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Sensitivity Analysis on Technical Parameters of Foam Assisted Water Alternating Gas (FAWAG) for Heavy and High Viscosity Oil Case

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Abstract

The use of gas injection for oil recovery is challenging for heavy and high viscosity oil case. The difference between gas and heavy oil density allows the occurrence of gravity segregation of the gas phase, and the high oil viscosity creates viscous instability which results poor mobility ratio of the fluids. This increase the possibility of early gas breakthrough, hence decreasing effectivity of oil recovery. Foaming surfactant has been used to improve the mobility ratio of gas phase and liquid phase, therefore delaying gas breakthrough and improving sweep efficiency.

Foam Assisted Water Alternating Gas (FAWAG) is known as one of the foam injection methods, in which the gas and surfactant solutions are injected in separate slugs from a single well. FAWAG is favored as a foam injection method due to the improvement in injectivity and the reduced risk of corrosion and material compatibility. This study used CMG STARS to simulate the field scale application of FAWAG. The local-equilibrium foam model introduced a function FM: the effect of foam on gas mobility is represented as modification of gas relative permeability.

This study conducted sensitivity analysis on technical parameters of FAWAG: foam quality, slug injections duration, injection rates, and feasibility on different reservoir permeabilities. This study also analyzed the impact of FAWAG in improving oil recovery and production performance in comparison to other EOR methods: water flooding, CO2 flooding, and Water-Alternating-Gas. The results proved that with oil recovery factor of 43.47%, the application of FAWAG significantly improved oil recovery; more than 10% gain of recovery factor in comparison to the former methods. The results also showed that FAWAG is only effective when applied on reservoir with high permeability; as for reservoir with permeability lower than 600 mD, FAWAG is not able to significantly improve oil recovery compared to WAG.

Introduction

The use of foaming surfactants has been proposed to improve the common problems of gas injection as well as Water-Alternating-Gas. Foaming surfactant is aimed to create active foam in the reservoir that effectively reduces gas mobility (Rossen, 1995; Groenenboom et al., 2017). The purpose is to improve the inherent poor mobility ratio of gas phase and liquid phase, therefore delaying the gas breakthrough and improving the volumetric sweep efficiency.

Foam injection is aimed to control the gas mobility by creating lamellae (foam films) along the gas flow paths in the porous medium (Farajzadeh et al., 2015). The lamellae are stabilized by surface active material, such as surfactants. Most of the lamellae remain stationary, which results in tapping a large fraction of the gas without compromising its efficiency. Because of formation of foam, part of the gas is diverted into the oil-rich part of the reservoir and the volumetric sweep is improved (Li et al., 2010).

One of the known method of foam injection is through the Foam-Assisted-Water-Alternating-Gas (FAWAG). Injection of foam in the FAWAG method is more favorable on the field scale when foam is applied to provide mobility control because of several reasons (Farajzadeh et al., 2015):

1. Improved injectivity due to alternating injection of gas and surfactant solution.
2. Reduced risk of corrosion and material compatibility related risks due to separate injection of the gas and the liquid (especially in acid- and sour-gas projects).

This study is conducted to understand the mechanisms of FAWAG on increasing oil recovery factor for heavy and high viscosity oil case. This study is also intended to compare FAWAG with other EOR methods (WAG, waterflood, CO2 flooding) in improving production performance as well as increasing recovery factor, and also to identify the impact

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of natural and operational parameters for FAWAG in increasing recovery factor for heavy and high viscosity oil case through sensitivity and feasibility study.

Data and Method

This study comprehends a series of sensitivity and feasibility studies are conducted with the step-by-step procedure as shown on Figure 1.

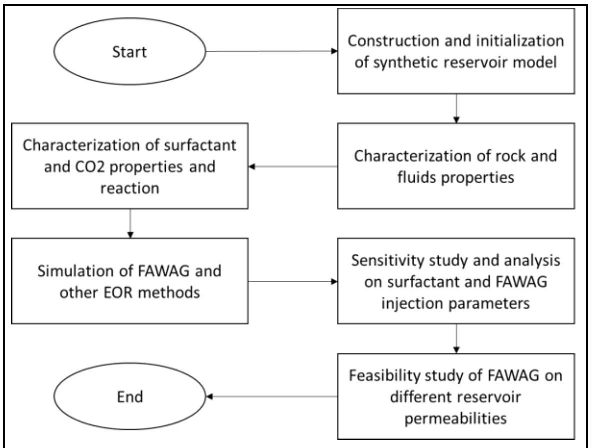

Figure 1: Step-by-step procedure of study

Certain assumptions are applied in this study, such as:

- Reservoir model is synthetic and homogeneous.
- No aquifer is modeled (no water influx).
- Constant reservoir thickness.
- No skin/wellbore damage on production and injection wells.
- Reservoir pressure achieved MMP for CO_2 injection.

