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Abstract

The first ever field pilot on Alaska North Slope (ANS) to validate the use of polymer floods for heavy oil EOR is currently ongoing. One of the major concerns of the operator is the effect of polymer on oil-water separation efficiency after polymer breakthrough. This paper investigates the influence of polymer on separation behavior of heavy oil emulsions and evaluates the performance of emulsion breakers (EBs). In this study, two types of heavy oil emulsions were prepared and tested at 20% and 50% water cut (WC), respectively. The bottle test method was employed in the experiments, in which the separated water volume with time, the separated water quality and the volume fraction of phases were recorded. Results showed that polymer accelerated the oil-water separation acting as emulsion inhibitor at 20% WC but tended to impede the water separation at 50% WC. Regardless of WC, polymer resulted in poor water quality and the formation of a stable intermediate o/w emulsion, owing to the increased viscosity of the water phase. The performance of EBs showed a complex dependency upon the WC, the type of demulsifier and dosage, and the polymer concentration. Despite the varied conditions encountered in the heavy oil-water-polymer-demulsifier system, a compound emulsion breaker, achieved satisfactory demulsification performance, showing the best potential for deployment in the current ANS polymer flooding pilot.

Introduction

Alaska North Slope (ANS) contains vast viscous and heavy oil resources ranging between 20-25 billion barrels, which are primarily concentrated in West Sak (also called Schrader Bluff) and Ugnu reservoirs (Targac et al. 2005). The development pace of these resources has been slow due to various factors such as high costs, low oil recovery using conventional techniques, and the inapplicability of thermal methods due to the presence of continuous permafrost. Given the successful application of polymers in China and Canada (Standnes and Skjevrak, 2014) in enhancing the heavy oil recovery, due to better mobility control and higher oil sweep efficiency, and the initial scoping studies for ANS' heavy oil reservoirs, polymer flooding was chosen for this first ever pilot on ANS. Currently, the US Department of Energy and Hilcorp is sponsoring this advanced polymer flooding pilot test in the Schrader Bluff viscous oil reservoir with an in-situ oil viscosity of 330 cP. However, the use of polymers in heavy oil EOR presents a potential

problem, as this could upset the separation facilities and disrupt existing field operations by negatively influencing the efficiency of oil-water separation after polymer breakthrough into production systems.

With the worldwide application of polymer flooding, the oil-water separation characteristics after the polymer breakthrough have been extensively addressed by field engineers and researchers (Feng et al. 1994, Deng et al. 2002, Wang et al. 2009, Zheng et al. 2011, Wylde et al. 2013, Al Kalbani et al. 2014, Chen et al. 2015, Liu et al. 2015). Two common emulsions, both w/o and o/w emulsion, have been studied to illustrate the potential problems of polymer flooding. As for the o/w emulsion, it is generally believed the presence of polymer can result in highly stable emulsion by increasing produced water viscosity, electronegativity and the strength of interfacial film between oil and water, thus preventing coalescence of oil droplets (Wu et al. 1999, Argillier et al. 2014, Chen et al. 2015, Liu et al. 2015). Moreover, the suspended particles, such as clay, carried by polymer flooding can synergistically absorb on the oil-water interface to further stabilize the o/w emulsion (Wang et al. 2012, Li et al. 2014, Liu et al. 2014). However, the influence of polymer on the stability of w/o emulsion is much more complicated, depending on variable factors such as the crude oil composition, property of polymer, and the presence of surfactant. For example, the studies of Kang et al. (2011) and Liu et al. (2015) showed that polymer enhances the stability of w/o (light oil) emulsion by forming a more rigid oil-water interfacial film. In addition, Dalmazzone et al. (2012), Argillier et al. (2013) and Sjoblom et al. (2017) found the polymer itself had no significant influence on the stability of w/o (heavy oil) emulsion since they determined that the polymer had no interaction with the surface-active agents at the oil-water interface. It was also found that, in the presence of surfactant, the polymer can contribute to the stable intermediate w/o emulsion at low water cut (Dalmazzone et al. 2012, Argillier et al. 2013). Some studies reported that especially the hydrophilic polymer could favor oil-water separation by reducing the stability of the emulsion (Wu et al. 1999, Lin et al. 2008, Argillier et al. 2014, Al-Kayiem and Javed 2017). The unpredictable impact of polymer on w/o emulsion brings a significant challenge in evaluating the influence of polymer on actual oil-water separation in oilfield production systems since the actually produced fluids are composed of both w/o emulsion and o/w emulsion. Therefore, the real oil-water separation issues should be investigated as a whole using the on-site crude oil, produced water, and the injected polymer under specific oilfield conditions to obtain reliable conclusions.

As a consequence, treating produced liquid from polymer flooding has become a great challenge in oilfields where emulsions with enhanced stability occur, as it is of critical importance to produce dry oil and clean water. Many new techniques, such as electrical dehydrator coupled with gravity settling (Liu et al. 2009, Liu et al. 2015), novel crossflow oil-water separator (Deng et al. 2002), new hydrocyclone (Liu et al. 2007) and new flotation device (Chen et al. 2015), have been developed to solve the oil-water separation problems. However, chemical methods, i.e., demulsifiers and water treatment chemistries, are still the most popular techniques due to their effectiveness, ease of implementation, and low cost. Fang et al. (2014) evaluated the demulsification efficiency of cationic surfactants, i.e., alkyltrimethylammonium bromides (CTAB), which were applied to treat produced fluids directly obtained from a heavy oil polymer flooding project in China. They found C₁₄TAB and C₁₆TAB, can effectively break both w/o and o/w emulsions existing in the produced fluids since they were found to be able to reduce interfacial film strength and neutralize the surface charge. Also, researchers have been making an effort to develop new demulsifiers to treat the chemical EOR induced emulsions. For example, Duan and his group (Duan et al. 2014, Zhang et al. 2015) developed a new type of non-ionic demulsifier which could effectively treat the o/w emulsion directly produced from an offshore polymer flooding project. Li et al. (2016) found a novel polyether demulsifier, TPEA19920, which exhibited an excellent performance to treat the produced heavy oil emulsions. Even though the development of demulsifiers has made significant progress, there are still no demulsifiers with universal applicability to process the produced fluids. In general, targeted demulsifiers need to be developed or selected through extensive evaluation tests since they are highly sensitive to the properties of the crude oil, produced water, applied chemicals, and the actual operating conditions.

In this paper, the traditional bottle test method has been employed to investigate the influence of

polymer on the separation of produced liquid prepared in the lab using actual heavy crude oil, produced water, and injected polymer obtained from the pilot test site on ANS and to evaluate the performance of several commercial demulsifiers. Various influence factors, including WC, polymer concentration, demulsifier type and concentration, and compound demulsifier, have been investigated. A radar chart composed of demulsification efficiency, separation speed, water clarity, and optimized dosage has been developed to evaluate the demulsification performance. Finally, the most applicable demulsifier has been proposed for field application.

