobility control. Considering the mobility control effect of foam flooding, defining MRF with respect to different geological physicochemical properties of reservoir rocks

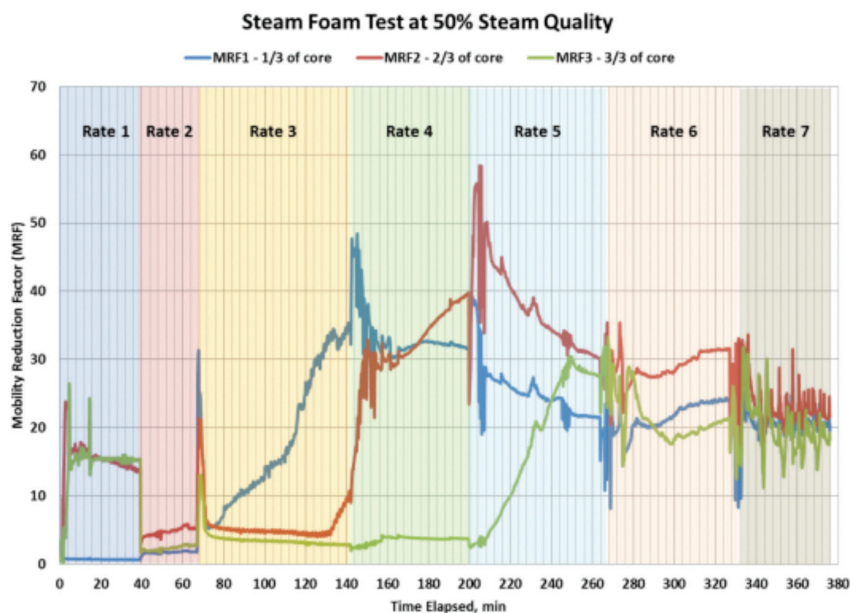


FIGURE 10. The MFR of different steam foam

is still an issue to be investigated to provide a consistent theory of MFR mechanisms in EOR.

Laboratory EOR-forms flooding (FAWAG) experiments Aghdam et al. (2013) studied the effect of EOR-foam in a water alternating gas method (WAG) and found out that injecting foams in a gas phase was more promising than in a water phase, however, the researchers noticed that, by increasing the surfactant concentration, recovery increased by a certain factor, but dropped after critical foam concentration was reached, hence suggested that for economic reasons, the critical foams concentration needs further investigations.

Tunio et al. (2012) compared the simultaneous water alternating gas (SWAG) with the FAWAG method using 2 wt. % surfactant in 30,000 ppm brine solution for an enhanced recovery study. They discovered that FAWAG increased recovery tremendously after SWAG method had reached an optimal recovery factor. They concluded that the FAWAG method could improve oil recovery if applied after any WAG method. However, from the understanding of authors of this paper, the critical concentration of foaming agents plays vital role, thus, different concentrations of foaming agents should have been thoroughly investigated to see the effects of the surfactant/brine solution at a different concentration range (not just 2 wt. % surfactant in 30,000 ppm brine solution) so as to provide reliable scientific data in the selection of a surfactant/brine solution system in any foam assisted flooding techniques.

The recovery experimental studies on different EOR techniques (water, hot water,  $N_2$ ,  $CO_2$ , associated gas and WAG ( $CO_2$ /water,  $N_2$ /water, associated gas/water and associated gas/hot water)) were conducted by Ahmadi et al. (2015). Their investigation showed that WAG (associated gas/hot water) in particular had a recovery of 88.5% heavy oil and was selected as the best method based on their

studies. Despite the fact that the FAWAG method is the most effective recovery method as reported in many open literature, yet the scope of their research did not focus on FAWAG which could have added value in their comparative studies. Furthermore, the selection of associated gas/hot water as the favored method for WAG seems not conclusive. Reason being that, if WAG (associated gas/water) and WAG ( $CO_2$ /water) methods in the same study could recover 83 and 80% heavy oils, respectively, by considering the slight differences between the two recovery values above, what would be the EOR if the WAG ( $CO_2$ /hot water) method had been further investigated? Therefore, further research is recommended to investigate the effect of  $CO_2$ /hot water and hot foams (FAWAG) in oil recovery.

The review of Shabib et al. (2014) highlighted the advantages of (FAWAG) method over other EOR methods and reported that a minimal amount of laboratory work were carried out on foam generation in heterogeneous porous media which consequently had led to lack of adequate understanding of the foaming mechanisms.

#### FIELD APPLICATION OF EOR-FOAM AND CHALLENGES

As discussed in this paper, the biggest detrimental effect to foam property is the extreme reservoir conditions which has attracted the interest of researchers within the industry and academia in putting more efforts to bringing the lasting solutions for foam instability. However, apart from this, the transition of foam flooding from laboratory to pilot and to that of field application is not clearly understood and specified. These are attributed to offshore application, economic and technical issues as well as lack of good engineering technology for EOR-foam flooding plant. However, it should be noted that despite such challenges, various field-foam application had been successfully executed in the past years. Some examples are given in

TABLE 3. EOR-foam application in the oilfield (Hou et al. 2012; Li et al. 2009; Sheng 2013)

Field name	Year of project	Challenges to overcome	Foam flooding advantage	Challenges due to foam flooding
Daqin	2012	High water cut, poor sweep efficiency and severe heterogeneity	Mobility control and blockage of high thief zones	No
Shengali Tuo11	2004	High water cut and gas override	Water cut dropped and oil production increased	No
Snorre	1996	Premature gas breakthrough	50 % reduction in GOR for 2 months	Yes: Difficult to evaluate foam performance due to geological complexity
East Mallet Unit, Texas	1994	Gas channeling and production	Reduction of gas channeling and production	Yes: (operational problem with coinjection)
East Vaccum grayburg, Mexico	1993	The reservoir pressure dropped below MMP and strange breakthrough patterns evolved	Indepth diversion of a gas	Yes: Economical (chemical and operational costs)
North Ward-Ester, Texas	1991	Vertical conformance poor sweep and low oil recovery	Diversion of CO <sub>2</sub> from thief zone to unswept region and improved oil production	No

Table 3. The arising problems/challenges that prompted the application of foam in such fields are also presented in the table.

#### CONCLUSION

This paper presented and discussed the present status, stability, performance and application of EOR-foam from the perspective of laboratory scale to field application. It analyses and recommended areas of the knowledge gaps which require further research for successful field application.

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Center of Research in Enhanced Oil Recovery (COREOR)  
Universiti Teknologi Petronas  
32610 Bandar Seri Iskandar, Perak Darul Ridzuan  
Malaysia

Fundamental and Applied Sciences Department  
Universiti Teknologi Petronas  
32610 Bandar Seri Iskandar, Perak Darul Ridzuan  
Malaysia

\*Corresponding author; email: chandram1457@gmail.com

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