This study only applies in a certain scope of work as following:

- EOR methods considered for comparison purpose are water flooding, CO_2 flooding, and WAG (Water-Alternating-Gas).
- Foam model used is based on simulation data by Ma (2013) for CMG STARS as shown on Table 1.
- Sensitivity study conducted only on foam quality (*fmmob*, *fmdry*, *epdry*), injection duration, surfactant injection rate, gas injection rate, and reservoir permeability parameters.
- Simulation is run for 20 years production.

Table 2: FM parameters (Ma,2013)

FM **Parameter**	**Value**
epdry	500
fmmob	47196
fmdry	0.1006

Sensitivity analysis are conducted for 4 operational parameters and one reservoir parameter for feasibility study, which consist of the following:

1. Sensitivity analysis on foam quality (*fmmob*, *fmdry*, *epdry*).
2. Sensitivity analysis on duration of alternating injection between surfactant slugs and CO_2 slugs.
3. Sensitivity analysis on surfactant injection rate.
4. Sensitivity analysis on CO_2 injection rate.
5. Feasibility study on reservoir permeability.

Result and Discussion

Comparison to Other EOR Methods

The base case of FAWAG injection is compared to other EOR methods to analyze on its impact in improving oil recovery and production performance. The EOR methods to be compared are water flooding, CO_2 flooding, and WAG (water-alternating-gas) injection. Water flooding is applied for 18 years after 2 years of natural production with water injection rate of 1000 bbl/d. CO_2 flooding is applied also for 18 years after 2 years of natural production with gas injection rate of 2 MMscfd. WAG injection is applied for 18 years after 2 years of natural production with alternating injection duration for the water and CO_2 slugs of 3 months each, with injection rate of 1000 bbl/d of water and 2 MMscfd of CO_2 gas. The recovery factor and production rates of each method is then compared after 20 years of production using CMG STARS simulator as shown on Figure 2 to 4.

