Assessment of Surfactant Flooding With Variations of Slug Injection Strategies in Waterflooded Reservoir

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***Abstract*—Injection of surfactant into waterflooded reservoir which has considerably high water saturation may cause a reduction in surfactant efficiency by means of surfactant dilution and adsorption. Therefore, to maintain expected lowest interfacial tension (IFT) condition, large amount of surfactant, which leads to higher cost, is inevitable. Several studies have observed that reduction in surfactant concentration slug at the late time can cause a shift in surface equilibrium, resulting in desorption of retained active surfactant agents and therefore, it is possible to obtain benefit from this phenomenon to achieve longer period of the lowest IFT condition while maintaining the amount of surfactant used. Hence, this study aims to evaluate effects of two-slug surfactant flooding compared to single-slug while maintaining amount of surfactant used constant in waterflooded reservoir. The performance is evaluated based on additional oil recovery using STAR® reservoir simulation program. Simulated results indicated that two-slug surfactant injection yields better oil recovery than conventional single-slug surfactant flooding due to benefit of sacrificial adsorption and desorption process of active surfactant. Selecting type of two-slug surfactant flooding strategy would depend on surfactant concentration of single-slug which is chosen for modification; whereas, the selection of magnitude of concentration contrast between two slugs would depend on placement of surfactant mass ratio.**

***Index Terms*: Surfactant adsorption, surfactant desorption, surfactant flooding**

I. INTRODUCTION

In many oil fields, large amount of remaining oil is still left behind after secondary recovery stage. This may be due to unfavourable wetting condition, which causes high capillary pressure, making external energy from secondary recovery to be insufficient. For this reason, Enhance Oil Recovery (EOR), which is a process where external fluids that are absent in the reservoir are injected to physically and chemically interact with reservoir rock and fluids to generate a favourable condition for oil production. One of the widely used EOR techniques is surfactant flooding, which is a technique performed to reduce interfacial tension (IFT) at interface between two immiscible fluids. The reduction in IFT enables oil to emulsify into flowing aqueous phase in a form of small droplet or emulsion. This small form of droplet can easily pass through pore throats [1,2].

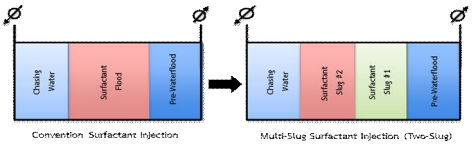


Fig. 1: Multiple-slug surfactant flooding development diagram.

However, introduction of surfactant into the waterflooded reservoir which has considerably high water saturation may cause the reduction in surfactant efficiency by means of surfactant dilution and surfactant adsorption. Therefore, in order to maintain expected lowest interfacial tension (IFT) condition, large amount of surfactant is inevitable. This is a critical economical challenge for surfactant flooding process owing to the high cost of surfactant agent.

Though, it is possible to overcome this challenge by executing suitable injecting sequence. The surfactant solution could be divided into multiple slugs with different surfactant concentrations, injection rates, and commencement dates. Several studies have observed that reduction in surfactant concentration slug can cause a shift in equilibrium, resulting in desorption of retaining active surfactant monomer. Therefore, it is possible to gain benefit from the change in equilibrium to achieve longer period of expected lowest IFT condition while maintaining the amount of surfactant use.

Somasundaran and Hanna [3] investigated adsorption and desorption of sulfonates by reservoir rock minerals in solution of various sulfonate concentrations. The experimental results indicated that significant amount of sulfonate can be de-abstracted from surface by diluted surfactant concentration.

Gogoi [4] investigated the effects of desorbed surfactant and alkali concentration in the extended waterflood on oil-water IFT reduction and oil recovery. Experimental results indicated a presence of both desorbed surfactant and NaOH in the extended waterflood.

From several literature reviews, it can be seen that surfactant agents not only adsorb onto but can also desorb from rock surface with respect to the change in surfactant concentration in the system. Moreover, these desorbed surfactants could still promote a favorable expected ultra-low IFT condition.

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However, none of literatures have emphasized on injection strategy of multi-slug surfactant with different slug concentration, injection rate, and time to implement surfactant injection after water pre-injection. Hence, this study aims to evaluate the effects of surfactant flooding with multi-slug grading in waterflooded reservoir on the additional oil recovery using STAR® reservoir simulation program.