Experimental Method

Materials

The produced fluid was sampled directly from the wellhead of a production well on polymer flooding pilot site on ANS, which was initially separated by thermal settling. The upper heavy oil was further dehydrated by centrifuge until no water separated, whereas the bottom produced water was filtered by 0.2 μm water-wet filter paper (Tianjin Jinteng Experimental Equipment Co., China) to remove the suspended oil and particulate matter. The properties of heavy oil and produced water are listed in **Table 1** and **Table 2** respectively. The polymer used, Flopaam 3630s having a molecular weight of 18-20 MM Dalton and 30% hydrolysis, was supplied by SNF, Inc. Commercial emulsion breakers, E12085A, E18276A, N1691, and R01319 were used in this study. All chemical reagents such as petroleum ether, methanol, and xylene (VWR International) were used as received.

Table 1–Properties of heavy oil

Density (g/cm^3 , 22 °C)	Viscosity (cP, 22 °C)
0.9557	3500

Table 2–Properties of produced water

TDS (ppm)	pH	Conductivity ($\mu\text{S}/\text{m}$)
6645	5.61	8128

Polymer solution preparation

A polymer mother solution of 1,000 ppm concentration was prepared by dissolving a certain amount of polymer powder into the filtered produced water under gentle stirring at room temperature for 24 h until no fish eyes were remaining. Subsequently, the mother solution was diluted with the filtered produced water to obtain the desired polymer solution with concentrations of 150 ppm, 400 ppm, and 800 ppm. The apparent viscosity of each polymer solution was measured by Brookfield viscometer (Brookfield Engineering Laboratories Inc., USA) as a function of shear rate at 130 °F.

Demulsifier solution preparation

10,000 mg/L demulsifier original solution was prepared by dissolving a certain amount of demulsifier into a specific solvent. Oil soluble demulsifiers, E12085A, E18276A, and R01319, were dissolved into xylene, and water soluble demulsifier, N1691, was dissolved into methanol.

Emulsion preparation

The separated heavy oil and produced water or polymer solution were added to a beaker according to designed ratios (20% WC and 50% WC) and preheated to 130 °F in the water bath to promote the incorporation of two phases. The IKA Ultra-Turrax T18 Digital homogenizer was used to stir the mixture at 5000 rpm for 3 min to prepare the emulsion.

Microscopic observation

A small drop of the prepared emulsion was immediately transferred by a syringe onto a glass slide. The emulsion was observed using an Olympus BX60 microscope at the magnification of 20 \times 20. Several images on each slide were captured to ensure uniformity.

Bottle test method

In gravitational separation tests, the emulsion was transferred into a graduated tube immediately after preparation. The tube was placed into the water bath to observe the separation characteristics of emulsion under the action of gravity. In chemical demulsification tests, after transferring the prepared emulsion, a certain amount of demulsifier solution was added to the test tube based on the volume of the emulsion. The tube was shaken by hand for 3 minutes to mix the emulsion and demulsifier thoroughly and then kept in the water bath for the chemical separation test. All the separation tests were performed at the temperature of 130 °F. During the separation process, the separated water volume and the volume fraction of each phase (oil, emulsion and aqueous phase) were recorded with respect to time. In addition, the sharpness of the interface between the oil phase and the separated water phase and the clarity of the separated water was observed. Eventually, the oil content in separated water was measured after 24 hours by using Genesys 10s UV-Vis spectrophotometer (Thermal Fisher Scientific Inc., USA).

Results and Discussion

The viscosity of polymer solutions

The viscosity of prepared polymer solutions as a function of shear rate is shown in **Figure 1**. Polymer solution at each concentration can be characterized as non-Newtonian fluid showing shearing-thinning behavior as the viscosity of polymer solution decreased with the shear rate. The viscosity-shear rate decline trend clearly complies with the power-law model, which is consistent with the study of Gao (2013). It is also obvious that higher polymer concentration led to higher viscosity.

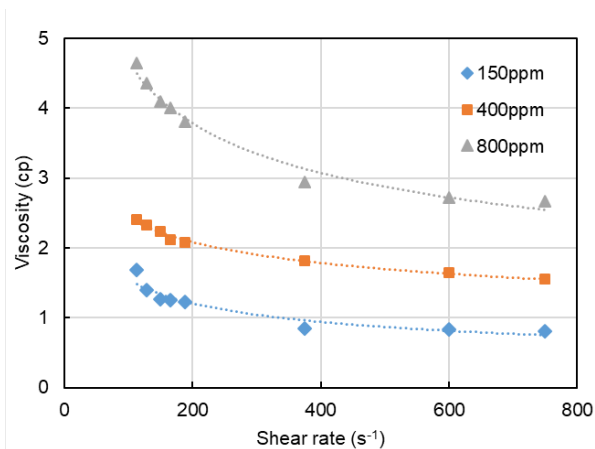
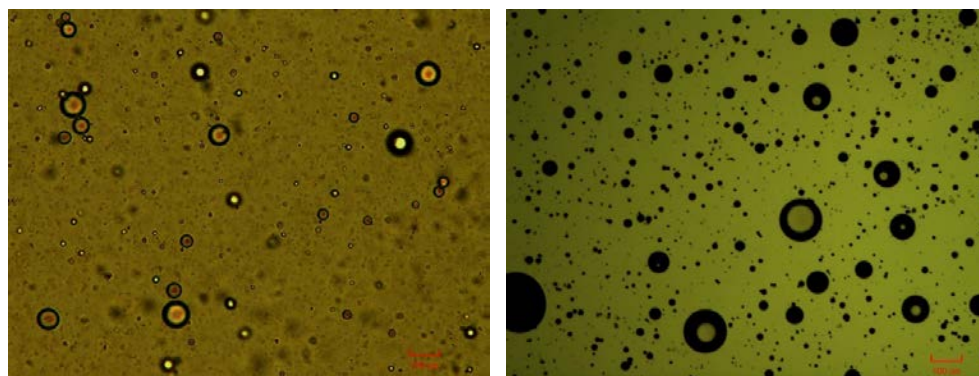


Figure 1–The viscosity of polymer solutions as a function of shear rate

Gravitational separation behavior

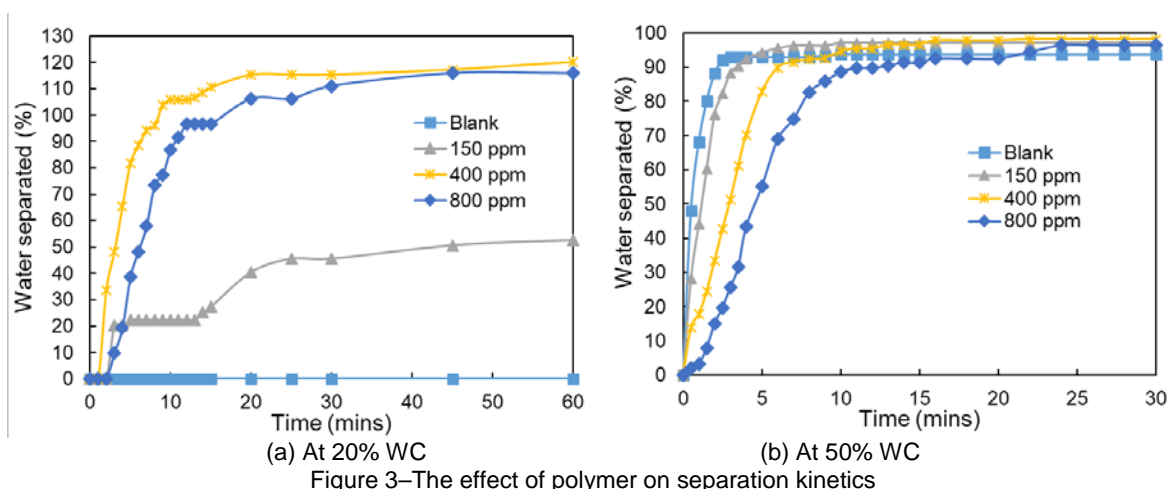
The micromorphology and separation behavior of heavy oil emulsions were studied. During the microscopic observation, the impact of the water cut was evaluated. In the study of separation behavior, water separation kinetics, oil content in the separated water (OIW) and volume fraction of the separated phases were analyzed at various water cut and polymer concentration.