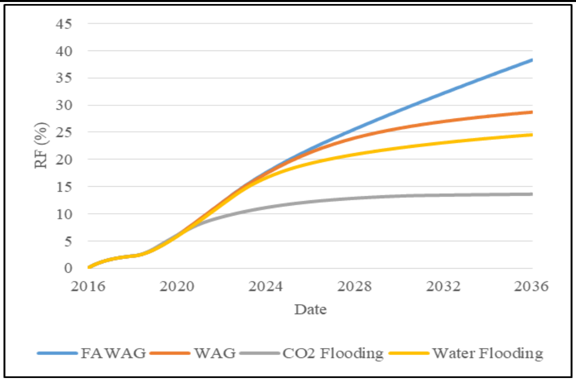

Figure 2: Oil recovery factor comparison of FAWAG and other EOR methods

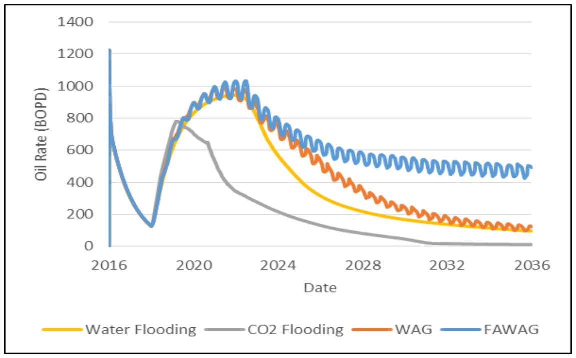

Figure 3: Oil production rate comparison of FAWAG and other EOR methods

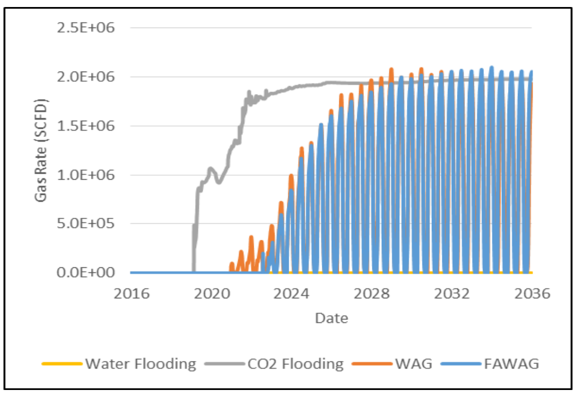

Figure 4: Gas production rate comparison of FAWAG and other EOR methods

The oil recovery factor at the end of the production period using FAWAG injection is 38.29%, while the recovery factor for WAG, water flooding, and CO_2 flooding are 28.71%, 24.54%, and 13.62% respectively. Production using CO_2 flooding reaches the fastest production rate decline which corresponds to the lowest oil recovery out of the 4 EOR methods. Production using water flooding experiences a less steep rate decline than the CO_2 flooding case to a production rate of around 100 BOPD. The WAG production case experiences an even less steep rate decline but eventually reach the same production rate with the water flooding case of around 100 BOPD at the end of the production. Meanwhile, the production case using FAWAG shows a maintained decline rate compared to former EOR methods with a production rate of around 500 BOPD at the end of the production periods, which also results a significant gain of oil recovery factor in comparison to the other methods.

Production case using FAWAG injection also shows a significant impact in delaying gas breakthrough. The FAWAG case delays gas breakthrough for 4 years compared to CO_2 flooding case, while the WAG case only holds the breakthrough for 2 years. FAWAG shows an even more significant impact in lowering the production GOR which contribute in improving oil recovery.

Sensitivity on Foam Quality

Sensitivity study is conducted on FM parameters representing the foam quality for the FAWAG application. The foam model used in this study is a local-equilibrium model which does not explicitly capture the dynamic behavior of foam, but assumes that foam creation and coalescence has reached equilibrium (Groenenboom, 2017).

The sensitivity study is conducted for 3 parameters in the FM function of the foam model. These parameters are *fmmob*, *fmdry*, and *epdry*. The parameter *fmmob* is the reference gas mobility reduction factor for wet foams (Rossen and Boeiji, 2013). This parameter corresponds to the maximum attainable mobility reduction. In this study, the sensitivity analysis for parameter *fmmob* is conducted by applying multiplying factors of 1%, 10%, 100%, 200%, and 500%, which gives result on its impact on oil recovery as shown on Figure 5 with a variety of recovery factor ranging not more than 0.1% for all cases.

$$k_{rg}^{f} = k_{rg} \cdot FM$$

$$FM = \frac{1}{1 + fmmob \cdot F_1 \cdot F_2 \cdot F_3 \cdot F_4 \cdot F_5 \cdot F_6 \cdot F_7}$$

Equation 1: *FM* function

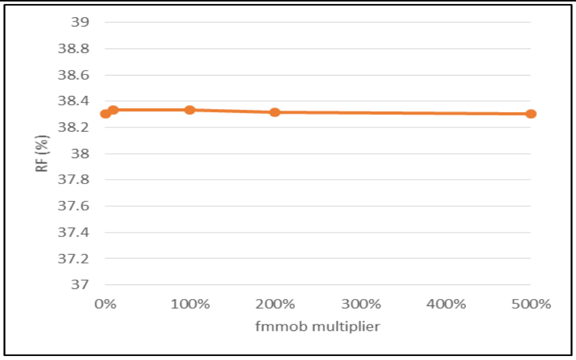

Figure 5: Impact of *fmmob* parameter multiplier on oil recovery factor

The parameter *fmdry* respresents S_w*, the water saturation at which foam collapses corresponding to the limiting capillary pressure for foam stability, if the transition between regimes is abrupt (Rossen and Boeiji, 2013). In this study, the sensitivity analysis for parameter *fmdry* is conducted by applying multiplying factors of 10%, 100%, and 200%. This sensitivity directly interfere with the parameter F_7 as illustrated by Equation 2. Table 2 shows how each case affect the parameter F_7. The result of the sensitivity analysis on parameter *fmdry* is shown on Figure 6, which shows an increasing oil recovery factor for the higher value of *fmdry* parameter.

