The Oil and Water Separation from Surfactant Produced Water by Using a Flotation Column

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Abstract. The objective of this paper is to study the effect of amphoteric surfactant at different operating conditions concerning the oil–water separation from Dulang Oil field by using a laboratory-scale flotation column. A model has been developed to optimize the flotation process by using response surface method (RSM). The produced water containing surfactant was created by mixing the Dulang crude oil with the initial concentration of 1000 ppm, brines at 14000 ppm concentration, and MFOMAX amphoteric surfactant ranging from 0 to 500 ppm. A total of 32 experiments were conducted, and the effect of gas flowrate, MFOMAX concentration, and duration of flotation on the efficiency of oil removal from the flotation units has been analyzed. The experimental data results were then statistically analyzed, and the experiments were conducted for verification. The experimental results were found in fair agreement with the model's predicted value, suggesting that the model could define the relationship between parameters. With the presence of MFOMAX, the optimal combination of parameters was at 4 L/min gas flowrate at the duration of 9 min with the efficiency of 87.3%. Confirmatory experiments were conducted at the optimum parameters to verify the model. The experimental value of 82.8% (STD 1.60) was obtained which indicated a good agreement with the predicted results.

Keywords: Produced water treatment · Surfactant produced water · Oil–water separation · Flotation unit

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1 Introduction

In tertiary oil recovery, chemicals such as polymers and surfactants are being added in purpose to increase the oil recovery [1]. During this process, there will be a breakthrough of the chemicals, and as result, a stable emulsion will be formed, which will be difficult to treat in a conventional produced water treatment system [2]. Treating this produced water is crucial as it needs to follow the environment specification before it is beingdischarged into the ocean or sea.

A conventional produced water treatment system consists of several integrated systems, for example, primary, secondary, and tertiary processes. Primary process includes the usage of gravity separator that functions to remove solid particles and larger oil droplets. The separation of a gravity separator works based on a density difference between the oil, particles, and water. In secondary system, hydrocyclone and flotation equipment are usually used to remove the small particles and oil droplets. Hydrocyclone works by a centrifugal force that separates the oil and water based on the density, while the flotation unit uses the gas bubbles to enhance the oil and water separation. Finally, in the tertiary system, nutshell media filter is usually used to remove the dissolved matter.

In the tertiary oil recovery, surfactant is added to reduce the interfacial tension (IFT) between oil and water [3] and to increase the oil sweeping process that will result in more oil recovery. In previous researches, it was indicated that the presence of surfactant had stabilized the emulsion and complicated the produced water treatment system [2], [4], [5]. Numerous researches had been done to increase the efficiency of the oil removal in the presence of surfactant. One approach is to increase the flotation unit in the secondary system.

Flotation equipment used injection of gas through sparger that will create gas bubbles. The gas bubble attaches to the oil droplets and brings the oil droplets to the surface for an efficient oil removal. The presence of these gas bubbles is advantageous to decrease the time of separation [6]. Four steps that determine the effectiveness of a gas flotation system were identified as follows [7], [8]:

(a) generation of gas bubbles
(b) the collision between the gas bubbles and the oil droplets
(c) attachment of the gas bubbles with the oil droplets
(d) the rise of the attachments to the surface.

Optimizing the flotation parameters is important to ensure the flotation works in the optimum conditions and reduces the operating cost for the produced water treatment system.

A lot of researches have been conducted to investigate the effect of flotation operating parameters on the oil and water separation [9–12]. However, few of it has investigated the effect of amphoteric surfactant to the oil and water separation by using the flotation unit.

In this research, the effect of amphoteric surfactant (MFOMAX) on the oil and water separation at different flotation operating conditions has been studied. The effect of the MFOMAX concentration, gas flowrate, and duration of flotation were studied and optimized to achieve the maximum efficiency of the oil removal by using RSM approach. ANOVA statistical analysis was performed to generate the best equation that can describe the efficiency of oil removal in the flotation unit with the presence of amphoteric surfactant. Finally, confirmatory experiments have been conducted to validate the model performance.

2 Materials and Method

2.1 Materials

Dulang crude oil with the density of 0.8454 g/cm^3 and the viscosity of 30.56 cP at 40 °C was used in the experiments. The amphoteric surfactant (MFOMAX) was supplied by PETRONAS Research Sdn. Bhd, Bangi, Malaysia.