Micromorphology of emulsion. **Figure 2** shows the micromorphology of emulsion generated at 20% WC and 50% WC with no addition of polymer. At 20% WC, w/o emulsion was observed with water droplets dispersed in the oil phase as seen from Figure 2(a). At 50% WC, the droplets in forms of w/o emulsion were trapped in the water phase, forming complex w/o/w emulsion as indicated by Figure 2(b).



(a) At 20% WC (b) At 50% WC
Figure 2–Microscopic images of emulsion (a) at 20% WC and (b) at 50% WC

The effect of polymer on separation kinetics. Water separation kinetics can be used to describe the emulsion stability; the faster the water can separate, the less stable the emulsion is (Nguyen and Nick, 2011). **Figure 3** shows the impact of polymer concentration on separation kinetics at 20% and 50% WC.



With no addition of polymer (blank sample), the emulsion generated at 20% WC was much more stable than that at 50% WC. The w/o emulsion generated at 20% WC was stable for at least 24 h (not shown in the plot but was observed); however, the w/o/w emulsion generated at 50% WC was quite unstable, separating into two layers in less than 5 min.

For emulsions at 20% WC, as shown in Figure 3(a), the water separation was accelerated in the presence of polymer compared to the blank sample. The destabilization effect of polymer for w/o emulsion has been previously reported due to the increased coherent energy of polymer molecules (Wu et al. 1999). It could also be attributed to the increased density of polymer solution (Sjoblom et al. 2017). According to the Stokes equation:

$$v = \frac{\Delta\rho g d^2}{18\eta} \quad (1)$$

Where v is the sedimentation or creaming rate, $\Delta\rho$ is the density difference between oil and water, d is the diameter of the dispersed droplets, and η is the viscosity of the continuous phase. As the viscosity for the continuous oil phase is constant, the increased density of polymer solution contributes to larger $\Delta\rho$, facilitating the sedimentation of water droplets. To be noted in Figure 3(a) is the water separation in excess of 100% at 400 ppm and 800 ppm polymer concentration, which is attributed to the intermediate layer (it is believed to be an o/w emulsion layer, see **Figure 5**) that was included in the separated water volume since the interface between the water layer and the intermediate layer cannot be well defined.

It is also noteworthy that although the water separation was enhanced with the addition of polymer at 20% WC compared to the blank sample, the amount of separated water at first increased with increasing

polymer concentration until a critical point of 400 ppm was reached and then decreased. Even though such critical point has not been reported previously, this trend may be due to the phase inversion (the w/o emulsion could be converted to o/w emulsion) resulting from the increase of polymer concentration (Preziosi et al. 2013, Liu et al. 2015). Thus, in this study, water continuous emulsion could be generated starting from the polymer concentration of 400 ppm at 20% WC. And then, the reduced water separation after the critical point could be attributed to the increased viscosity of the continuous phase (i.e., water phase).

For water continuous emulsion at 50% WC, as shown in Figure 3(b), the presence of polymer impeded the phase separation, which could be attributed to the increasing viscosity of polymer solution as described in Figure 1. Whereas, there was not much difference in final water separation volume as the residence time extended to 30 min, implying extending settlement time is one potential method to minimize the stabilization effect of polymer. To be noted, the final separation efficiency (i.e., at 30 min) with the presence of polymer was slightly higher than that of the emulsion without polymer. It is because of the massive oil droplets in the separated water, which could affect the measurement of separated water volume.

The effect of polymer on separated water quality. The effect of polymer on the separated water quality after 24 hours is displayed in Figure 4. In general, the polymer had a negative effect on the separated water quality, and the OIW significantly increased with increasing polymer concentration. That is because adding polymer could generate more stable o/w emulsion in the separated water phase (Liu et al. 2015). When the OIW at tested polymer concentrations is compared, the oil content at 50% WC is nearly double than at 20% WC, which implies that the water treatment would be much more challenging at higher WC. That is because, at higher water cut, the distance between oil droplets becomes larger which makes it harder to collide and coalesce.

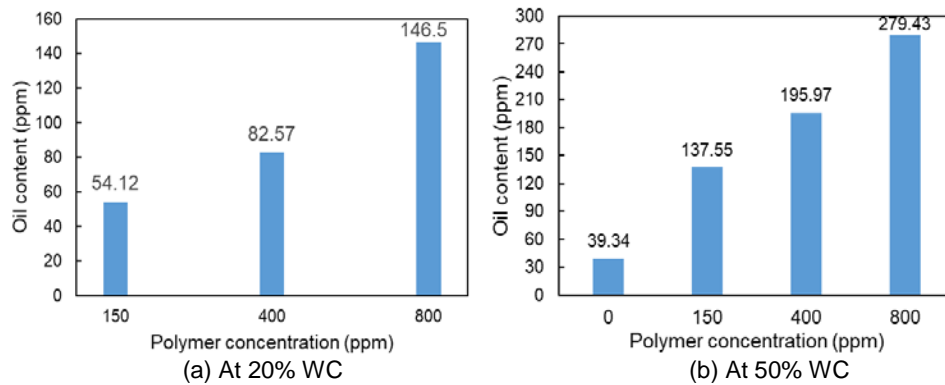


Figure 4—The effect of polymer on water quality

The effect of polymer on the volume fraction of phases. It is worth mentioning that the addition of polymer resulted in a concentrated o/w emulsion layer sandwiched between the top oil layer (w/o emulsion) and the bottom separated water layer during the oil-water separation process, as shown in Figure 5. According to our observation, the interfaces between this intermediate layer and the top layer or bottom layer became clearer with prolonged settling time. After 24 hours, this intermediate emulsion layer still existed, and the intermediate layer at 20% WC was thicker than that at 50% WC. At the same water cut, the more the separated water, the thicker the intermediate layer, which was more difficult to eliminate. The thickness change of this layer with respect to time was also related to the water cut. The intermediate layer became thinner with time at 20% WC but slightly thicker at 50% WC. The formation of the middle emulsion layer may result from the higher viscosity of the aqueous phase generating concentrated stable o/w emulsion.