$$F_7 = 0.5 + \frac{\arctan[epdry\,(S_w - fmdry)]}{\pi}$$

Equation 2: Foam dry-out effect function, *F7*

Table 2: Impact of *fmdry* parameter multiplier on *F7* parameter

Swi	Swa	epdry	fmdry	F7 @ Swi	F7 @ Swa
0.47	0.56	500	0.01006	0.9986159	0.9988424
			0.1006	0.9982766	0.9986143
			0.2012	0.9976317	0.9982257

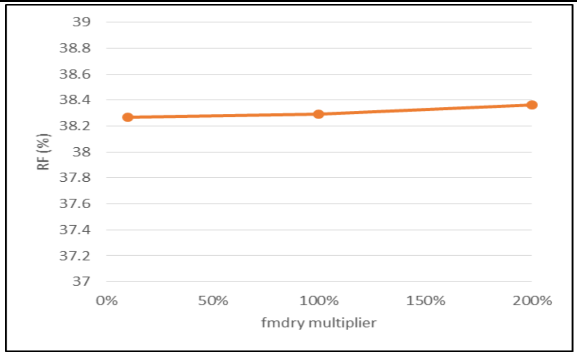

Figure 6: Impact of *fmdry* parameter multiplier on oil recovery factor

The parameter *epdry* controls the abruptness of the foam collapse as a function of water saturation (Rossen and Boeiji, 2013). Smaller values give a gradual transition between the two regimes, while larger values yield a sharper, albeit still continuous, transition. In this study, the sensitivity analysis for parameter *epdry* is conducted by applying multiplying factors of 10%, 100%, and 200%. This sensitivity also directly interfere with the parameter F_7 as illustrated by Equation 2. Table 3 shows how each case affect the parameter F_7. The result of the sensitivity analysis on parameter *epdry* is shown on Figure 7, which shows an decreasing oil recovery factor for the higher value of *epdry* parameter.

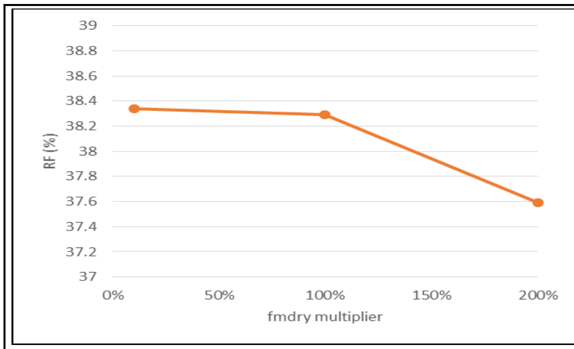

Figure 7: Impact of *epdry* parameter multiplier on oil recovery factor

Table 3: Impact of *epdry* parameter multiplier on *F7* parameter

Swi	Swa	fmdry	epdry	F7@Swi	F7@Swa
0.47	0.56	0.1006	50	0.9827829	0.9861511
			500	0.9982766	0.9986143
			1000	0.9991383	0.9993071

Sensitivity on Surfactant Injection Rate

Sensitivity study is conducted for surfactant injection rate of 600, 1000, and 1400 bbl/d while the CO_2 injection rate is kept at 2 MMscfd with the results as shown on Figure 8. The oil recovery factors for injection rate of 600, 1000, and 1400 bbl/d are 29.08%, 38.29%, and 44.73% respectively.

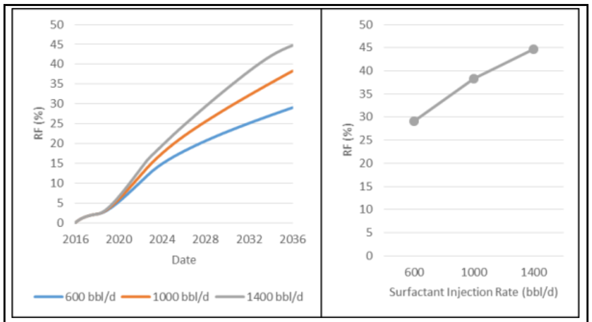

Figure 8: Impact of surfactant injection rate on oil recovery factor

The results shows that an increase of the surfactant injection rate gives significant gain in oil recovery. However, an increase of surfactant rate also significantly increase the reservoir pressure, therefore it is constrained on the maximum pressure allowed in consideration of the reservoir rock fracture pressure. The results also shows that the alteration of surfactant pressure does not significantly affect the gas breakthrough time.

