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3D Simulation of Low Salinity, Polymer, Conventional, Water-flooding & Combination IOR Methods – Heterogeneous & Varying Wetting Conditions

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Abstract

In this paper a five spot well patterns is used to study Low Salinity, Polymer, Conventional, Water-flooding and the combination of Polymer flooding and LSWF. The aforementioned cases are applied under different wetting conditions. Oil recovery is a function of reservoir forces. Effective IOR implementation requires the proactive identification and contribution of the dominating reservoir forces, over the course of the field development. The work in this paper uses a validated, compositional simulator in addition to validated relative permeability and capillary formulations to simulate LSWF, PF, Conventional, Water-flooding and combination of PF + LSWF in a multi-dimensional, anisotropic and aerially heterogeneous model, under various wetting conditions. Wettability modification is also simulated using start and end relative permeability, captured and validated from literature.

The initial wetting state is an important criterion for LSWF. The incremental recovery in oil-wet systems, or ″typical carbonate reservoirs,″ is more rapid and thus requires less dilution of the injected brine salinity. In addition, simulation results indicate substantial un-swept quantities of available oil saturation. Therefore, the role of polymer flooding is examined along with conventional water-flooding in wetting conditions where LSWF may not achieve significant incremental recovery. LSWF is not effective in intermediate wetting conditions and Polymer flooding yields higher recovery factors in all water wet conditions.

The impact of reservoir damage has an adverse effect on the development's recovery factor and polymer flooding yields the highest incremental recovery in case of low permeability formations. In oil wet conditions the performance of PF and LSWF is similar especially in weak oil wet systems due to the equal contribution of their respective displacement efficiencies. In strong oil-wet conditions the combination of PF + LSWF yields the highest recovery factor. The wetting conditions, formation heterogeneity and permeability magnitude all impact IOR selection and suggest that each oil reservoir has a unique ionic environment that changes naturally and by human intervention, therefore it is important to study different IOR methods at different stages of the field development.

Introduction

Oil recovery is the product of displacement efficiency (E_D) and sweep efficiency (E_S). EOR methods focus on increasing either displacement efficiency by reducing residual oil saturation in swept regions or sweep efficiency by displacing the remaining oil in unswept regions. Residual oil saturation is a function of the capillary number, which is the ratio of viscous force to capillary force. Typically, the capillary number for water flooding is confined to below 10_{-6}, usually to 10_{-7}. The capillary number increases during effective EOR by three magnitudes to about 10_{-3} to 10_{-4}.

The capillary number can be reduced significantly by either lowering the IFT or altering the rock's wettability to create a more water-wet surface. Although the capillary number also can be reduced by increasing the viscous forces, the reservoir fracture gradient and pressure drops across the wells are limiting factors in this method (Green and Wilhite, 1998). Oil in unswept regions can be recovered by (1) increasing the viscosity of the displacing fluid, (2) reducing oil viscosity, (3) modifying permeability, and/or (4) altering wettability.

In this paper a five spot well patterns is used to study LSWF, PF, Conventional, water flooding and combination of PF and LSWF. The aforementioned four cases are applied under different wetting conditions using relative permeability and capillary formulations from literature and validated simulation results.

Guiding Principles for Developing Enhanced Oil Recovery Methods

Once the secondary oil recovery process has been exhausted, about two-thirds of the original oil in place (OOIP) is left behind due to both microscopic and macroscopic factors. EOR methods aim to recover the remaining OOIP (Green and Wilhite, 1998).

Microscopic Factors Microscopic Factors include the various effects of oil-water interfacial tension (IFT) and rock-fluid interaction (wettability) that give rise to oil in pores and crevices; this oil cannot be dislodged under even large applied pressures (Stegemeier, 1977; Slattery, 1974). The reservoir pore size may be as small as 0.1 μm or less; therefore, it is not surprising that IFT influences oil mobilization. The oil left behind after a sweep is called residual oil saturation, expressed as *Sor*.