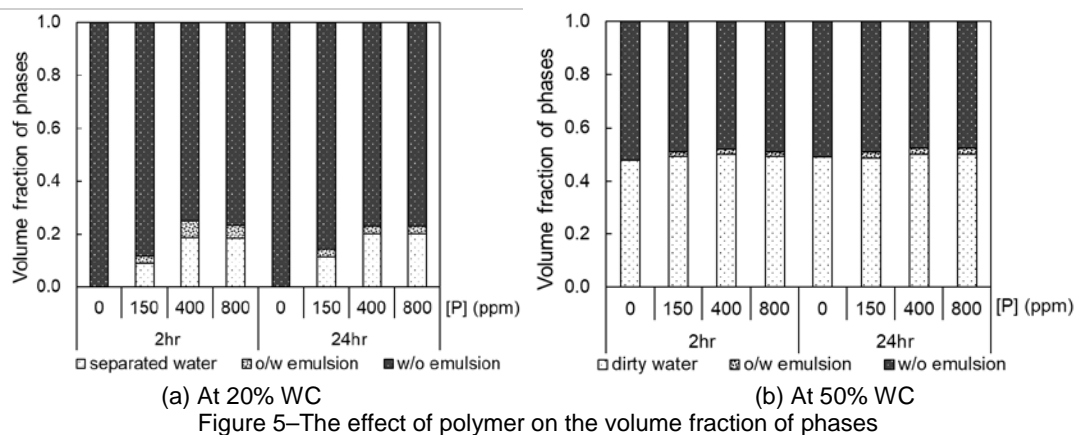


Figure 5–The effect of polymer on the volume fraction of phases

Chemical demulsification without polymer

In most oilfields, the typical requirement for the total separation process is to produce dry oil and clean water. Dry oil should contain no more than 0.3% water by volume and clean water should have an oil content of less than 100 ppm, preferably 50 ppm (Hirasaki et al. 2010). The separation process on ANS consists of a slug catcher (130 °F), a heater and a separator (170 °F). In our experiment, we mimicked the first stage separation in the slug catcher, the demulsification efficiency of over 90% and oil content of less than 100 ppm would be acceptable (Hilcorp, personal communication, July 05, 2019).

The performance of individual demulsifiers. Figure 6 shows the performance of four types of demulsifiers with a dosage of 100 ppm at 20% WC. As can be seen, three oil-soluble demulsifiers, E12085A, E18276A, and R01319, promoted oil-water separation, and clear separated water was obtained with an oil content less than 20 ppm. The demulsification efficiency of the three oil-soluble demulsifiers at 12 hours in decreasing order was E18276A, E12085A and R01319. It also can be seen that, as for E18276A, water separated rapidly in the first 2 hours and then slowly until it reached the plateau after 6 hours. However, as for E12085A and R01319, the time needed to reach the plateau was 10 hours, indicating a slower separation rate. In terms of OIW shown in Figure 6(b), E18276A yielded the lowest value. Therefore, E18276A is the best emulsion breaker from the perspective of demulsification efficiency, separation rate and OIW. Whereas, in the case of water-soluble demulsifier, N1691, no water separation was observed, since N1691 can be rarely soluble in the continuous oil phase, causing the barriers to the diffusion and adsorption process of N1691 molecules on the oil-water interface (Kang et al. 2018). Note that even though E18276A had the best performance, it did not render complete separation of the water phase in the measured time scale.

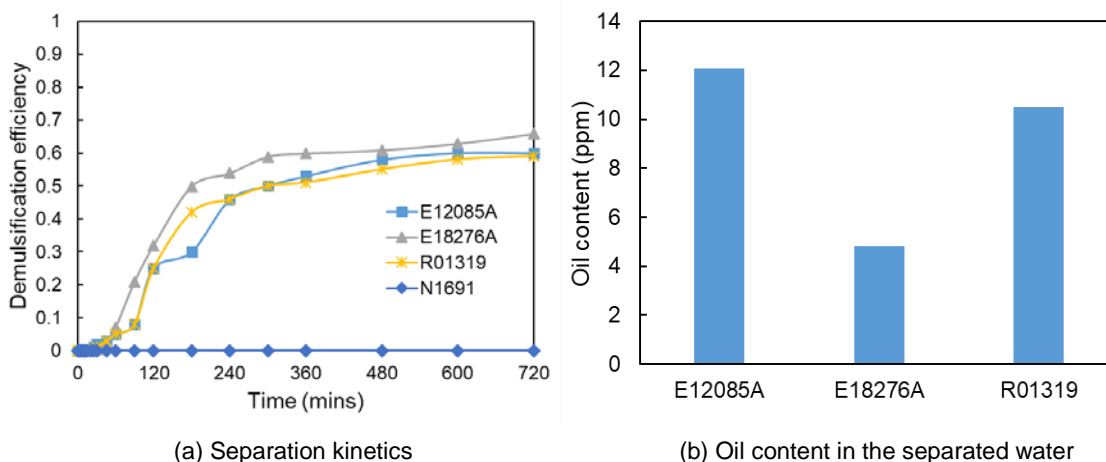


Figure 6–The performance of demulsifiers on oil-water separation at 20% WC

The performance of the four demulsifiers at a dosage of 100 ppm for emulsion generated at 50% WC is shown in **Figure 7**. As can be seen from Figure 7, the addition of the four demulsifiers generally impeded the oil-water separation but helped to reduce OIW. However, N1691 had an advantage over the other three oil-soluble demulsifiers in terms of separation speed, resulting in higher separation efficiency within 60 mins, since the unstable w/o/w emulsion was converted to stable w/o emulsion after the addition of three oil-soluble demulsifiers as shown in **Figure 8**. Thus, the slower separation occurred due to the high viscosity of continuous heavy oil. Comparing Figure 6(a) and Figure 7(a), it can be seen that although R01319 was not as good as E18276A for emulsion generated at 20% WC, R01319 had a higher separation speed than E18276A at 50% WC, implying R01319 has poor diffusivity in oil but could disrupt the interfacial film effectively. Note that if the settlement time was 4 hours, E12085A performed better than N1691 and R01319 with the highest efficiency and lowest oil content in water. Generally, no emulsion breaker can perform well for emulsion at 50% WC from the standpoint of the three criteria.

