

# The Effects Of Controlling Parameters On Polymer Enhanced Foam (PEF) Stability

Amin Azdarpour<sup>a,b,\*</sup>, Radzuan Junin<sup>a</sup>, Muhammad Manan<sup>a</sup>, Hossein Hamidi<sup>b</sup>, Roozbeh Rafati<sup>b</sup>

<sup>a</sup>Department of Petroleum Engineering, Faculty of Petroleum and Renewable Energy Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Malaysia

<sup>b</sup>Faculty of Chemical Engineering, Universiti Teknologi MARA (UiTM), 40450, Shah Alam, Selangor, Malaysia

\*Corresponding author: aminazh22@gmail.com

## Article history

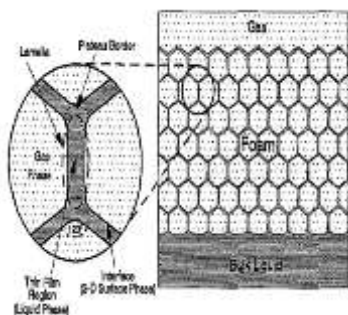
Received: 30 April 2014

Received in revised form:

11 December 2014

Accepted: 1 February 2015

## Graphical abstract



## Abstract

In the present study, four surfactants including AOS, SDS, SDBS, and TX100 were used as the foaming agent and a PHPA polymer with relatively low to high concentrations was added to the solutions prepared in both fresh water and 8 wt. % NaCl. Also, paraffin and vaseline oils with different viscosities were used to investigate the effect of oil on PEF stability. Polymer addition to foam can effectively improve foam stability compared with conventional foam stability. In addition, the polymer concentration increase could lead to foam stability increase; thus, the maximum polymer concentration in solutions could produce the most stable foam. Solutions with 8 wt. % NaCl had destabilizing effect, that is, unlike solutions with fresh water, it slightly reduced foam stability. Contacted oil in the solutions could substantially reduce foam stability. Also, the destabilizing effect was more severe with paraffin oil rather than vaseline oil. Of all the four surfactants used in this research, SDS had the highest compatibility with PHPA and produced the most stable foam, while AOS, SDBS, and finally TX100 surfactants were in next orders. In addition, microscopic photos showed that the type of solution has a significant effect on bubble size and foam stability.

**Keywords:** PHPA; Surfactant; Foam; PEF; NaCl

© 2015 Penerbit UTM Press. All rights reserved.

## 1.0 INTRODUCTION

Gas dispersion in a continuous liquid phase produces foam. This gas phase could be discontinued by a thin liquid phase called lamella [1-4]. A foam as a mobility controller mainly enhances the efficiency of EOR methods; thus foam stability could be one of the most important parameters in any foam flooding process. On the contrary of less stable foams, high stable foams lead to better sweep efficiency and oil recovery [5]. Polymers as viscous agents in EOR processes are able to increase solution viscosity and decrease displacing fluid mobility. The PHPA is a water soluble polymer in which the repulsive forces between the negative charges of its chain provide a high viscosity in water. Even adding low concentrations of PHPA can significantly increase solution viscosity [6]. Adding polymer to foam solutions improves foam stability and enhances foam performance since it improves the foam lamellae thickness and retards the lamellae drainage rate. This process is known as Polymer Enhanced Foam (PEF) during which polymer increases the lamella viscosity, and as a result stronger and more stable foams are produced in

comparison with the conventional foam [7]. Due to this feature, PHPA polymer is extensively used in EOR processes.

Sydansk [8,9] conducted one of the earliest and most comprehensive researches to find out the effects of different concentrations and types of polymers, surfactant type and concentration, foam quality, gas type, absolute pressure, rheology and the effect of shear rate on PEF process. He concluded that PEF was completely successful because the produced foam was more stable than the conventional one. Comparing the results of viscosity with and without polymer showed that PEF was more viscous than the conventional foam due to adding polymer for the mobility control. The combination of polyacrylamide polymer and AOS surfactant with different concentrations promoted solution viscosity and foam stability. Polyacrylamide polymer molecular weight (MW) positively affected foam stability so that high MW polymers produced more stable foam compared with low MW ones.

Mei et al., [10] investigated the factors affecting polymer foam stability enhancement made by partially hydrolyzed polyacrylamide polymer and AOS surfactant. According to the results, producing foam involves an AOS with the optimum

concentration of 1000 ppm, which is the Critical Micelle Concentration value (CMC). The foam stability is under the effects of polymer concentration increase. Even a small amount of polymer could positively affect the foam stability, so that the most stable foam could be produced by the highest polymer concentration, and minimum polymer addition to the solution could lead to the least stable foam. The foam stability got affection from polymer molecular weight as well, it means compared to low MW polymers, high MW polymers improve the foam stability in higher degrees.