2.2 Methods

1. Preparation of the Surfactant Produced Water

The produced water was prepared by mixing the Dulang crude oil, brine, and MFOMAX by using Ika T18 Ultra Turrax for 10 min at 13000 rpm. Brine was prepared by using salts as listed in Table 1, making a total salinity of 14000 ppm. The system was operated at 60 °C following the actual produced water treatment system in Dulang Oil field. The initial oil concentration of the Dulang crude oil was set to 1000 ppm for every experiment, and the MFOMAX was ranged from 0 to 500 ppm.

Table 1. Brine compositions

Salts	g/L
$CaCl_2{\cdot}(H_2O)_2$	0.7251
$MgCl_2{\cdot}(H_2O)_6$	0.7726
NaCl	10.0267
$FeCl_3$	0.0009
$SrCl_2{\cdot}(H2O)_6$	0.0295
KCl	0.3129
$NaHCO_3$	3.6065
Na_2SO_4	0.7840

2. Flotation Column Test

In this study, the size of flotation unit is 5 cm in diameter and 100 cm in height as shown in Fig. 1. The flotation column is connected to a nitrogen tank and gas flowmeter. The gas control valve is connected to the nitrogen tank to control the gas flow into the flotation column. The surfactant produced water was placed in the flotation column with the initial oil concentration of 1000 ppm. The removal of oil in the flotation column is accomplished by infusing the gas bubbles into the flotation column. The gas bubbles will attach and collide with the oil droplets and bring the oil droplets to the surface for disposal. Nitrogen gas is used as the flotation medium for its inert properties and does not easily undergo chemical reactions. The flotation column is shown in Fig. 1.

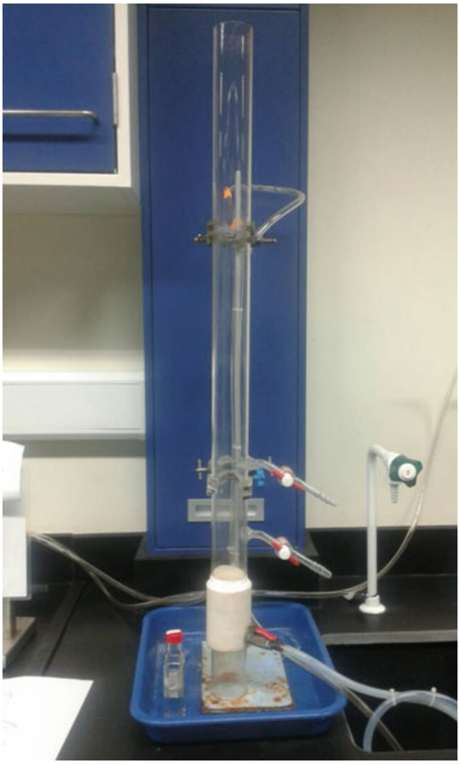

Fig. 1. Flotation column

The efficiency of the oil removal by using flotation unit can be calculated by using Eq. 1.

$$\varepsilon = 1 - \frac{\boldsymbol{C}_{\mathbf{underflow}}}{\boldsymbol{C}_{\mathbf{inlet}}} \times 100\% \tag{1}$$

where $C_{\text{underflow}}$ is the oil concentration in the effluent, and C_{inlet} is the oil concentration in the inlet. Based on Eq. 2, the concentration of the oil in the effluents can be determined by using Oil-in-Water Analyzer (TD-500D) as shown in Fig. 2. n-Hexane was used to extract the oil from the effluents before being analyzed in TD-500D.

Fig. 2. TD-500D Oil-in-Water analyzer

3. Experimental Work

A total of 32 experiments were conducted, and the effect of gas flowrate, MFO-MAX concentration, and duration of flotation on the efficiency of oil removal from the flotation units has been analyzed. The independent variables in this study are the concentration of MFOMAX (ppm) (X_1), gas flowrate (L/min) (X_2), and duration of flotation (minutes) (X_3). The predicted response, flotation efficiency (%) is designated as Y. The coded and actual values of the independent parameter are given in Table 2. The equations were validated by using analysis of variance (ANOVA). The coefficients were calculated by using Design Expert 9.0.