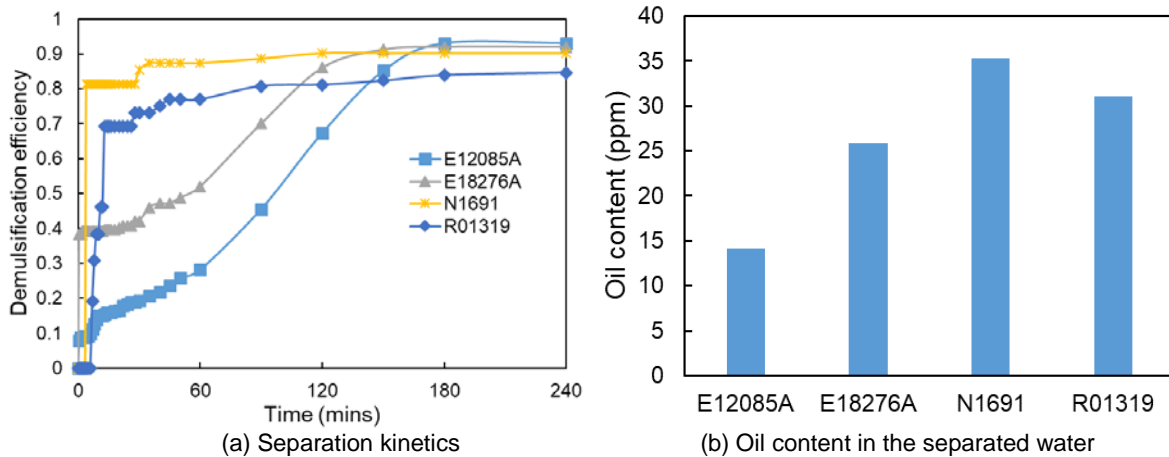


Figure 7–The performance of demulsifiers on oil-water separation at 50% WC

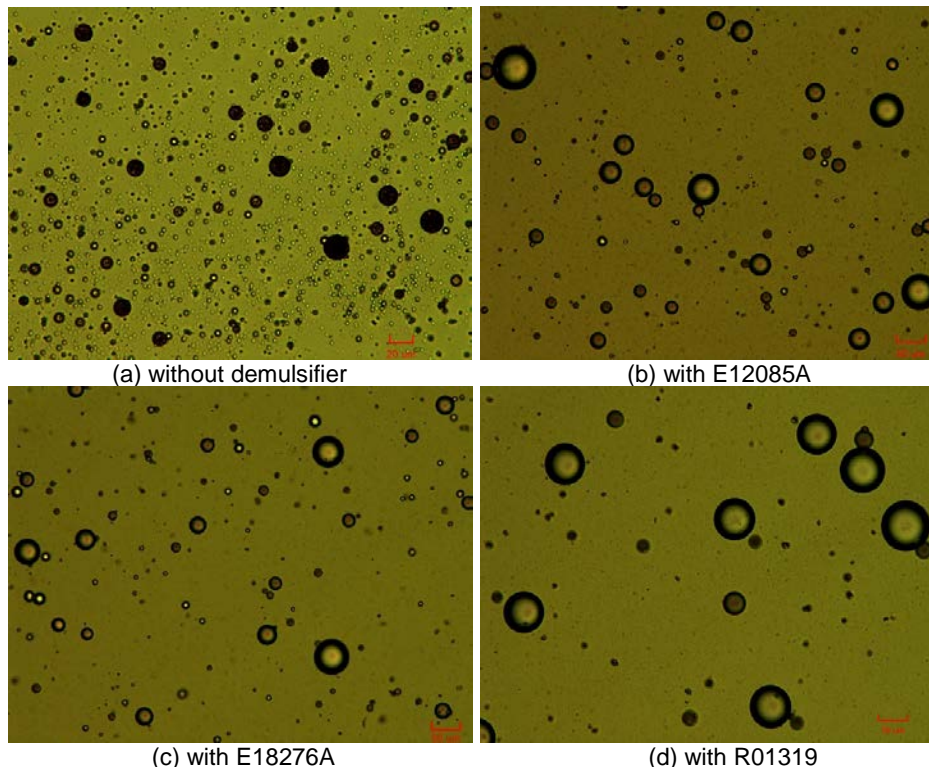


Figure 8–Microscopic images of emulsions (a) without demulsifier (b) with E12085A (c) with E18276A (d) with R01319

The effect of demulsifier dosage. Demulsifier dosage is one important factor affecting the demulsification performance and thus in determining the overall cost of demulsification in the application. Besides, overdosage of demulsifiers may lead to counterproductive effects, such as resulting in more stable w/o emulsion and producing stable reverse o/w emulsion (Manning and Richard, 1995). As shown in Figure 6, the best demulsifier, E18276A, did not yield a separation efficiency of over 90% at the dosage of 100 ppm. Therefore, the influence of the demulsifier dosage of E18276A on oil-water separation was investigated for which the results are shown in **Figure 9**. Although increased dosage enhanced the demulsification efficiency, it was offset by higher OIW.

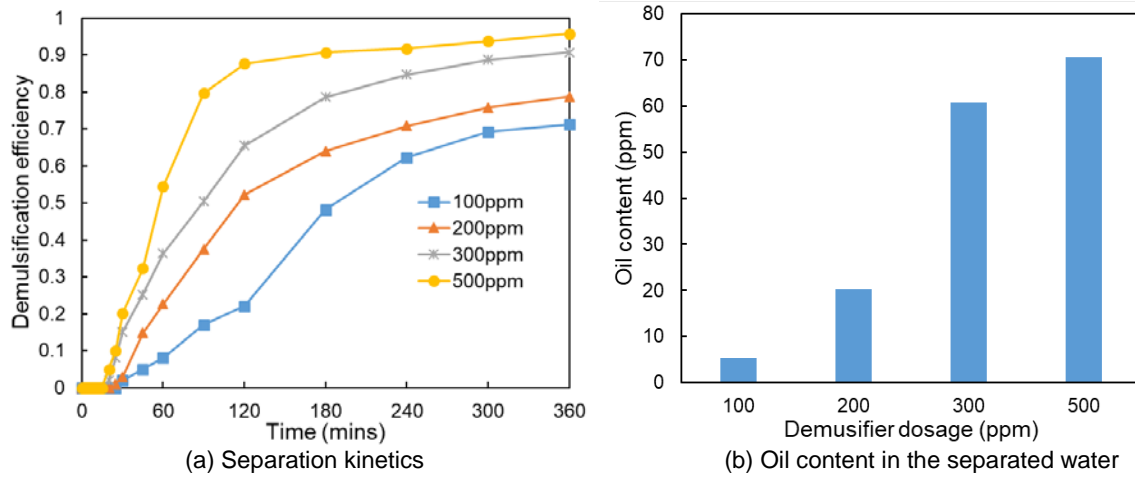


Figure 9–The effect of dosage on the performance of E18276A for emulsions at 20% WC

The performance of the compound demulsifiers. Multiple compound emulsion breakers were also proposed and evaluated to find the best combination which can make use of the advantage of individual emulsion breaker to a maximum extent. Based on the analysis for each emulsion breaker performance in previous tests, E12085A produced the best water quality and the highest separation efficiency if the residence time was long enough; E18276A had the best performance for w/o emulsion; N1691 was capable of breaking the emulsion at 50% WC in a short residence time at low dosage; R01319 had better ability to disrupt the interfacial film. Thus, the performance of compound emulsion breakers, E12+N16, E12+R13 and E12+E18, were investigated at 100 ppm, as shown in **Figure 10**. E12+E18 is the most promising compound emulsion breaker which achieved a faster and more efficient separation than either E12085A or E18276A at the same dosage. E12+N16 increased the separation efficiency from 65% to 80% at 2 hours compared with E12085A itself and yielded better water quality than either E12085A (Figure 10 (b)) or N1691 (Figure 7(b)). However, the combination of E12+R13 is undesirable because it lowered the final separation efficiency.