To investigate the effects of polymer type, concentration and MW, surfactant type and concentration, as well as the effect of solution salinity on PEF performance, Zhu et al. [11] used nitrogen and sand pack as the foam generators. They found that polymer addition could exceedingly improve foam characteristics and even a small amount of polymer increased the foam stability. In their view, the higher polymer concentration and MW, the more stable foam. A considerable amount of crude oil had a negative effect on PEF performance, and its contact with oil decreased foam stability. Due to low crude viscosity, crude oil had a more critical destabilizing effect on PEF stability. AOS surfactant had a high extent of compatibility with polymer addition, resulted in a more stable foam in which the optimum surfactant concentration and its CMC value were so close to each other; in other words, values higher than CMC concentration had no significant effect on foam stability.

Foam stability enhancement is under the influence of polymer addition; however, there are other parameters playing the same role, such as type of polymer, type of surfactant, compatibility of surfactant with polymer, the presence of brine, the presence of crude oil and the viscosity of crude oil. Some researchers have investigated about the positive impact of polymer on foam stability, while the role of other parameters such as the crude oil viscosity effect in conjunction with different surfactants is still unknown. Thus, the present study expands its research scope to find out the effects of multiple parameters such as crude oil viscosity, surfactant type, as well as the presence and absence of NaCl on foam stability.

## 2.0 MATERIALS AND METHODS

### 2.1 Materials

For the purpose of this study, four different surfactants that are SDS, AOS, TX100, and SDBS were used. Also, PHPA was selected as the polymer. To prepare the solution, the fresh water and 8 wt% NaCl were used. Paraffin oil (viscosity of 1.5 cp) and vaseline oil (viscosity of 23 cp) were applied as well. Analytical CO<sub>2</sub> with 99.99% purity was used to prepare the foam solutions.

### 2.2 Foam Stability Apparatus

The standard test method for foaming characteristics of lubricating oils called as ASTM D892 [12] was used as the basis for designing the foam stability apparatus which includes a 1000 ml graduated cylinder (foam column), an HPLC pump, a CO<sub>2</sub> tank, and a solution container. The graduated cylinder is fastened to a 25.4 mm (1 in.) in diameter spherical stone gas diffuser from the bottom. To generate bubbles, the gas diffuser is made up of sintered five-micron porous stainless steel. The cylinder includes a stopper at the top with a hole in the center for CO<sub>2</sub> outlet. A cylinder with an initial pressure of 68 bar has to supply the CO<sub>2</sub>. The schematic diagram of the foam stability apparatus is shown in Figure 1.

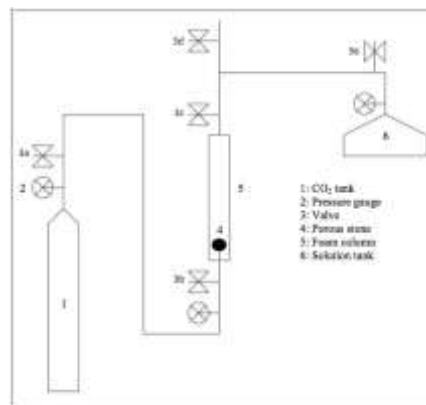


Figure 1 Schematic diagram of foam stability apparatus

### 2.3 Foam Stability Procedure

The pressure adjustment in the cell is the basis of this method. Prior to entering the cell, the gas pressure was set at two atmospheres (atm.). The valve 3a. was opened and the gas was allowed to pass through the permeable stone where it could enter the cell and generate foam in there. Through the porous stone the CO<sub>2</sub> flowed upward and based on the effectiveness of the surfactant for producing foam, the bubbles made a layer of foam. The gas was continually injected before the injection valve closure and the whole cell became full of foam. At the same time, the foam stability was measured. At the end of the experiment, the solutions were taken out of the system, the cell was washed and prepared for the next test. Here, foam stability meant the time required to drain 80% of the liquid from the foam column. This was the time the gas injection was decreased until just 20% of the initial foam was remained in the cell column [13].

### 2.4 Solution Preparation

To prepare surfactant solutions in a standard 1000 ml volumetric flask, first the surfactants were weighed on a mass basis, then they were poured into the volumetric flask, and finally the distilled water was added to complete the solution to the final weight (1 kg). After the stock solution was ready, it was diluted to the desired concentrations of 200, 500, 1000, 2000, 3000, 4000, and 5000 ppm. The polymer solutions were prepared by magnetically driven stirrer method. A magnetic stir bar was used to pour the distilled water into a beaker. The stirrer was turned on vigorously enough to generate a vortex, then lightly sprinkled polymer powders were directly put into the vortex. To avoid any mechanical degradation, the stirrer speed was decreased at the time of PHPA adding. However, stirring was continued for several hours to achieve a uniform solution. After passing the required time (depending on PHPA concentration, it would approximately be 1-4 hours), stirring was stopped and the prepared solutions were stood overnight. NaCl availability led to all the solutions preparation instead of the distilled water. Different polymer concentrations were prepared by repeating this procedure, then paraffin and vaseline oils were added to the solutions.