Table 2. Actual and coded values of the parameters

Parameter	Symbol	Parameter Level		
		Low -1	Center 0	High +1
		Actual value		
MFOMAX concentration (ppm)	X_1	0	250	500
Gas flowrate (L/min)	X_2	1	3	5
Duration (min)	X_3	2	6	10

3 Results and Discussions

3.1 ANOVA Statistical Analysis

The ANOVA statistical analysis was presented in Table 3, and the model equation in coded factor representing the efficiency of separation (Y) was expressed as a function of concentration of MFOMAX (ppm) (X_1) and duration of flotation (minutes) (X_3) as shown in Eq. 2.

$$\begin{aligned} Y = 76.62 - 11.61X_1 + 27.69X_2 + 13.45X_3 \\ - 5.15X_1X_2 + 5.48X_1X_3 - 6.64X_2X_3 \\ - 7.37X_1^2 - 36.58X_2^2 - 12.11X_3^2 \end{aligned} \quad (2)$$

Table 3. Analysis of variance (ANOVA) of the response surface model to predict the efficiency of oil removal

	Mean	F	p value	
Source	Square	Value	Prob > F	Significant (S)
Model	3681.34	28.90	<0.0001	
A-Surfactant concentration	*2426.49*	*19.1*	*0.0002*	*S*
B-Gas flowrate	*13,805.1*	*108.4*	*<0.0001*	*S*
C-Duration	*3254.6*	*25.6*	*<0.0001*	*S*
AB	*318.2*	*2.5*	*0.1283*	
AC	*360.8*	*2.83*	*0.1065*	
BC	*528.5*	*4.15*	*0.0539*	
A^2	*388.9*	*3.05*	*0.0946*	
B^2	*9574.5*	*75.2*	*<0.0001*	
C^2	*1049.5*	*8.24*	*0.0089*	
Residual	127.4			
Lack of Fit	*164.9*			
Pure Error	*0.000*			
Cor Total				

Referring to Table 2, the statistical analysis suggested that all the parameters, MFOMAX concentration, gas flowrate, and duration of flotation, have given significant effect on the oil and water separation in the flotation unit with the P value of 0.0002, <0.0001 and <0.0001. The coefficient of R^2 and R^2_{adj} were found to be 0.922 and 0.8901. The high value R^2 closer to 1 indicates that the model predicted values co-relate well with the experimental values. All the parameters are significant in this model. This was in good agreement between actual and predicted efficiency of oil removal as shown in Fig. 3. The good correlation implied that the quadratic model is a good representation of the experimental system.

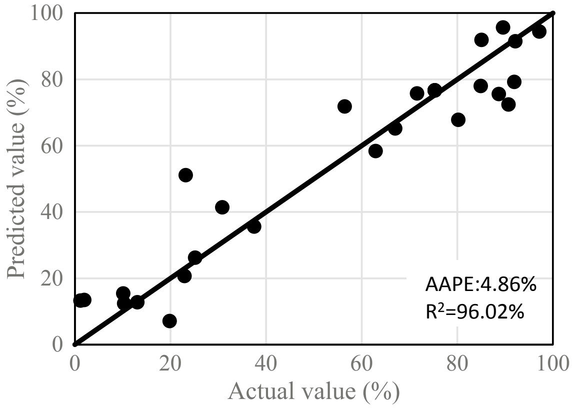

Fig. 3. Actual and predicted values

3.2 Contour Plots

Contour plots for the effect of surfactant concentration and gas flowrate on the efficiency of oil removal at 2, 6, and 10 min are shown in Figs. 4, 5, and 6.

Referring to Fig. 4, the efficiency of the oil removal at 1 L/min with and without the presence of surfactant is rather low compared to the efficiency of oil removal at 3 L/min and at 5 L/min. However, when the gas flowrate was increased to 5 L/min, the efficiency of oil removal has dropped. In this case, the gas flowrate at 5 L/min has created a turbulence effect that decreases the efficiency of the oil removal [13]. At 2 min of flotation, the highest efficiency has been indicated at 3 L/min at 0 ppm of surfactant. This is because, with the addition of surfactant, the IFT between the oil and water has decreased that will complicate the oil and water separation.