Macroscopic Factors Macroscopic Factors include reservoir stratification, with some strata showing varying degrees of permeability. Thus, the displacing fluid travels through the high permeability zones, leaving oil in the low-permeability zones unswept (Bai and colleagues 2007a; Bai and colleagues 2007b). Even in a uniformly permeable reservoir, uniform displacement can break down when the displacing fluid is less viscous than the crude, a situation known as adverse mobility ratio. In places, the less viscous fluid penetrates the oil, a situation known as viscous fingering. Another important reason why oil remains unswept is the negative capillary force in oil-wet formations; this force impedes water imbibition into pore spaces in the reservoir rock. This situation often occurs in carbonate reservoirs, more than 80% of which are said to be oil wet. Other factors, such as areal heterogeneity, permeability anisotropy, and well patterns, also leave some oil unswept by water. The unswept oil is called remaining oil, and its corresponding saturation is called remaining oil saturation.

LSWF Literature Review

The main highlights of LSWF literature review is (a) core-flooding experiment for sandstone and carbonate reservoirs report significantly higher incremental recovery compared to field trials, (b) in all studied cases significant variance is indicated in incremental recovery. Therefore, the following is underlined:

- The role of macroscopic displacement efficiency in LSWF modeling;
- Heterogeneity amongst reservoirs' chemical species, organic complexes and changes in the ionic environments.

Laboratory Experiments Data from laboratory core-flooding experiments have shown that LSWF in sandstone reservoirs (Tang and Morrow, 1997), as well as low-salinity seawater flooding (LSSWF) in carbonate reservoirs (Yousef and colleagues 2010), could result in a substantial improvement in oil recovery (up to 25% in sandstone reservoirs and 17% in carbonate reservoirs) over traditional water flooding. LSWF imbibition experiments conducted by Tang and Morrow (1997) indicate significant incremental recovery rates of about 20% and 33% when the salinity (mainly KCl) is reduced by 10:1 and 100:1, respectively. LSWF core-flooding experiments for both outcrop sandstone and reservoir cores indicate incremental recovery rates of about 13% and 25% for reductions in the salinity concentration (mainly NaCl) of 10:1 and 100:1, respectively (Tang and Morrow, 1997; McGuire and colleagues 2005; Zhang and colleagues 2007; Ashraf and colleagues 2010). LSSWF imbibition experiments conducted by Bagci and colleagues in 2001 and Webb and colleagues in 2005 concluded favorable wettability modifications. Coreflooding experiments also have shown that LSSWF improves oil recovery up to 17% in carbonate cores when diluted to a ratio of 20:1 (Yousef and colleagues 2010).

Field Trials Single-well chemical tracer tests indicate incremental recovery rates from 8% to 19% for four different wells (McGuire and colleagues 2005). The well with the lowest incremental recovery rate has been flooded with comparably higher salinity water (7000ppm, compared to other wells at >5000ppm). Zhang and colleagues (2007) also reported this observation when no incremental recovery was observed for core flooding with water having a salinity of 8000ppm. Recovery rates for the remaining three wells range from 15% to 19%. The well with the highest incremental recovery experiences a reduction in residual oil saturation from 43% to 34%, which may indicate the weightage of the microscopic sweep efficiency in LSWF modeling. The greatest reduction in residual oil saturation is from 21% to 13%; however, the incremental recovery rate is 18% (McGuire and colleagues 2005), which could indicate the weightage of the macroscopic displacement efficiency in LSWF modeling and the probable need to increase the low salinity water viscosity to mitigate viscous fingering (Ligthelm and colleagues 2009).

Published oil production figures for a pilot well (Seccombe and colleagues 2010) suggest a 10% incremental recovery rate from June 2008 through April 2009. The salinity was lowered from approximately 27500ppm to approximately 13000ppm. The oil production rate does not increase with a decrease in water salinity; however, water production figures indicate a clear decrease after the start of LSWF. A field-wide scale application of LSWF as a secondary recovery method was inadvertently implemented in Syria because the only available source of water was river water (1991-2004). After injecting 0.6 PV of low-salinity water in 2004, produced water was injected thereafter. As of 2009, 0.6PV of produced water had been injected. Studies conclude that wettability alteration has resulted in LSWF's incremental recovery rate of 10-15% (Vledder and colleagues 2010).