### 2.5 Surface Tension Measurement

The CMC value of different surfactant solutions was determined by the surface tension technique. In addition, to measure the surface tension, a Krüss tensiometer (Krüss GmbH, Hamburg,

Instrument Nr, K6) with a platinum-iridium ring was used. Prior to any measurement, the tensionmeter was calibrated by ASTM designation of D1331-98. This method involved measurement of the required force to pull the platinum ring from the surface film. CMC reading was repeated three times for each solution to minimize the errors, and then the average of these readings was calculated. During the calibration and surface tension measurements the room temperature was constantly  $25 \pm 1$  °C. Plots of surface tension and surfactant concentrations were drawn for each surfactant. Also, the CMC value for each surfactant was defined as the point of the lowest surface tension after which the surface tension values would be almost constant with little changes.

### 3.0 RESULTS AND DISCUSSIONS

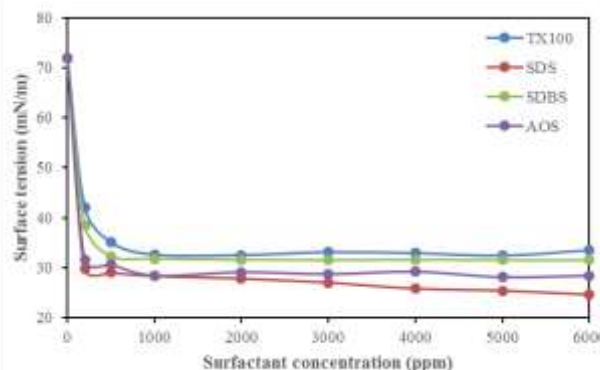
#### 3.1 Surface Tension Measurement

For the purpose of this research, three different surfactants (AOS, SDS, TX100, and SDBS) were used as the foaming agent. All the surfactant solutions with two concentrations (200-6000 ppm) were prepared in fresh water. Then after, Krüss tensionmeter was used to measure the surface tension of each solution. Table 1 indicates the results. Adding even a small amount of surfactant (200 ppm) to fresh water resulted in a significant decrease of surface tension for all four surfactants. According to the results, SDS reduced the surface tension more efficiently followed by AOS, SDBS and finally TX100.

Critical micelle concentration (CMC) refers to the concentration of surfactant solutions to form a large amount of micelles as one of the main parameters of each surfactant. The plot of surface tension variation versus surfactant concentration is shown in Figure 2. According to this figure, the surface tension was reduced significantly up to a concentration of 1000 ppm, and then the variation of surface tension would be negligible. In other words, the CMC of these three surfactants was 1000-ppm. Therefore, SDS, AOS, and SDBS surfactants with 1000-ppm concentration would be used as the foaming agents in all the experiments.

**Table 1** Surface tension measurement using Krüss tensiometer

Surfactant concentration (ppm)	TX100 surface tension (mN/m)	SDS surface tension (mN/m)	SDBS surface tension (mN/m)	AOS surface tension (mN/m)
0	72.0	72.0	72.0	72.0
200	42.1	29.7	38.5	31.5
500	35.1	29.0	32.3	30.6
1000	32.6	28.3	31.8	28.4
2000	32.5	27.8	31.6	29.1
3000	33.1	27.0	31.5	28.7
4000	32.9	25.8	31.6	29.2
5000	32.4	25.4	31.5	28.1
6000	33.5	24.6	31.5	28.4



**Figure 2** Variation of surface tension with surfactant concentration

#### 3.2 Conventional Foam Stability

Conventional foam is a foam without any polymer in structure. This kind of foam was produced to highlight the polymer effect on foam stability. Each solution was prepared in both fresh water and 8 wt. % NaCl with and without applying oil. Four surfactants i.e., AOS, TX100, SDS, and SDBS were used as the foaming agents and the time spent to drain 80% of the liquid from the column was measured for each solution. Table 2 indicates the results of conventional foam stability for the four surfactants. According to this Table, solutions made with 8 wt. % NaCl were less stable than solutions made with fresh water as the aqueous medium.

Experiments on oil-included solutions indicated that adding oil to the solutions could destabilize the foam and reduce foam stability. Using fresh water to prepare foam leads to more stable Lamellas and plateau boarders, but adding NaCl to solutions could reduce the solution viscosity through screening the negative charges along the surfactants [6]. Solutions made with 8 wt. % NaCl (with and without oil) showed lower stability than solutions made with fresh water (with and without oil). The most stable foams in all solutions were produced by SDS as a surfactant, followed by AOS, SDBS, and finally TX100. Using oil in the solutions affected foam stability and foams generated with vaseline oil were more stable than the foams generated with paraffin oil.