Figure 5 shows the effect of surfactant concentration and gas flowrate to the efficiency of oil removal at 6 min flotation duration. From the figure, the efficiency of oil removal decreases when the surfactant increases from 0 to 500 ppm at 1 and 5 L/min. However, at 3 L/min, the addition of surfactant increases the efficiency of oil removal. At 6 min of flotation duration, the highest efficiency has been given at 0 ppm of surfactant concentration and gas flowrate 3 L/min.

The effect of surfactant concentration and gas flowrate at 10 min of flotation duration (Fig. 6) has shown similar trend to the 6-min flotation duration. The increase in surfactant concentration has decreased the efficiency of oil removal at 1 and 5 L/min. However, at 3 L/min, the increase in surfactant concentration has increased the efficiency of oil removal. This indicates that 3 L/min has given the best operating gas flowrate due to its capability to increase the efficiency at higher surfactant concentration. At 10-min flotation duration, the highest efficiency has been given at 0 ppm surfactant concentration at 3 L/min.

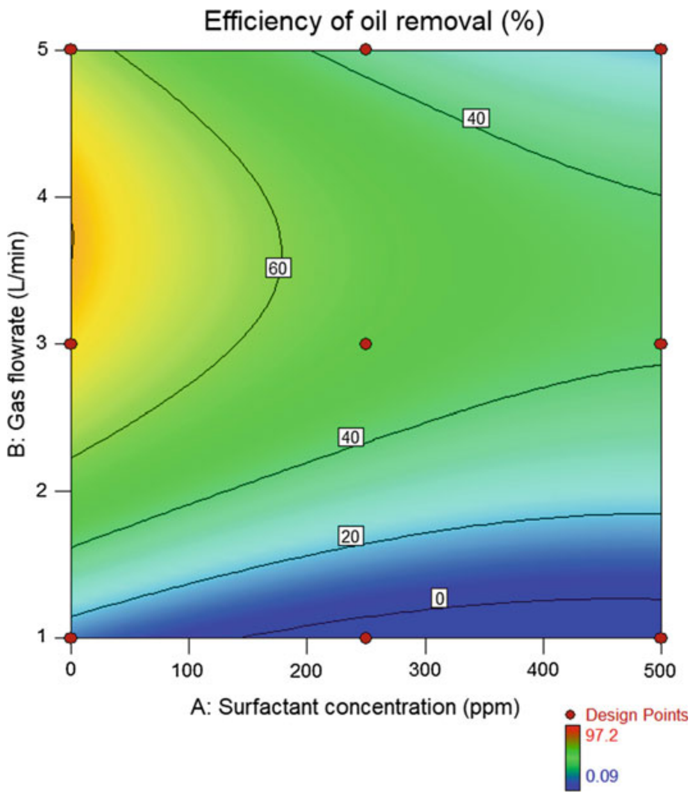

Fig. 4. Effect of surfactant concentration and gas flowrate on the efficiency of oil removal at 2-min flotation duration

Based on the equation generated, the optimum result that has been predicted was at 4 L/min gas flowrate at the duration of 9 min with the efficiency of 87.3%. Three confirmatory experiments have been conducted to validate the equation. The result is shown in Table 4. Based on the results, the mean value is 82.76%, STD 1.6, and AAPE 5.5%, which is in good agreement with the predicted results. It is considered that the model can provide a guideline to optimize the flotation process with the presence of MFOMAX surfactant.