Sensitivity on CO_2 Injection Rate

Sensitivity study is conducted for CO_2 injection rate of 1, 1.5, and 2 MMscfd while the surfactant injection rate is kept at 1000 bbl/d with the results as shown on Figure 9. The oil recovery factors for injection rate of 1, 1.5, and 2 MMscfd are 37.67%, 38.27%, and 38.29% respectively.

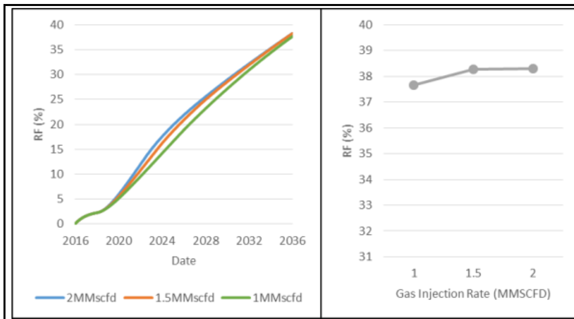

Figure 9: Impact of CO_2 injection rate on oil recovery factor

The results shows that an increase of CO_2 injection rate does not give a significant increase of oil recovery at the end of the production period. However, alteration of the CO_2 injection rate gives a significant impact on gas breakthrough time. Gas breakthrough for injection rate of 2 MMscfd results gas breakthrough time of 4 years after FAWAG injection, and each 0.5 MMscfd reduction of the injection rate delays the breakthrough time for 2 years to the former breakthrough time.

Sensitivity on Duration of Injection

Sensitivity study is conducted on the injection duration of each alternating slugs of surfactant and CO_2. The default for one injection period is 3 months, and the sensitivity study is done by altering the ratio of injection periods between surfactant and CO_2 slugs. Sensitivity study is conducted for injection period ratio between surfactant and CO_2 of 1:1 (3 months surfactant & 3 months CO_2), 1:2 (3 months surfactant & 6 months CO_2), 2:1 (6 months surfactant & 3 months CO_2), and 3:1 (9 months surfactant & 3 months CO_2).

The result shows a significant difference of oil recovery factor; 38.29%, 30.77%, 44.08%, and 45.11% respectively, as shown on Figure 10 to 12. Increasing the duration of CO_2 slug injection appears to be ineffective in improving oil recovery, and even shows a poorer recovery factor than the base case. Doubling the duration of surfactant slug injection, on the other hand, appears to improve the oil recovery factor significantly. Further increase of surfactant slug injection duration, however, does not give a significant improvement of recovery factor compared to the former case.

The result on production rates shows that the longer the surfactant slug injection duration in comparison to the CO_2 slug injection duration will result longer gas breakthrough time. The 3:1 and 2:1 injection duration ratio gives a maintained decline rate of oil production but eventually dropped lower than the base case, while the 1:2 case shows a similar trend to the base case but with a faster decline of production rate.