Plateau boarder with lower liquid pressure and lamella with higher liquid pressure are combined to make a foam since the gas-solid interface is curved. Due to liquid moving from the lamella into the plateau boarder, lamella becomes thinner and finally it ruptures. Placing at the gas-solid interface rather than in the bulk, surfactant as a foaming agent has to reduce the interface surface tension [14,15]. Thus, the foam generated with pure liquids such as pure water is less stable than the one produced with surface-active materials such as a surfactant. Marangoni shear stress, which acts on the liquid at the interface due to surface-active gradient generation, determines the stability and instability of the plateau boarders [16,17]. The AOS, SDS, and SDBS surfactants could significantly reduce surface tension; however, the produced foams (conventional foams) still suffered from instability and rapid rupture compared to polymer enhanced foams.

**Table 2** Conventional foam stability with no polymer addition

Surfactant solution	Foam stability (min)					
	Fresh water	8 wt.% NaCl	Fresh water and paraffin oil	Fresh water and vaseline oil	8 wt.% NaCl and paraffin oil	8 wt.% NaCl and vaseline oil
1000 ppm SDS	76	47	41	54	17	24
1000 ppm AOS	59	35	34	41	14	19
1000 ppm SDBS	51	32	31	36	13	17
1000 ppm TX100	43	29	27	30	12	15

### 3.3 Polymer Addition To Foam Solutions Made By SDS Surfactant

Both fresh water and 8 wt. % NaCl was used to prepare polymers with relatively low to high concentrations (200-5000 ppm). Then paraffin oil and vaseline oil were separately added to the solutions and finally SDS surfactant with concentration of 1000 ppm was added to each solution. The produced solutions were poured into the cell, then CO<sub>2</sub> was injected into the cell and the desired foam was generated. The injection was stopped when the required time was spent to fulfill the whole set, and then foam stability was measured for each solution. Table 3 represents the foam stability results.

In general, six different solutions, i.e., freshwater, 8 wt. % NaCl, fresh water and paraffin oil, fresh water and vaseline oil, 8 wt. % NaCl and paraffin oil, as well as 8 wt. % NaCl and vaseline oil were prepared with variable polymer concentrations. Comparison of these results with those of conventional foam stability reveals that adding polymer significantly increases foam stability and even the minimum concentration of polymer substantially enhances foam stability. A direct relationship was seen between polymer foam stability and polymer concentration and in all cases, the lowest polymer concentration (200 ppm) was used to generate the least stable foam while the highest polymer concentration (5000 ppm) was applied to produce the most stable foam. The results showed a high compatibility between polyacrylamide and fresh water, also solutions made with 8 wt. % NaCl were less stable than polymer foam solutions made from fresh water. Even the presence of paraffin and vaseline oils led to a relationship and solutions made from fresh water were more stable than the solutions generated with 8 wt. % NaCl; however, the stability results were under the influence of the oil presence significantly so that foam stabilities were reduced. Unlike paraffin oil with lower viscosity, vaseline oil with higher viscosity played a little role in the foam stability reduction.

Partially hydrolyzed polyacrylamide polymer is the most available and widely used of polymers for increasing solution viscosity and controlling the mobility [18]. The maximum chain extension is a result of repulsion between the negative charges of high molecular weight polymer; therefore adding a small concentration of PHPA to water can increase solution viscosity significantly in the absence of electrolyte. However, salt presence makes it possible to screen the negative charges along the polymer and decrease the solution viscosity [6]. Depending on the salt concentration and shear rate, the solution viscosity reduction with divalent salts can be as high as a magnitude order compared with mono-valent salt [19]. When oil is added to foam solution, two phenomena may happen. While at the time of water spreading over the oil, pseudo-emulsion film phenomena may happen;

therefore, foam stability is improved due to the enhancement of lamella and plateau boarder stability. The second phenomenon observed in the present study is called unstable pseudo-emulsion film, that is, water is unable to spread over the oil and to make it wet. As a result, the capillary forces minimize the oil-water contact, the film is ruptured and the foam stability is decreased [20, 21]. Thus, adding oil to foam solutions leads to a significant reduction of the foam stability.

**Table 3** Foam stability solutions made by SDS surfactant

Polymer conc. (ppm)	Foam stability (min)					
	Fresh water	8 w% NaCl	Fresh water and paraffin oil	Fresh water and vaseline oil	8 wt. % NaCl and paraffin oil	8 wt. % NaCl and vaseline oil
200	91	61	43	59	24	33
500	99	66	60	74	30	38
700	108	75	73	90	34	43
1000	124	93	86	102	40	57
2000	212	147	119	139	49	66
3000	289	195	147	216	69	84
5000	417	298	195	299	84	112