II. RESEARCH METHODOLOGY

1) Construct reservoir simulation model.
2) Perform waterflooding in constructed reservoir simulation model to obtain reference oil recovery values.
3) Perform surfactant flooding after water pre-injection in single-slug mode where the concentration of surfactant remains constant throughout the surfactant slug. Amount of surfactant used in all cases are fixed.
   - Surfactant concentration: 0.5, 0.75, 1.0 wt.%
   - Injection rate: 500, 750, 1,000 bbl/day
   - Time to implement surfactant flooding after water pre-injection (through watercut at production well): at water break through, 25%, 50%, 75%
4) Perform surfactant flooding in multi-slug grading mode with two-slug. In this stage, surfactant concentration of the #1 and #2 slug are varied to investigate the effects of surfactant concentration reduction and accretion on oil recovery, while maintaining amount of surfactant used to be the same as in previous step for the purpose of comparing results between single-slug injection and multi-slug injection. Four injection strategies of two-slug surfactant flooding with three different mass ratios design are investigated in this section. The four injection strategies include:
   - Reduction-High contrast (R-H)
   - Reduction-Low contrast (R-L)
   - Accretion-High contrast (A-H)
   - Accretion-Low contrast (A-L)

   The following three different designs are investigated:
   - Slug #1 endorsement (80% of surfactant mass is in the slug #1)
   - Slug #2 endorsement (80% surfactant mass is in the slug #2)
   - Surfactant mass is divided equally for slug #1 and #2.

III. RESERVOIR SIMULATION MODEL

STAR® reservoir simulation program, commercialized by Computer Modeling Group (CMG), is employed in this study to construct a simulated reservoir model as well as to investigate the results.

The model is constructed in Cartesian coordinate as shown in **Error! Reference source not found.** According to the reservoir size, effective porosity and initial water saturation, the total effective pore volume of this reservoir model is equivalent to 1.68 MMbbl and Original Oil in Place (OOIP) of 1.34 MMbbl. The reservoir model is constructed as a homogenous model. All essential reservoir data are listed and summarized in **Error! Reference source not found.**.

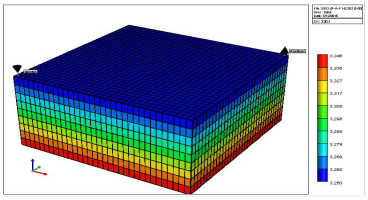


Fig. 2: 3-D reservoir model in STARS reservoir simulation program.

Table I: Data for reservoir model [5,6]

Parameters	Values	Unit
Grid dimension	33 x 33 x 9	Block
Grid size	20 x 20 x 12	ft
Top of reservoir	3,250	ft
Effective porosity (φ)	20	%
Horizontal permeability (k_H)	100	mD
Vertical permeability (k_V)	0.1 k_H	mD
Initial water saturation (S_{wi})	20	%
Reference pressure at datum depth	1,400	psia
Reservoir temperature	122	^oF
Oil gravity	30	^{o}API
Gas gravity	0.7	
Solution Gas Oil Ratio (R_s)	264	SCF/STB
Bubble Point Pressure (P_b)	1,350	psia
Total production time	20	years

This work uses a quarter-five-spot well pattern, where the production and injection wells are placed at the opposite corners. Both wells have identical specifications, where wellbore radius is set to be 0.25 ft., and skin around the wellbore is assumed to be zero with full-to-base perforation. Total simulation period is 20 years, and flooding operation starts from day one.

During the simulation period, certain operation and monitoring are set as well constraints to control activity of the wells. Any violation of well constrains may terminate the reservoir simulation process. Table II and Table III. Summarize well constraints and actions of injection well and production well, respectively.

Table II: Well Constraints Of Injection Well

Constraint	Parameters	Limit/Mode	Value	Unit	Action
Operate	Bottomhole pressure	Max	1,800	psi	Cont.
Operate	Surface water rate	Max	Vary	bbl/day	Cont.

Table III: Well constraints of production well

Constraint	Parameters	Limit/Mode	Value	Unit	Action
Operate	Bottomhole pressure	Min	200	psi	Cont.
Operate	Surface liquid rate	Max	Vary	bbl/day	Cont.
Monitor	Watercut		0.95	fraction	Stop

Relative permeability curves, wettability, and adsorption function are properties between rock and fluid inside the reservoir. In this work, sandstone formation is employed, and therefore wettability of rock formation is water-wet. Initial relative permeability curves are plotted as shown in Fig. 1.