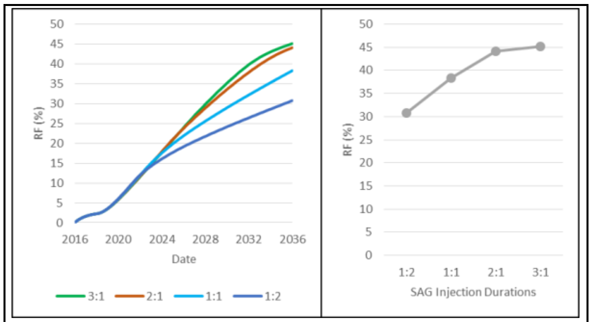

Figure 10: Impact of injection duration on oil recovery factor

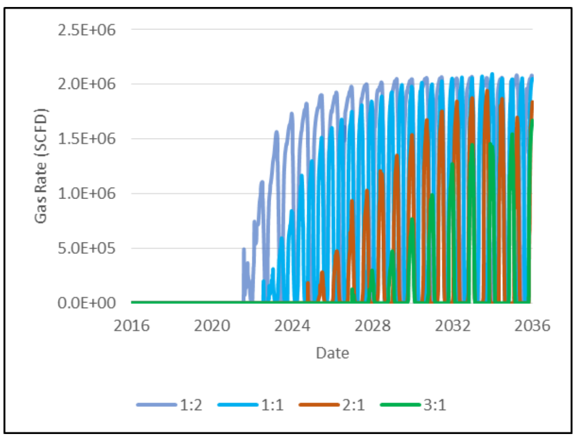

Figure 11: Impact of injection duration on gas production rate

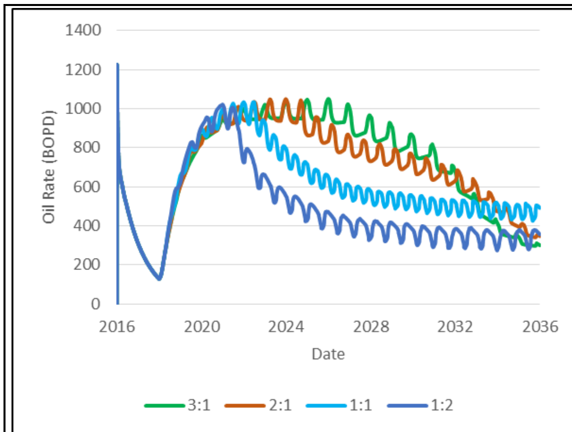

Figure 12: Impact of injection duration on oil production rate

Tapered Slug Case

Sensitivity study is also conducted for tapered slug case, in which surfactant is injected only part of the time (Groenenboom, 2017). In this case the surfactant slug is chased by water injection, allowing the foam application to aim at an improved mobility ratio without compromising injectivity to maintain pore volume throughput rate.

The tapered slug case is applied for injection duration ratio for surfactant and CO_2 slugs of 1:1 and 2:1. For the 1:1 duration ratio case, the surfactant is injected for 2 months with water injection for the following 1 month. For the 2:1 duration ratio case, the surfactant is injected for 3 months with water injection for the following 3 months. The results, as shown on Figure 13 and 14, indicate that both tapered slug cases achieve the same improvement of oil recovery and production performance as the cases with surfactant injection for the whole injection time. This would most likely gives a significant consideration for further economic analysis as for the required amount of surfactant in the application of FAWAG.

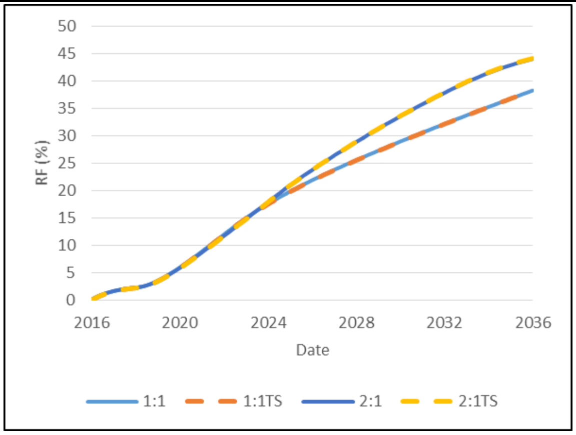

Figure 13: Impact of tapered slug application on oil recovery factor

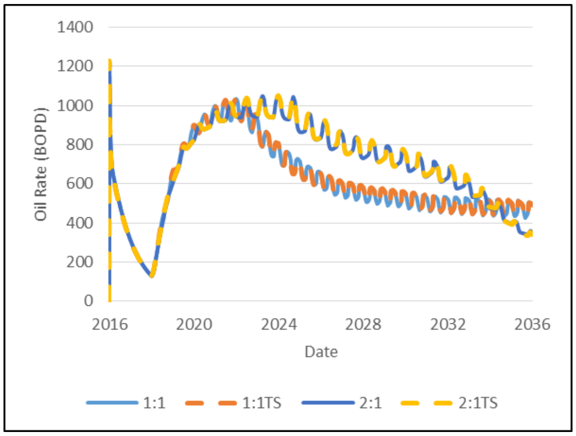

Figure 14: Impact of tapered slug application on oil production rate

Feasibility on Reservoir Permeability

Feasibility study for FAWAG is conducted by doing sensitivity analysis over the reservoir permeability on its impact in improving oil recovery in comparison to WAG at the same reservoir condition. The aim of this feasibility study is to determine at which reservoir permeability is FAWAG considered insignificant in improving oil recovery prior to WAG. The sensitivity analysis is conducted for horizontal reservoir permeability of 1500, 1200, 900, 600, and 300 milidarcies. The vertical permeability is kept at a ratio of half of the horizontal permeability, prior to the former base case. The difference in oil recovery factor (i.e. RF gain) between FAWAG and WAG of the same reservoir permeability is then compared to analyze the significance of applying FAWAG.