### 3.4 Polymer Addition To Foam Solutions Made By AOS Surfactant

AOS surfactant was used as the foaming agent for the second sets of experiments. Different concentrations of polyacrylamide polymer were added to 1000 ppm surfactant in fresh water and 8 wt. % NaCl in the presence and absence of paraffin and vaseline oils. Table 4 indicates the results of foam stability measured for each solution. As it was expected, foam stability was significantly improved due to adding polymer so that foam stability was directly increased through increasing polymer concentration. Maximum polymer concentration produced the most stable foam and polymer with 200 ppm concentration generated the least stable one. Solutions made with fresh water had a significant compatibility with foam stability; however, adding 8 wt. % NaCl led to foam stability reduction. For instance, a 5000 ppm polymer resulted in a 341 minute foam stability for fresh water solutions and a 217 minute one for 8 wt. % NaCl solutions. Oil presence in both fresh water solutions and 8 wt. % NaCl ones reduced substantially foam stability. This impact was more common with paraffin oil rather than vaseline oil. For example, in solutions with 5000 ppm polyacrylamide polymer and paraffin oil in fresh water, the foam stability was 131 minutes, while for solutions in fresh water and vaseline oil it was 189 minutes. Also, foam stability for 8 wt. % NaCl and paraffin oil was 62 minutes, and finally for 8 wt. % NaCl and vaseline oil, it was 76 minutes.

Foam is the product of gas phase dispersion in a continuous liquid phase. One of the main factors which controls foam stability is the liquid film thickness called lamella. The foam structure cannot be drained and ruptured in the presence of thick lamella. Thus, liquid drainage decrease due to increasing solution viscosity enhances foam stability significantly [22, 23]. Polymer absorption at the liquid-gas interface which increases the surface rheological properties can decrease the drainage rate. Furthermore, regardless of increase in the bulk viscosity, the drainage rate of foam can be controlled by repulsive and attractive forces that are a function of the degree of polymer absorption at the interface [24, 25]. However, any increase in bulk viscosity of the solution is the main mechanism reducing the drainage rate of foam at polymer enhanced foam solutions. Thus, fluid drainage out of plateau boarders slows down and the foam is more stable



than the conventional one [23]. The more polymer concentration leads to the more solution viscosity and consequently to the more foam stability. Unlike minimum polymer concentration, maximum polymer concentration improves foam stability highly; however, even adding a small amount of polymer to the foam is able to increase foam stability significantly compared to a conventional foam excluding polymer. Once added to foam solutions, the oil contacted the gas water interface directly and due to oil movement and pinch off through lamellas, the foam was ruptured. When the bridging coefficient is positive and rupturing the gas-water-oil contact lines leads to bubble coalescence, the pinch off phenomena is accelerated [26,27]. In the presence of crude oil, these phenomena decrease foam stability.

### 3.5 Polymer Addition To Foam Solutions Made By SDBS and TX100 Surfactants

SDBS surfactants with 1000 ppm concentration were used to conduct the third set of experiments to generate the foam. Surfactant solutions, made from fresh water and 8 wt. % NaCl in the presence and absence of paraffin and vaseline oils, were combined with different polymer concentrations. For each solution, the time spent for 80% of the liquid was measured. Table 5 indicates the experimental results. According to this table, solutions prepared in fresh water have the highest extent of foam stability. Here, the foam stability significantly increased due to polymer concentration increase from 200 to 5000 ppm. However, compared to conventional foam, foam stability was improved even by the minimum polymer concentration (200 ppm).

Compared to solutions made from fresh water, the 8 wt. % NaCl solutions slightly reduced foam stability; however, the foams produced with variable polymer concentration were more stable than the conventional foams. In other experiments, Paraffin and vaseline oils were added to foam solutions in fresh water. Results showed that increasing polymer concentration to maximum extent can substantially increase foam stability. While lower concentrations of polymer cannot significantly increase foam stability. Solutions prepared in 8 wt. % NaCl instead of fresh water make this phenomenon worst. Presence of paraffin and vaseline oils and adding 8 wt. % NaCl to foams with variable polymer concentration, reduced substantially the foam stability in comparison to solutions without oil. However, compared with conventional foam stability results, these findings showed that polymer addition to the foam was effective even in the presence of paraffin and vaseline oils. The destabilizing effect of paraffin oil in all tested solutions, was more than that of vaseline oil.

**Table 4** Foam stability solutions made by AOS surfactant

Polymer conc. (ppm)	Foam stability (min)					
	Fresh water	8 wt. % NaCl	Fresh water and paraffin oil	Fresh water and vaseline oil	8 wt. % NaCl and paraffin oil	8 wt. % NaCl and vaseline oil
200	67	39	36	44	20	25
500	80	46	39	49	21	27
700	95	57	45	56	25	31
1000	116	75	53	71	30	36
2000	189	113	71	93	36	48
3000	236	143	94	134	43	58
5000	341	178	131	189	62	76

The results of adding polymer to foam solutions made from fresh water and 8 wt. % NaCl in the presence or absence of paraffin and vaseline oils were compared and showed that adding polymer to a

foam produced in fresh water produced the most stable foam and polymer addition to a foam generated with 8 wt. % NaCl together with paraffin oil produced the least stable foam. For instance, the solution made by 5000 ppm polymer in fresh water had a 239 minute foam stability; while this value declined to 75 minutes when 5000 ppm polymer was prepared in 8 wt. % NaCl and paraffin oil, and to 102 minutes in the case of exchanging the oil with vaseline oil.