In order to provide a comprehensive analysis, the performances of the qualified emulsion breakers for emulsion at 50% WC without polymer are compared in the radar chart (**Figure 11**) in terms of demulsification efficiency, water clarity, separation speed and dosage. These four parameters are defined as the dimensionless number in the following equations:

$$Efficiency = \frac{V_s}{V_t} \quad (2)$$

$$Water\ clarity = \frac{C_a - C_m}{C_a} \quad (3)$$

$$Separation\ speed = \frac{T_m - T_e}{T_m} \quad (4)$$

$$Dosage = \frac{C_{max} - C}{C_{max}} \quad (5)$$

where, V_s is the separated water volume at 4 hours;

V_t is the total water volume;

C_a is the allowed oil content in water, typically less than 100 ppm;

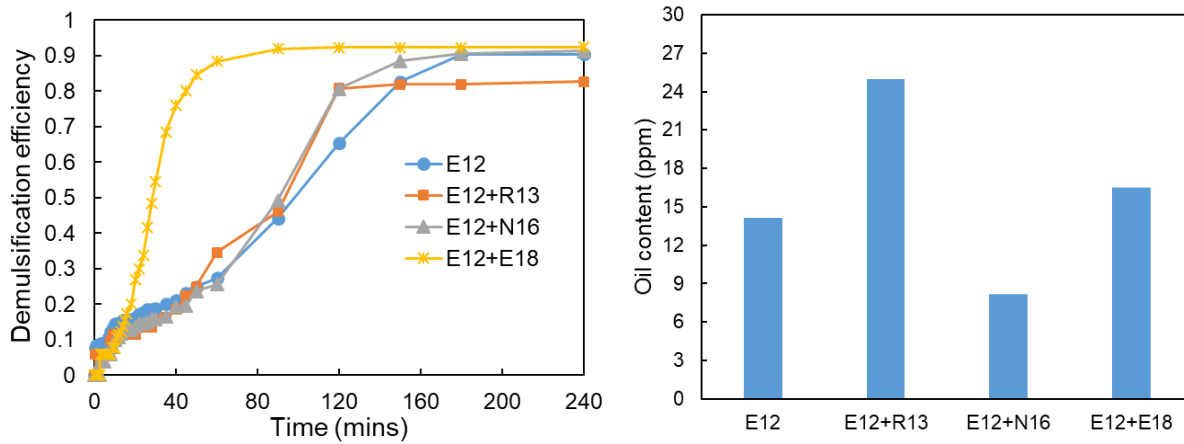
C_m is the measured oil content in water after 24 h;

T_m is the measurement time for separation which is 4 h;

T_e is the time required to reach the separation equilibrium;

C_{max} is the maximum dosage of emulsion breaker used in the experiment;

According to the definition, the larger the enclosed area in the radar chart, the better the performance of the corresponding emulsion breaker. It is obviously seen from Figure 11, E12+E18, E12+N16 and N1691 are the better performing demulsifiers. E12+E18 is the best emulsion breaker in terms of dosage and separation efficiency; E12+N16 is the best emulsion breaker in terms of water clarity; N1691 is the best emulsion breaker in terms of dosage and separation speed.



(a) Separation kinetics (b) Oil content in the separated water
 Figure 10–The performance of compound demulsifiers at 50% WC

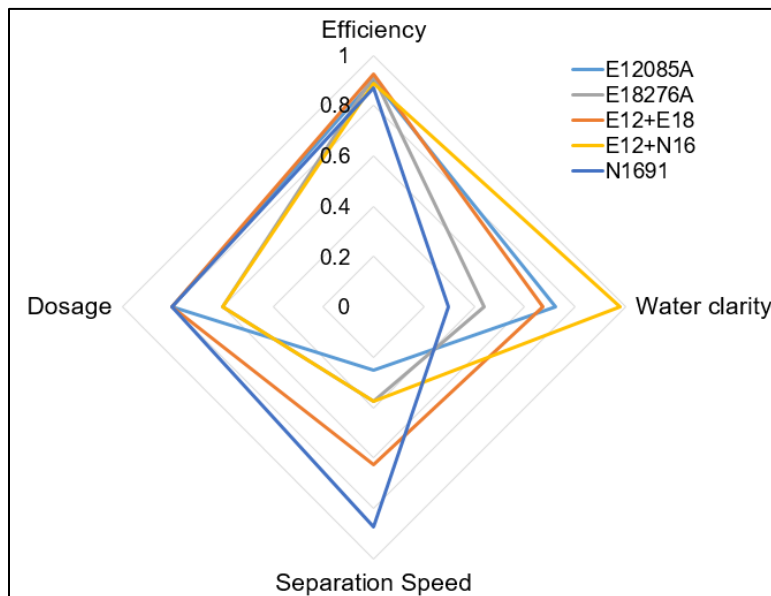


Figure 11–Radar chart for the performance of demulsifiers at 50% WC

Chemical demulsification in the presence of polymer

In the presence of polymer, the performance of the four individual emulsion breakers and the aforementioned compound emulsion breakers were evaluated and the emulsion breaker with the best performance was proposed. The effect of polymer concentration on the proposed emulsion breaker was also investigated.

The performance of individual demulsifiers. The performance of the four demulsifiers with the dosage of 100 ppm was evaluated for the emulsion with 150 ppm polymer at 20% WC. **Figure 12 (a)** shows that all three oil-soluble demulsifiers performed better than the water soluble demulsifier. According to the observation during the separation process, the three oil-soluble demulsifiers could effectively eliminate the intermediate layer described in Figure 5 and obtain a clear water phase. As can be seen from **Figure 12**, E18276A had the best performance in terms of separation efficiency, separation speed and OIW; however, the dosage appeared to be insufficient to achieve a separation efficiency above 90%.

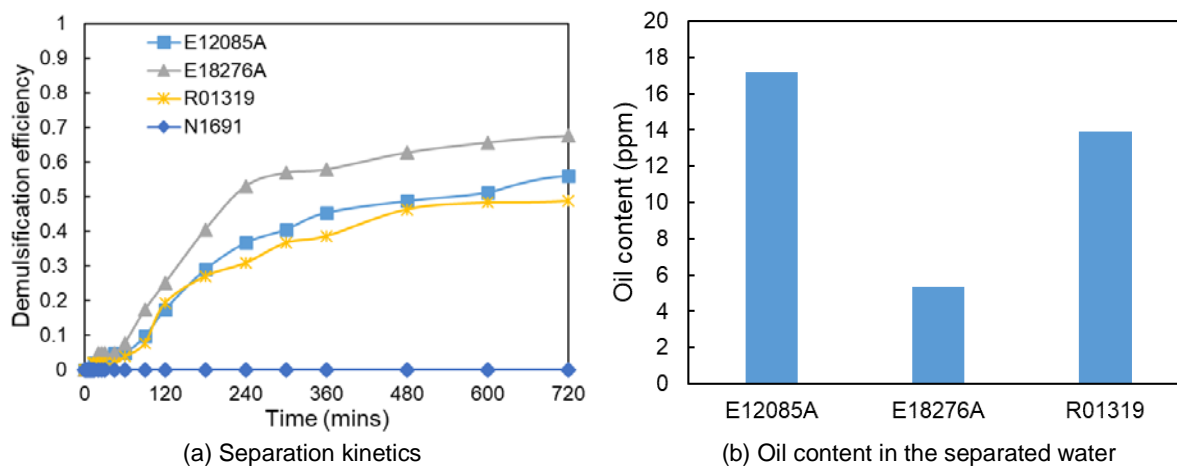


Figure 12–The performance of demulsifiers for emulsion with 150 ppm polymer at 20% WC

The performance of the emulsion breakers with the dosage of 50 ppm for the emulsion with 800 ppm polymer at 50% WC is shown in **Figure 13**. All the four emulsion breakers achieved a separation efficiency of over 90% in less than 15 mins, and the three oil-soluble emulsion breakers achieved an OIW lower than 50 ppm. However, the water-soluble emulsion breaker, N1691, yielded an unsatisfactory OIW of 160 ppm. Therefore, the application of N1691 after polymer breakthrough may be limited due to its poor performance. E12085 and R01319 are highly competent for emulsions in the presence of polymer at 50% WC.