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Sodium Dodecylbenzenesulfonate, which is an anionic surfactant, is chosen as a surfactant agent in this study. IFT and adsorption values as a function of surfactant concentration used in this study are summarized in Table IV. For surfactant flooding models, four additional interpolation sets are constructed with different end-point saturations, relative permeability values at irreducible water saturation and residual oil saturation, and Corey's exponent values as illustrated in Fig. 2. The changes in capillary number of the system are resulted from the alternation of system IFT from the intervention of rock and fluid properties by surfactant agent.

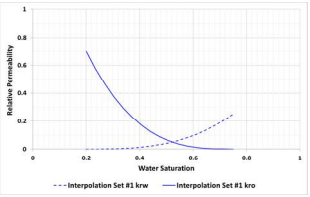


Fig. 1. Initial relative permeability curves for the reservoir model.

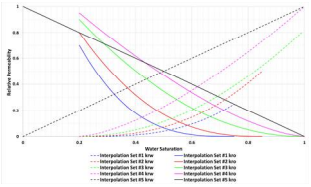


Fig. 2. Relative permeability curves for different interpolation sets.

Table IV: Values of interfacial tension as a function of surfactant concentration [7]

Weight Surfactant (%)	Interfacial Tension (dynes/cm)	Surfactant Adsorption (mg)/(100gm of rock)
0	18.2	0
0.5	0.001	interpolated
1	0.0001	27.5

IV. RESULT AND DISCUSSION

A. Waterflooding Base Case

Waterflooding is performed first in the simulated reservoir model with three different injection rates (500, 750, 1,000 bbl/day). The process starts from the first day of production until one of the production constrains is attained. Simulated results are used as reference values to compare with conventional surfactant flooding and multi-slug grading surfactant flooding in following sections.

Figure 5 shows oil recovery factors obtained from three different injection rates as a function of time for waterflooding base case. According to the result, this yields oil recovery factor up to approximately 53%. This indicates that large amount of oil is still remained inside the reservoir.

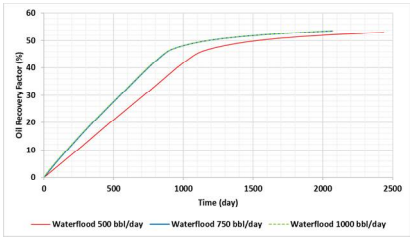


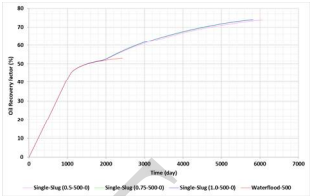
Fig. 3. Oil recovery factors obtained from waterflooding at different injection rates as a function of time.

B. Single-Slug Surfactant Flooding

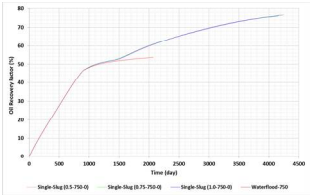
Surfactant flooding in single-slug mode, where the concentration of surfactant remains constant throughout the surfactant slug, are performed in this section. Amount of surfactant used in all cases are fixed, and therefore slug sizes will be changed accordingly, to achieve desired surfactant concentration. The amount of surfactant used in this study is fixed at the boundary condition of 1wt.% and 0.25 PV slug size.

1) Effect of Surfactant Concentration

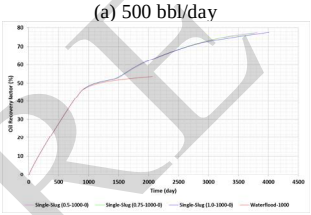
Figure 6 (a), (b), and (c) show graphical results of oil recovery factors of waterflooding compared to surfactant flooding at different surfactant concentrations. According to the result, oil recovery factor of surfactant flooding at any surfactant concentration yields greater value compared to waterflooding base case. The additional oil recovery due to surfactant flooding is approximately 22%. This indicates that the presence of surfactant agent gives benefits in term of additional oil recovery.



(a) 500 bbl/day



(b) 750 bbl/day



(c) 1,000 bbl/day

Fig. 4. Oil recovery factors of surfactant flooding implemented at water breakthrough with different surfactant concentrations compared to oil recovery factors of waterflooding at three different fixed injection rates.