The experimental results of the final set of experiments are summarized in Table 6. According to this table, foam stability with fresh water solutions had better performance than the solutions made with 8 wt. % NaCl. In addition, for both fresh water and 8 wt% NaCl, the solutions made with paraffin oil had less stability than those including vaseline oil. All experiments witnessed the positive effect of adding polymer on foam stability; whereas, adding 5000 ppm polymer generated maximum foam stability and 200 ppm polymer produced minimum foam stability.

Foam stability in the presence of crude oil is under the influence of several factors such as surfactant partitioning in the oil, depletion in the aqueous phase, producing less desirable state for foaming due to surfactant adsorption by lamella, wetting alteration because of oil component absorption, displacing the foam stabilizing interface through spreading oil on foam lamella, emulsifying oil to break and rupture the lamellas, and bridging of foam films by oil droplets [27,28]. The presence of oil in the system enhanced polymer foam stability significantly, in other words, oil viscosity changed foam stability. It means, a less viscous oil (paraffin oil) played a more significant role in reducing the polymer enhanced foam stability than a high viscosity oil (vaseline oil); however, the performance of foams contacted with oils were improved by the polymer additives and foam stability was enhanced by these additives [11].

**Table 5** Foam stability solutions made by SDBS surfactant

Polymer conc. (ppm)	Foam stability (min)					
	Fresh water	8 wt. % NaCl	Fresh water and paraffin oil	Fresh water and vaseline oil	8 wt. % NaCl and paraffin oil	8 wt. % NaCl and vaseline oil
200	49	31	29	36	16	21
500	56	37	34	40	20	24
700	64	43	41	49	25	28
1000	81	57	53	62	30	39
2000	137	75	75	89	41	50
3000	174	105	96	120	52	71
5000	239	153	132	178	75	102

**Table 6** Foam stability solutions made by TX100 surfactant

Polymer conc. (ppm)	Foam stability (min)					
	Fresh water	8 wt. % NaCl	Fresh water and paraffin oil	Fresh water and vaseline oil	8 wt. % NaCl and paraffin oil	8 wt. % NaCl and vaseline oil
200	32	21	19	24	11	13
500	37	25	22	26	13	16
700	42	28	27	32	16	18
1000	53	37	35	41	20	25
2000	90	49	49	58	27	33
3000	114	69	63	79	34	46
5000	157	101	87	117	49	66

### 3.6 Foam Texture Evaluation

TX100 surfactant was used to investigate the effect of different solution environments on foam texture and bubble size. In addition, the presence of polymer was represented by experiments with 1000 ppm PHPA. Further bubble size analysis involved the use of three different solutions: fresh water, 8 wt% NaCl, and finally fresh water with vaseline oil. Foam bubble patterns for the solution are represented in figures 3-5 respectively. A 10 mm magnitude has been considered for all these microscopic photos.

Foam stability is a function of foam bubble size; that is, whenever the bubble size decreases, the foam stability increases. In addition, whenever the foam rupture increases, the foam size increases and as a result stability declines. Regarding foam stability, the aforementioned discussions suggested that unlike solutions made in 8 wt.% NaCl and oil, solutions produced in fresh water were the most stable foam. The foam stability results are confirmed by the foam texture pictures. Figure 3 shows that the very small foam bubble size results in high foam stability. As Figure 4 shows, the foam bubble size is increased due to the presence of 8 wt% NaCl which reduces the foam stability. The foam texture of the solutions made with fresh water in the presence of vaseline oil is represented in Figure 5. According to this figure, the bubble size is very large that reduces foam stability and ruptures it.

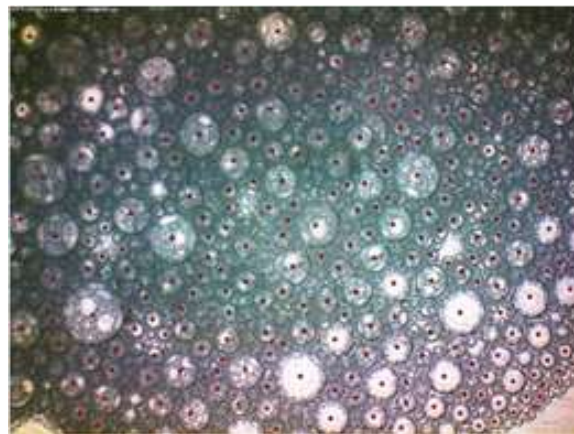
Adding polymer to foam shrinks the foaming volume, but raises the foam half-life, in other words, the presence of polymer leads to foaming ability reduction, but significant enhancement of foam stability because during the aqueous phase the polymer molecules increase the viscosity, which significantly influence the drainage rate. Co-adsorption of polymer molecules makes the polymer/surfactant complexes to be formed at the water/gas surface. These complexes in turn form a relatively dense surface layer. Then the produced dense surface layer increases surface elasticity significantly, which stops the liquid to be separated from foam films and explains how the stability of the foam films is enhanced. Whenever the polymer concentrations increase, polymer molecule adsorption increases until to reach the saturation level. Furthermore, adding polymer enhanced the lamellae and produced a foam with relatively constant size [29].