The results of this feasibility study are shown on Table 4 and Figure 15. At 900 to 1500 mD, FAWAG is still considered significant in improving oil recovery, with an RF gain of more than 5.9%. The gain, however, is reduced to only 0.63% at 600 mD which shows that at the reservoir condition, FAWAG and WAG delivered a similar performance in improving oil recovery. Further reduction of reservoir permeability even shows a negative gain at permeability of 300 mD, which indicates that at the reservoir condition, the recovery factor of FAWAG is even smaller than that of WAG. These results indicate that FAWAG is only effective when applied for reservoir with high permeability, as for permeability of 600 mD or lower, FAWAG shows insignificant improvement in oil recovery.

Table 4: Oil RF comparison of WAG and FAWAG on different reservoir permeabilities

Permeability (mD)	**RF (%)**		**RF Gain (%)**
	WAG	**FAWAG**	
1500	28.71	38.29	**9.58**
1200	28.44	35.18	**6.74**
900	27.88	33.79	**5.9**
600	26.44	27.08	**0.63**
300	20.4	17.73	**-2.66**

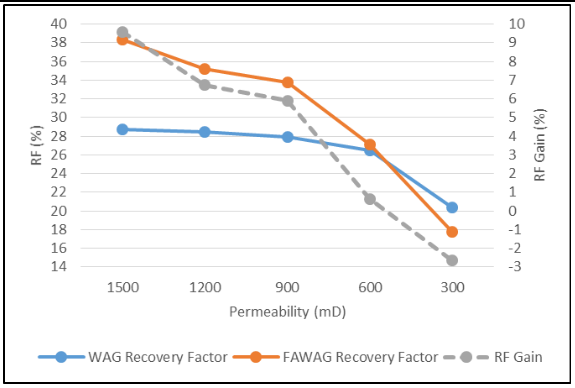

Figure 15: Oil RF comparison of WAG and FAWAG on different reservoir permeabilities

Conclusions

From this study, several conclusions can be drawn as follows:

1. FAWAG (Foam-Assisted-Water-Alternating-Gas) improves oil recovery by creating lamellae along the gas flow paths, tapping a large fraction of the gas without compromising its efficiency and improving volumetric sweep, such process mainly controlled by capillary pressure.
2. FAWAG is proven to improve oil recovery with a recovery factor of 38.29%, significantly better than WAG (28.71%), water flooding (24.54%), and CO_2 flooding (13.62%) for heavy and high viscosity oil case.
3. Sensitivity analysis on technical parameters of FAWAG results several conclusions as follows:

A. Modification of the local-equilibrium foam model gave varying recovery factors with the parameter *epdry* as the most affecting parameter resulting up to 0.7% RF gain.

B. Increasing the surfactant injection rate of FAWAG can increase oil recovery significantly with 1400 bbl/d injection rate resulting the highest recovery factor (44.73%). It is, however, unable to significantly improve the gas breakthrough time.

C. Increasing the CO_2 injection rate of FAWAG can increase oil recovery with 2 MMscfd injection rate resulting the highest recovery factor (38.29%). It can also significantly affect the gas breakthrough time with 2 years breakthrough time hold for every 0.5 MMscfd reduction.

D. FAWAG injection duration of 3:1 gives the highest recovery factor (45.11%), but the 2:1 injection duration gives the most significant gain of recovery factor (6% RF gain).

E. Application of tapered slug injection for FAWAG can reduce the requirement of surfactant while resulting the same oil recovery and production performance improvement as the former case.

F. FAWAG is suitable for improving oil recovery for reservoir with high permeability; application of FAWAG for reservoir permeability of 600 mD or lower is insignificant in improving, and even reducing, the oil recovery factor in comparison to WAG.

Further study of FAWAG is required to provide a more reliable model for heavy and high viscosity oil case. A coreflood experiment of foam injection along with a matched local-equilibrium foam model can improve the uncertainties in upscaling the foam behavior to a field-scale model. Economic analysis is also required to consider FAWAG as a method of EOR in respect to the high price of foaming surfactant.

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