However, at any particular flow rate and time to implement surfactant flooding, changes in surfactant concentration does not yield much different in term of final oil recovery. This is owing to the amount of surfactant used is fixed for all cases.

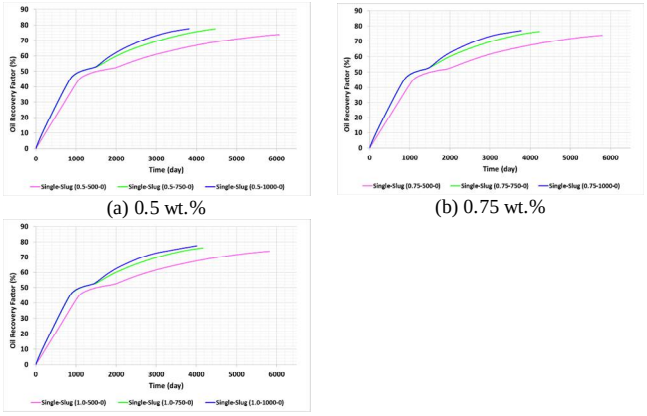
Hence, it can be concluded in this section that surfactant concentration at fixed amount of surfactant use does not affect the ultimate oil recovery but slightly shows effect on rate of change of oil recovery factor and oil production.

2) Surfactant Injection Rate

According to the results in Fig. 5, it can be observed that ultimate oil recovery as well as the rate of recovering increases as surfactant injection rate is increased. This phenomenon can be explained through the concept of surfactant retention time as well as the adsorption effect. The effects of adsorption can be obviously seen at high surfactant concentration. As shown in Fig. 6, adsorption profile illustrates greater area of surfactant adsorption at higher injection rate, indicating that the surfactant solution could reach and extract more residual oil in larger range. This is because at higher injection rate the contact time between surfactant solution and rock surface is diminished.

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(a) 0.5 wt.% (b) 0.75 wt.%

(c) 1.0 wt.%

Fig. 5. Oil recovery factors obtained from different injection rates at three different surfactant concentrations implemented at water breakthrough as a function of time.

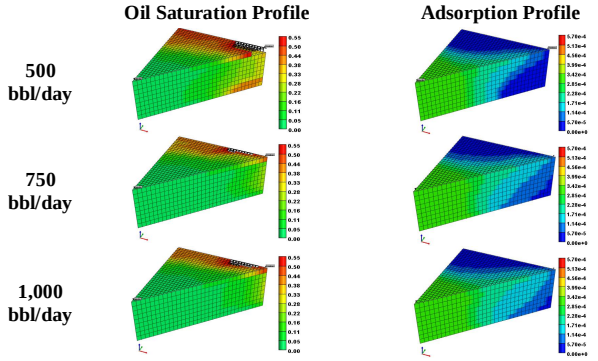


Fig. 6. Adsorption and oil saturation profiles from different surfactant injection rates at 1.0 wt.% surfactant concentration and implemented at water breakthrough at the end of production.

3) Time to Implement Surfactant Injection

Time to start implementation of surfactant flooding is indicated by watercut percentage observed at production well, which is set to be at water breakthrough, 25%, 50%, and 75%. According to the results, it can be observed that choosing to start surfactant flooding process at higher watercut percentage would only cause a delay in oil recovery.

As a common practice, recovering as much oil as possible at the earliest time is favorable in term of economics. Therefore, it is recommended to start surfactant flooding process as early as possible. Hence, in the next step, double-slug surfactant flooding is performed by taking into account only percentage of watercut at water breakthrough and 25% as a criterion for implementing surfactant flooding process.

C. Two-Slug Surfactant Flooding

According to the observations, there are two main mechanisms which allow surfactant flooding in two-slug surfactant flooding to yield higher oil recovery than single-slug surfactant flooding. The first mechanism is related to sacrificing of adsorption of the #1 slug surfactant monomer, causing lower adsorption of #2 slug surfactant monomers. Thus, the #2 slug can maintain its concentration and region of the lowest IFT condition could be expanded. The second mechanism is related to desorption of retained active surfactant monomer from the #1 surfactant slug. The desorbed surfactant monomer is then commingled with the #2 slug surfactant monomer and prolongs the lower IFT condition period at the late time.