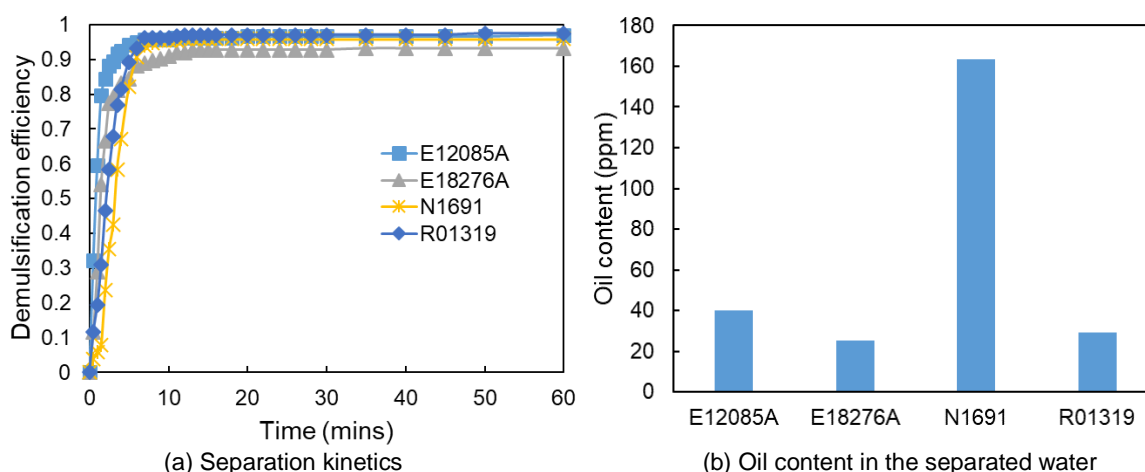


Figure 13–The performance of demulsifiers for emulsion with 800 ppm polymer at 50% WC

The performance of the compound demulsifier. The compound emulsion breakers, E12+E18 and E12+N16, were also evaluated for emulsion with 150 ppm polymer at 20% WC. The performance of the compound emulsion breakers is shown in **Figure 14**. Since there was no water separation for E12+N16, Figure 14 only shows the performances of E12+E18 and E18276A. At a dosage of 100 ppm, the separation efficiency of E12+E18 was slightly lower than that of E18276A. However, when the dosage was above 100 ppm, E12+E18 yielded a similar separation efficiency and lower OIW.

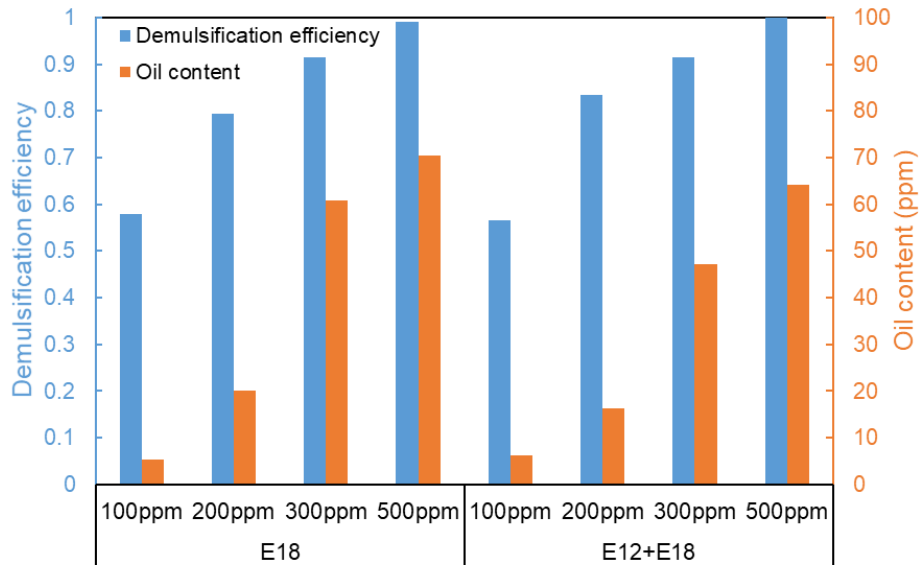


Figure 14–The performance of compound demulsifiers for emulsion with 150 ppm polymer at 20% WC

As mentioned in the previous analysis (Figure 13), two individual emulsion breakers E12085A and R01319 are most applicable to treat emulsion with 800 ppm polymer at 50% WC. The performances of compound emulsion breakers, E12+E18 and E12+N16, are compared with those of E12085A and R01319 by radar chart in **Figure 15**. It can be seen that E12+E18 exhibited the best performance.

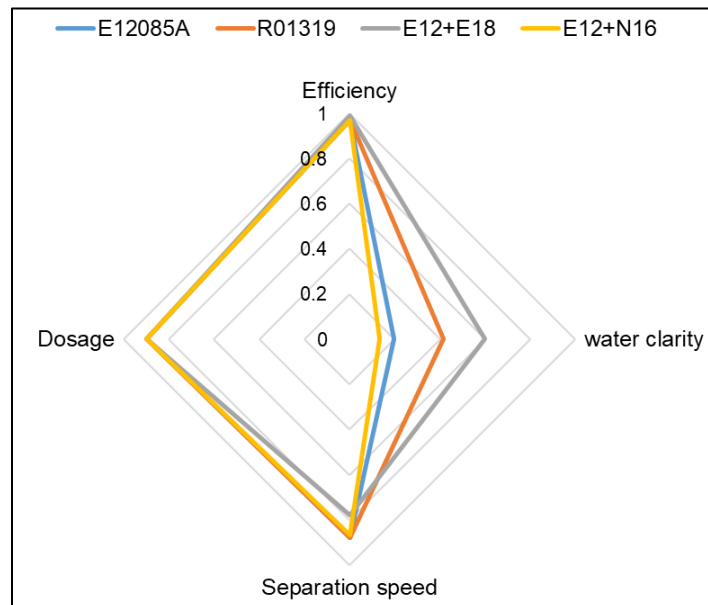


Figure 15–The performance of demulsifiers for emulsion with 800 ppm polymer at 50% WC

The effect of polymer concentration. Based on the above analysis, compound emulsion breaker, E12+E18, has the potential to be used for emulsions generated at both 20% WC and 50% WC. Since the varying water cut and polymer concentration after breakthrough can change the demulsifier demand, the influence of polymer concentration on the performance of demulsification was also investigated at the two water cuts. The effect of polymer concentration on the demulsification performance of E12+E18 for emulsion at 20% WC is shown in **Figure 16**. In this case, polymer concentration had no obvious effect on the demulsification performance. E12+E18 with a dosage of 500 ppm could help to achieve the separation requirements at varying polymer concentration. It may be expected that the required emulsion breaker dosage might be increased or a new demulsifier might be needed when the polymer concentration is above 800 ppm due to the decrease of demulsification efficiency and increase of OIW.