Due to the negative spreading coefficient of oil tolerant foam in oil, the oil droplets are unable to be spread on the gas/water surface. As the microscopic photos of the oil foam demonstrate, the oil droplets are not spread, but dispersed in the water phase. High speed mixing disperses the oil phase into oil droplets so that some isolated oil droplets and clustered oil droplets are seen both at the surface and the water phase. A water film covers these oil droplets and the oil-water emulsion is formed when the bubbles break [29].

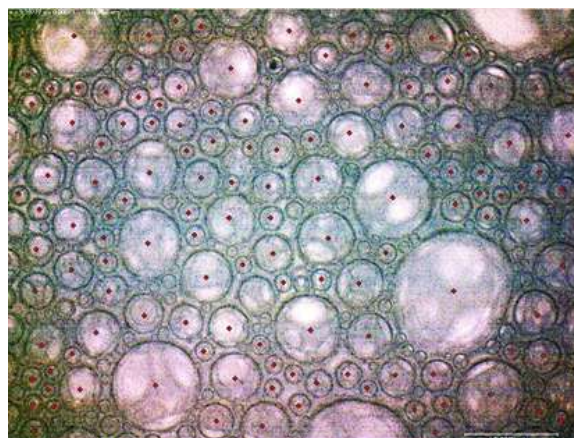
### 4.0 CONCLUSION

Adding polymer to foam increases solution viscosity which in turn decreases the liquid drainage time and improves foam stability. Different concentrations of the relatively hydrolyzed polyacrylamide polymers were used as the viscosifying agents of foams generated by three different surfactants: SDS, AOS, TX100, and SDBS in the presence and absence of 8 wt. % NaCl. Paraffin and vaseline oils were added to the solutions and then foam stability was measured. The time spent to obtain 80% of the liquid was measured and the results showed that adding polymer improves foam stability significantly in comparison with conventional foam. Adding 5000 ppm PHPA produced the most stable foam. Likewise, when the minimum polymer concentration (200 ppm) was added to foam, the least stable foam was

generated. Foam solutions prepared in fresh water had more stability than the solutions made in 8 wt. % NaCl. In both cases of conventional and polymer enhanced foam, the oil-foam contact led to significant reduction of foam stability; however, the destabilizing effect was severted with oil viscosity decline. All the three tested surfactants had compatibility with adding polymer; however, the most stable foam was produced by SDS surfactant rather than by AOS, SDBS, and TX100 ones.



**Figure 3** Bubble size pattern of foam made with fresh water and TX100 surfactant



**Figure 4** Bubble size pattern of foam made with 8 wt% NaCl and TX100 surfactant



**Figure 5** Bubble size pattern of foam made with fresh water, TX100 surfactant, and vaseline oil

### Acknowledgement

This research is financially supported by the Ministry of Education, Malaysia under the project No. R.J130000.7842.4F562 and Universiti Teknologi Malaysia (UTM); and also the Ministry of Education, Malaysia under the project No. 600-RMI/FRGS/5/3(98/2013); and the Research Management Institute, Universiti Teknologi Mara.