According to the percentage of oil recovery improvement for each single-slug concentration, the injection strategy that yields the best improvement at different mass ratios, flow rates, times of surfactant implementation and single-slug reference concentration are listed in **Error! Reference source not found.**.

Table V: Summary of recommended injection strategy

Mass Ratio	Injection Rate	Water Cut Percentage	Recommended Injection Strategy		
			For 1.0 wt.%	For 0.75 wt.%	For 0.5 wt.%
20:80	low	low	R-H	R-H	R-H
	low	high	R-H	R-H	-
	mid	low	R-H	R-H	-
	mid	high	R-H	R-H	R-L
	high	low	R-H	R-L	-
	high	high	-	-	R-H
80:20	low	low	A-H	R-L	A-H
	low	high	R-L	R-L	-
	mid	low	R-L	R-L	-
	mid	high	R-L	R-L	A-H
	high	low	R-L	R-H	-
	high	high	-	-	A-L
50:50	low	low	R-H	R-L	R-L
	low	high	R-H	R-L	A-L
	mid	low	R-L	R-L	-
	mid	high	R-L	R-L	R-L
	high	low	R-L	R-L	A-L
	high	high	-	-	R-L

* Blank cell refers to the case that two-slug surfactant flooding shows no benefit over single-slug surfactant flooding.
* Injection rate: low = 500 bbl/day, mid = 750 bbl/day, high = 1,000 bbl/day.
* Time to implement: low = at water breakthrough, high = at 25% watercut.

1) Two-slug Surfactant Injection from 1.0 wt.% Single-Slug

At high surfactant concentration (1.0 wt.%), regardless of the injection rate and watercut percentage, performing Type R injection strategy is more preferable. This is because degree of adsorption of the #2 slug solution, which has higher concentration, is alleviated by sacrificial adsorption from the #1 slug surfactant monomers.

As can be seen in Fig. 7,Type A injection strategy at the early time near the injector shows high adsorption profile. This adsorption is solely contributed from the surfactant monomer in 1.0 wt.% slug solution, whereas in case of Type R injection strategy, only part of surfactant monomers inside 1.0 wt.% are being adsorbed onto the rock surface to reach the maximum adsorption. At the first day of slug #2 injection, adsorption profiles of Type R-L and Type R-H have shown adsorption in green scale and light blue scale, respectively. Once the slug #2 injection has finished, the adsorption profile near wellbore increases to red scale for both cases. This indicates that the amount of surfactant monomer that is adsorbed and changes

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the scale from green and light blue into red scale is contributed from surfactant monomer inside slug #2.

And therefore, there is less amount of surfactant from 1.0 wt.% being adsorbed compared to Type A injection strategy. Hence, in term of areas at which the lowest IFT condition could be established, Type R injection strategy could expand larger area of the lowest IFT condition, as shown in Fig. 8, when compared to Type A injection strategy and single-slug surfactant injection. This is the reason why Type R injection strategy yields better oil recovery.

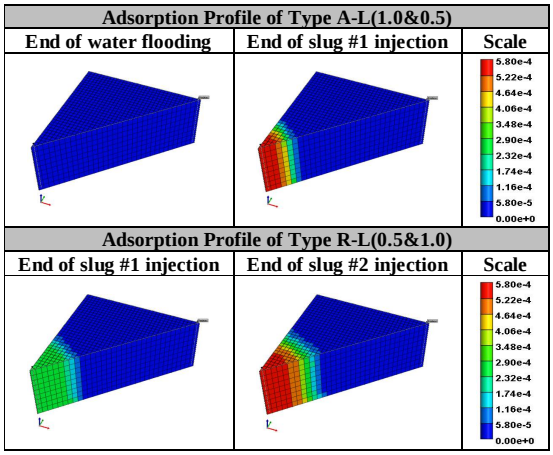


Fig. 7. Adsorption profiles of Type A-L (1.0&0.5) and Type R-L (0.5&1.0) injection strategy (1.0 wt.% base and equivalent mass between two slugs) implemented at water breakthrough with injection rate of 500 bbl/day.