For emulsion generated at 50% WC, the effect of polymer concentration on the demulsification performance of E12+E18 is shown in **Figure 17**. It is obvious that at the same dosage of 50 ppm, the demulsification efficiency was higher in the presence of polymer. In other words, a higher demulsifier dosage would be required in the case of no polymer.

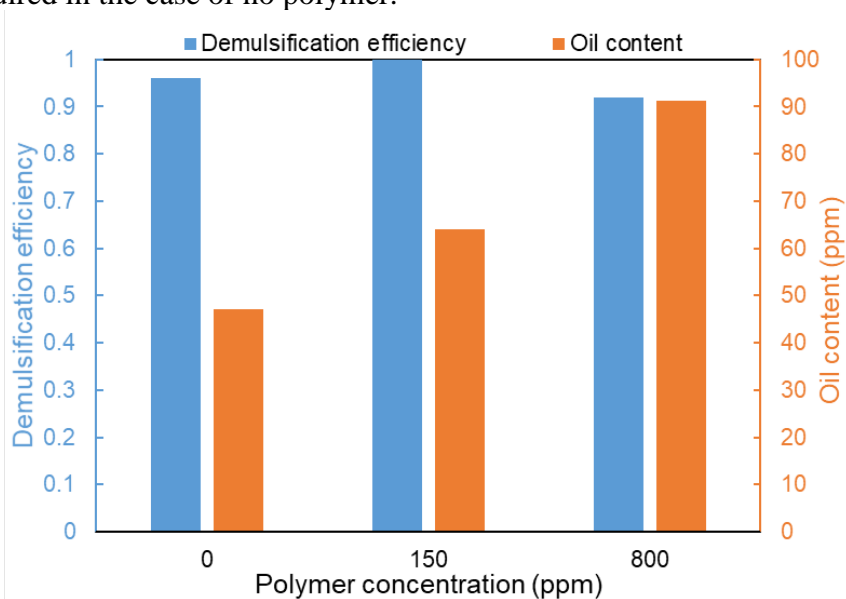


Figure 16–The effect of polymer concentration on demulsification for emulsion at 20% WC

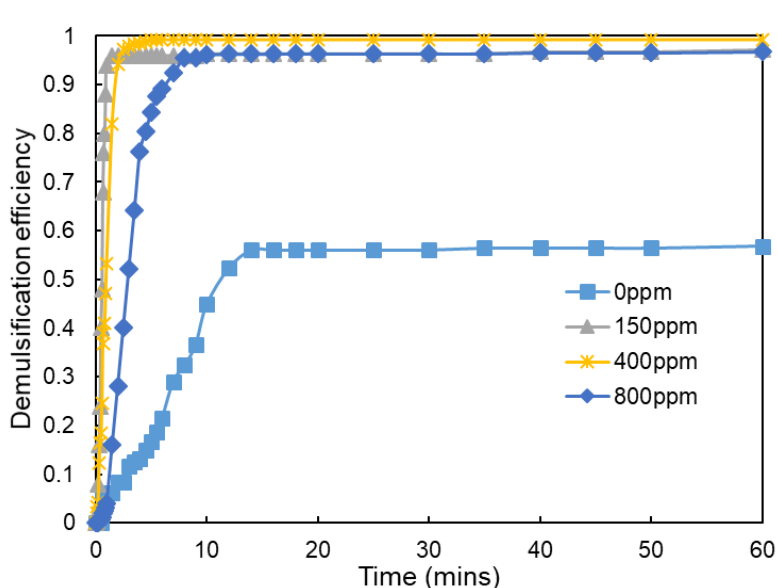


Figure 17–The effect of polymer concentration on demulsification for emulsion at 50% WC

Conclusions

In the framework of this study, the gravitational and chemical separation behavior of heavy oil emulsion prepared with actual heavy oil and produced water from the pilot site was investigated by the bottle test method against various influence factors. The main conclusions are as follows:

For the gravitational separation, polymer generally favored the oil-water separation for emulsion at 20% WC but in a complex manner. The maximum water volume was separated when the polymer concentration reached 400 ppm, but further increasing polymer concentration reduced the water separation. For emulsion at 50% WC, the emulsion became more stable with increasing polymer concentration which resulted from the increased viscosity of polymer solution. It is also observed that polymer resulted in poor water quality and contributed to the formation of a stable intermediate o/w emulsion layer regardless of water cut which was also attributed to the increased viscosity of the aqueous phase.

For the chemical demulsification, oil soluble demulsifiers exhibited better performance than water soluble demulsifier for emulsions both with and without polymer at 20% WC. E18276A was found to be the most effective emulsion breaker at the dosage of 500 ppm in terms of separation efficiency, separation speed and water clarity. As for emulsion at 50% WC, no individual emulsion breaker could perform the best from the standpoint of all three criteria. In this case, water soluble demulsifier N1691 exhibited the fastest separation in the absence of polymer; whereas the presence of polymer reduced the separation speed of N1691 and resulted in higher OIW by preventing the coalescence of oil droplets. E12085A yielded better performance in terms of separation efficiency and water quality for emulsion at 50% WC, irrespective of the polymer; while the disadvantage of E12085A lied in the slowest separation when the polymer was absent.

In spite of the complicated interactions involved in the system of heavy oil, produced water, polymer, and demulsifier, the compound emulsion breaker, E12+E18, was found to be the most effective demulsifier which could be potentially applied to the ANS polymer flooding pilot since it could achieve satisfactory demulsification performance at intricate operational conditions.

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Nomenclature

C_a = the allowed oil content in water, ppm [$\mu\text{g/g}$]

C_m = the measured oil content in water after 24 h, ppm [$\mu\text{g/g}$]

C_{max} = the maximum dosage of emulsion breaker used in the experiment, ppm [$\mu\text{g/g}$]

d = the diameter of the dispersed droplets, m

g = acceleration of gravity, m/s^2

OIW = oil content in water, ppm [$\mu\text{g/g}$]

ppm = parts per million, [mg/L] or [$\mu\text{g/g}$]

V_s = the separated water volume at 4 h, mL

V_t = the total water volume, mL

WC = water cut in percentage

TDS = total dissolved solid, ppm [$\mu\text{g/g}$]

T_m = the measurement time for separation, h

T_e = the time required to reach the separation equilibrium, h

η = the viscosity of the continuous phase, Pa·s [$\text{kg}/(\text{m}\cdot\text{s})$]

v = the sedimentation or creaming rate, m/s

$\Delta\rho$ = the density difference between oil and water, kg/m^3

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