### References

- [1] D.C. Bond, O.C. Holbrook. 1958. Gas Drive Oil Recovery Process. *United States Patents*. 2866507.
- [2] A. Azdarpour. 2011. *The Effects Of Polymer Concentrations On Polymer Enhanced Foam (PEF) Stability*. Msc thesis. Universiti Teknologi Malaysia.
- [3] D. Exerowa, P. M. Kruglyakov. 1998. *Foam and Foam Films*. Elsevier Science.
- [4] A. Azdarpour, O. Rahmani, E. Mohammadian, M. Parak, A.R.M. Daud, R. Junin. 2013. *Business Engineering and Industrial Applications Colloquium (BEIAC2013)*. Langkawi, Malaysia. DOI: 10.1109/BEIAC.2013.6560275.
- [5] G. J. Hirasaki. 1989. The Steam–Foam Process. *Journal of Petroleum Technology*. 41: 449–456.
- [6] S. Lee, D. H. Kim, C. Huh, G. A. Pope. 2009. *Development of a Comprehensive Rheological Property Database for EOR Polymers*. SPE Annual Technical Conference and Exhibition. New Orleans, Louisiana.
- [7] F.R. Wassmuth, L.H. Hodgins, L.L.S. Schramm, S.M. Kutay. 2001. Screening and Coreflood Testing of Gel Foams To Control Excessive Gas Production in Oil Wells. *SPE Reservoir Evaluation & Engineering*. 4: 187–194.
- [8] R.D. Sydansk. 1994a. *Polymer–Enhanced Foam*: Laboratory Development and Evaluation. SPE International Symposium of Oilfield Chemistry, New Orleans, USA.
- [9] R.D. Sydansk. 1994b. *Polymer–Enhanced Foam Propagation Through High–Permeability Sandpacks*. SPE International Symposium of Oilfield Chemistry, New Orleans, USA.
- [10] W.D. Mei, D.K. Han, G.L. Xu, L. Yang. 2008. Influence of partially hydrolyzed Polyacrylamide on the foam capability of Alpha Olefin Sulfonate surfactant. *Petroleum Exploration and Development*. 35: 335–338.
- [11] T. Zhu, O. Ogbe, S. Khataniar. 2004. Improving the Foam Performance for Mobility Control and Improved Sweep Efficiency in Gas Flooding. *Journal of Industrial & Engineering Chemistry Research*. 43: 4413–4421.
- [12] ASTM D892. 2006. US: An American National Standard.
- [13] T. Zhu, A. Strycker, C.J. Raible, K. Vineyard. 1998. *Foams for Mobility Control and Improved Sweep Efficiency in Gas Flooding*. SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.
- [14] A. Mandal, K. Ojha. 2008. *Optimum Formulation Of Alkaline Surfactant Polymer Systems For Enhanced Oil Recovery*. SPE Asia Pacific Oil and Gas Conference and Exhibition, Australia.
- [15] L. L. S. Schramm. 2000. *Surfactants: Fundamentals And Applications In The Petroleum Industry*. Cambridge, UK: Cambridge University Press.
- [16] S. Manning-Benson, C.D. Bain, R.C. Darton. 1997. Measurement of dynamic interfacial properties in an overflowing cylinder by ellipsometry. *Journal of Colloid and Interface Science*. 189: 109–116.
- [17] C.D. Bain, S. Manning-Benson, R.C. Darton. 2000. Rates of Mass Transfer and Adsorption of CTAB at an Expanding Air–Water Interface. *Journal of Colloid and Interface Science*. 229: 247–256.
- [18] F.D. Martin, L.G. Donaruma, M.J. Hatch. 1980. *Development Of Improved Mobility Control Agents For Surfactant /Polymer Flooding*. First Annual Report to the U.S. Department of Energy, Bartlesville, Oklahoma.
- [19] K.C. Tam, C. Tiu. 1990. Role of ionic species and valency on the steady shear behavior of partially hydrolyzed polyacrylamide polymer solutions. *Colloid And Polymer Science*. 268: 911–920.
- [20] T.J. Myers, C.J. Radke C. 2000. Transient foam displacement in the presence of residual oil: Experiment and simulation using a popular balance medel. *Ind. Eng. Chem. Res*. 39: 2725–2741.
- [21] T. Holt, F. Vassenden, I. Svorstol. 1996. *Effects Of Pressure On Foam Stability, Implications For Foam Screening*. SPE/DOE Tenth symposium on improved oil recovery, Tulsa, Oklahoma.
- [22] M. Safouane, A. Saint-Jalmes, V. Bergeron, D. Langevin. 2006. *Viscosity effects in foam drainage: Newtonian and non-newtonian foaming fluids*. *Eur Phys J E Soft Matter*. 19: 195–202.
- [23] B. Jean, L.T. Lee, B. Cabane, V. Bergeron. 2009. Foam Films from Thermosensitive PNIPAM and SDS Solutions. *Langmuir*. 25: 3966–3971.
- [24] S. Lionti-Addad, J.M. Di Meglio. 1992. Stabilization of aqueous foam by hydrosoluble polymers. 1. Sodium dodecyl sulfate-poly(ethylene oxide) system. *Langmuir*. 8: 324–327.
- [25] J. Klein, P. Luckham. 1982. Forces between two adsorbed polyethylene oxide layers immersed in a good aqueous solvent. *Nature*. 300: 429–431.
- [26] T. J. Myers. 1999. *The Role Of Residual Oil In The Mechanistic Simulation Of Foam Flow N Porous Media: Experiment And Simulation With The Population Balance Method*. PhD Dissertation, University of California, USA.
- [27] R. Farajzadeh, A. Andrianov, R. Krastev, G. J. Hirasaki, W. R. Rossen. 2012. Foam-Oil Interaction in Porous Media: Implications for Foam Assisted Enhanced Oil Recovery. *SPE EOR Conference at Oil and Gas West Asia*. Muscat, Oman.
- [28] S. Stöckle, P. Blecua, H. Möhwald, R. Krastev. 2010. Dynamics of thinning of foam films stabilized by n-dodecyl-beta-maltoside. *Langmuir*. 26: 4865–4872.
- [29] X. Duan, J. Houm T. Cheng, S. Li, Y. Ma. Evaluation of oil-tolerant foam for enhanced oil recovery: Laboratory study of a system of oil-tolerant foaming agents. *Journal of Petroleum Science and Engineering*. Article in press, DOI: 10.1016/j.petrol.2014.07.042.