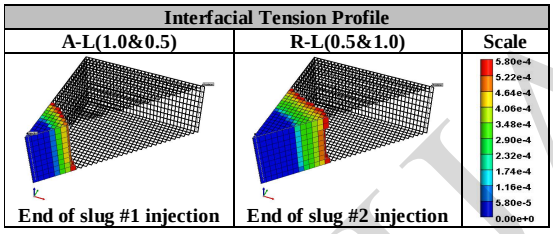


Fig. 8. Interfacial tension profiles of Type A-L (1.0&0.5) and Type R-L (0.5&1.0) injection strategy (1.0 wt.% base and equivalent mass between two slugs) implemented at water breakthrough with injection rate of 500 bbl/day.

2) Two-slug Surfactant Injection from 0.75wt.% Single-Slug

At middle surfactant concentration (0.75 wt.%), results indicate that regardless of watercut percentage and injection rate, performing two-slug surfactant flooding with Type R injection strategy would yield better oil recovery improvement. The reason why Type A injection strategy is not suitable in this case is because the slug concentration of 0.75 wt.% still leads to too high adsorption. High value of adsorption at early period is contributed solely from the slug #1 of Type A injection strategy, which has high surfactant concentration. Hence, by performing Type R injection strategy, effect of adsorption of key component slug is alleviated by the sacrificial adsorption, which leads to wider area of the lowest IFT condition.

At mass ratios of 80:20 and 50:50, Type R-L injection strategy is the most suitable strategy because there is the effect of sacrificial surfactant which allows surfactant monomers in slug #2 to be able to move further, and therefore lower IFT condition could be maintained for longer period.

As can be seen in Fig. 9, Type R-L injection strategy can maintain lower IFT condition (dark green area) at larger area when compared to other types of injection strategies as well as single-slug injection. As a result of prolonged lower IFT condition, Type R-L injection strategy could extend the production period longer than other types of injection sequence, which leads to higher oil recovery.

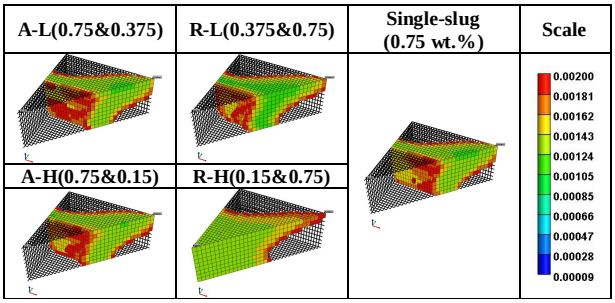


Fig. 9. Interfacial tension profiles of four different injections strategy (0.75 wt.% base and mass ratio of 80:20) and single-slug 0.75 wt.% implemented at water breakthrough with injection rate of 500 bbl/day (profiles are taken during chasing waterflooding period).

At mass ratio at 20:80, Type R-H is slightly better because there is sacrificial surfactant that are adsorbed onto rock surface, which alleviates the degree of adsorption of the second slug. This allows larger area of the lowest IFT to be established, as shown Fig. 10.

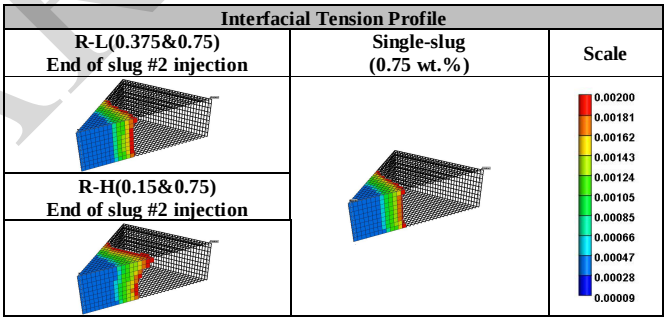


Fig. 10. Interfacial tension profiles of Type R-L(0.375&0.75) and Type R-H(0.15&0.75) injection strategy (0.75 wt.% base and mass ratio of 20:80) and single-slug 0.75 wt.% implemented at water breakthrough with injection rate of 500 bbl/day.

3) Two-slug Surfactant Injection from 0.5wt.% Single-Slug

At low surfactant concentration (0.5 wt.%), the recommendation of which injection strategy should be performed can be separated very clearly by mass ratio. For mass ratio of 80:20, it is recommended to perform Type A injection strategy, whereas for mass ratio of 20:80, Type R injection strategy is more preferable. This indicates that majority of surfactant mass should be placed in the slug with higher concentration when performing two-slug surfactant flooding with 0.5 wt.% single-slug as a base. This is because slug solution concentration of 0.1 wt.% and 0.25 wt.% may be too low to create adequately low IFT condition. Though,

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surfactant monomers in these two concentrations can serve as sacrificial agent, which enhance 0.5 wt.% slug solution to generate low IFT condition. For this reason, the key component in reducing IFT value here is 0.5 wt.% slug solution. Note that slug solution concentration of 0.5 wt.% has concentration not as high as in case of 1.0 wt.% and 0.75 wt.%. Therefore, the magnitude of adsorption is also lower.