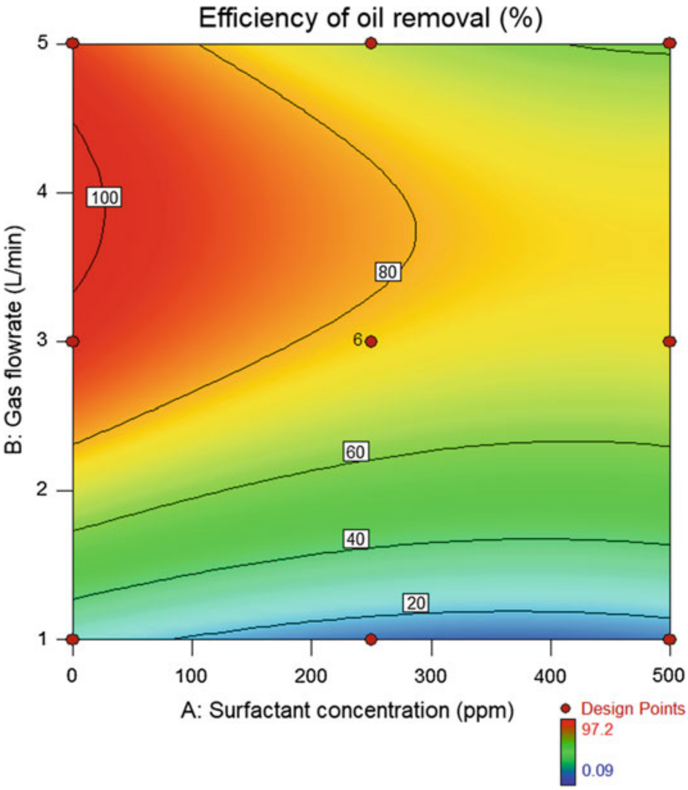

Fig. 5. Effect of surfactant concentration and gas flowrate on the efficiency of oil removal at 6-min flotation duration

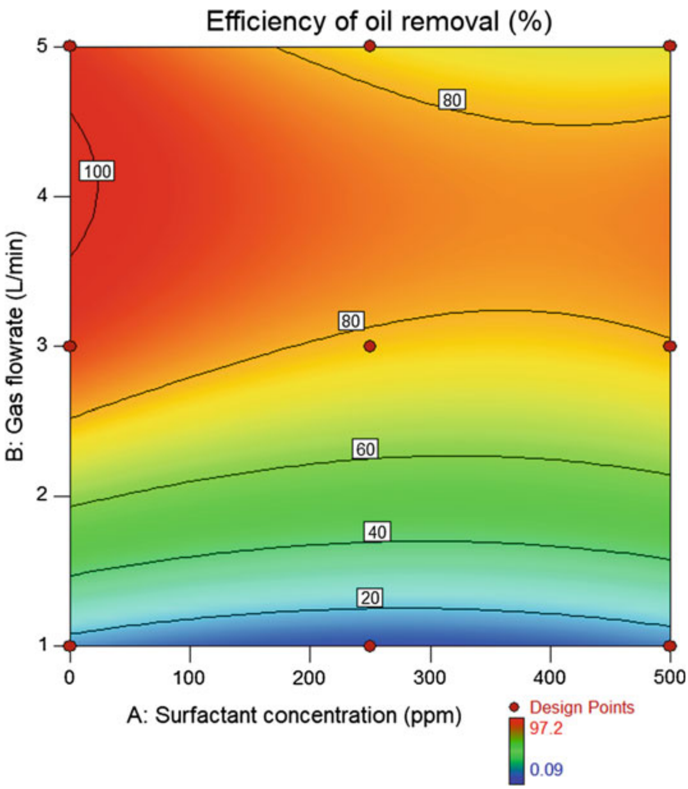

Fig. 6. Effect of surfactant concentration and gas flowrate on the efficiency of oil removal at 10-min flotation duration

Table 4. Mean value (%) and AAPE (%) of the actual and predicted values

	Actual	Prediction	AAPE %
Point 1	82.1	87.3	6.333739
Point 2	84.6	87.3	3.191489
Point 3	81.6	87.3	6.985294
Mean value	82.76667		5.503508

4 Conclusions

A statistical model was developed based on 32 experimental data to describe the efficiency of oil removal in the presence of an amphoteric surfactant, MFOMAX from 0 to 500 ppm concentration, gas flowrate 1–5 L/min, and duration of flotation at 2, 6, and 10 min. It was found that all of the parameters affect the efficiency of oil removal significantly. Confirmatory experiments were carried out to assess the proposed model, and the comparison of the predicted value has matched the experimental value with mean value of 82.76%, STD 1.6, and AAPE 5.5%. It is considered that the model can provide a guideline for optimizing the flotation unit to maximize the oil removal, in the presence of MFOMAX at a laboratory-scale conditions.

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