The magnitude of adsorption for 0.5 wt.% is found to be below the residual adsorption in this study. Therefore, regardless of injection strategy, no effect of desorption has been observed in this concentration. Hence, at mass ratio of 80:20, the reason why Type A-H injection strategy shows better improvement over single-slug surfactant flooding is mainly due to lower loss of surfactant monomers from adsorption, as shown in Fig. 11. As a result, this prolongs plateau rate of oil production of Type A-H injection strategy to be longer than the case of single-slug surfactant injection. On the other hand, Type R-L injection strategy also shows better oil recovery improvement over single-slug surfactant flooding.

This is due to the effects of sacrificial surfactant monomer from the lower concentration of the #1 slug. However, the improvement is not as much as Type A-H injection strategy because majority of surfactant mass is in the low concentration slug. Nevertheless, at high injection rate (1,000 bbl/day), Type A-L injection strategy is more preferable. This could possibly be because at high injection rate the adsorption magnitude of 0.25 wt.% is reduced and therefore, lower IFT could be reached by the greater amount of unabsorbed surfactant monomer in 0.25 wt.% slug solution.

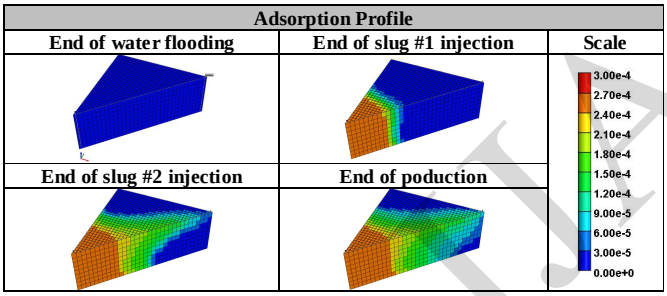


Fig. 11. Adsorption profiles at four different periods of Type A-H(0.5&0.1) injection strategy (0.5 wt.% base and mass ratio of 80:20) implemented at water breakthrough with injection rate of 500 bbl/day.

At mass ratio of 20:80, the same principle is followed. Type A injection strategy show lowest improvement of oil recovery compared to other type of injection strategy in two-slug mode at the same operating condition. Here, the benefit of sacrificial adsorption can be seen clearly. Greater amount of surfactant monomers is unabsorbed and could thoroughly reach out the reservoir in larger area. Hence, low IFT condition could be maintained for a longer period of time.

This result further support that 0.5 wt.% slug solution is still a key play and that the majority of surfactant mass should be located in highest concentration when performing two-slug surfactant flooding with 0.5 wt.% single-slug as a base. At the mass ratio of 50:50, there is no favor in amount of surfactant. Therefore, in order to see the improvement of oil recovery over single-slug surfactant flooding, concentration of the slug #1 and #2 should be similar.

V. CONCLUSIONS

In conclusion, single-slug and two-slug surfactant flooding are investigated in this work with fixed total amount of surfactant used. Effects of several operating parameters on the oil recovery process, which include surfactant slug concentration, surfactant injection rate, and time to implement surfactant flooding, have also been evaluated in single-slug surfactant injection process and can be conclude as follow:

1. Changes in surfactant slug concentration at fixed amount of surfactant use does not affect much on ultimate oil recovery, but slightly shows effect on rate of change of oil recovery.
2. Ultimate oil recovery and rate of recovering increase as surfactant injection rate is increased.
3. Starting surfactant injection process at higher watercut percentage would only cause a delay in oil recovery.

Two-slug surfactant is then investigated. According to the results, performing two-slug surfactant flooding yields improvement of oil recovery over single-slug surfactant flooding. This can be explained through the two main mechanisms which are related to sacrificing of adsorption and desorption of surfactant active monomers. However, type of two-slug injection strategy (R or A) that would be the most suitable for the process depends on concentration of single slug solution, which has been modified from. While, the design of high or low contrast depends on the chosen mass ratio.

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