Discussions Similar to alkaline flooding, LSWF spurred controversy amongst the scientific community because of the variability involving its recovery mechanism(s), which resulted from heterogeneous rock properties and different ionic environments. Another similarity between alkaline flooding and LSWF is the potential for clay flocculation and the consequent formation damage. Although it has been suggested (Clementz, 1982) that a tradeoff between microscopic sweep efficiency and macroscopic displacement efficiency will be necessary, EOR does not demand such a compromise. However, considering the heterogeneity amongst reservoirs' chemical species, organic complexes and changes in the ionic environments (Reed, 1967), each reservoir may be subject to core-flooding experiments and simulation prior to selecting an optimal chemical design.

Therefore, the purpose of this paper is to study macroscopic displacement efficiency in LSWF modeling in addition to the heterogeneity of reservoir characteristics and ionic environment.

Proposed Work Numerous LSWF core-flooding experiments have been undertaken (Aladasani and Colleagues, 2012a and 2012b), and three LSWF simulation models have been proposed (Wu and Bai, 2009; Tripathi et al. 2008, and Jerauld and colleagues, 2006). Aladasani and Colleagues, (2014a) studied 411 core-flooding experiments and conducted simulations to validate LSWF reservoir modeling. It is important to study multi-, dimensional and layered porous media, to effective evaluate LSWF reservoir candidacy. Furthermore each oil reservoir has a unique ionic environment that changes naturally and by human intervention, it is equally important to study different IOR methods at different stages of the reservoir development. Therefore, a five spot well patterns is used to study LSWF, Polymer contrasted with Conventional water flooding and combination of polymer flooding and LSWF. The aforementioned four cases are evaluated under different wetting conditions and reservoir characterizations captured from literature and validated simulation results.

Methodology

3D models are constructed to examine LSWF recovery under various wetting classifications (Case Set A). The role of sweep efficiency in oil recovery, especially in three-dimensional space, as well as reservoir heterogeneities (Anisotropic and Areal), will be examined (Case Set B).

Case Sets

The Case Set A consists of three up-scaled models to depict (Case A-1) water-wet conditions, (Case A-2) intermediate wetting conditions and (Case A-3) oil-wet conditions. The validated fluid relative permeability and capillary pressure, functions are adopted from Aladasani and colleagues, 2012c.

Published experiments will be used to validate the numerical solution. LSWF's performance in a stratified, 20-acre, 5-spot well pattern was modeled by Gaucher and Lindley (1960). The properties of Reservoir 4 will be adopted from Gaucher and Lindley (1960), as shown in Table 1, to construct a 20-acre, 5-spot water-flooding well pattern, as illustrated in Figure 1. The injection wells lie at each corner of the four quadrants and diagonal to the producer, which is positioned in the center. The injection and production rates are assumed constant, and the formations are assumed homogenous.

Table 1—Reservoir Properties for Five-Spot Water-Flooding Pattern

Areal Pattern	Units	Reservoir 5 (20-Acre, 5-Spot)
Top-Layer Thickness, h_a	Feet	10
Bottom-Layer Thickness, h_b	Feet	10
Top Layer, Absolute Permeability, k_a	md	16
Bottom Layer, Absolute Permeability, k_b	md	16
k_{owr}, a	md	13
k_{owr}, b	md	13
k_{wor}, a	md	9
k_{wor}, b	md	9
Top-Layer Porosity, ϕ_a	%	20
Bottom-Layer Porosity, ϕ_b	%	20
$1\text{-}S_{or}\text{-}S_{wr}$, a	%	0.50
$1\text{-}S_{or}\text{-}S_{wr}$, b	%	0.50
Oil Viscosity, μ_o	cp	2.17
Water Viscosity, μ_w	cp	0.50
Oil-Water Density Difference, $\Delta\rho$	gm/cc	0.20
Interfacial Tension, σ	dynes/cm	25
Water Injection Rate, i_w	B/D	44

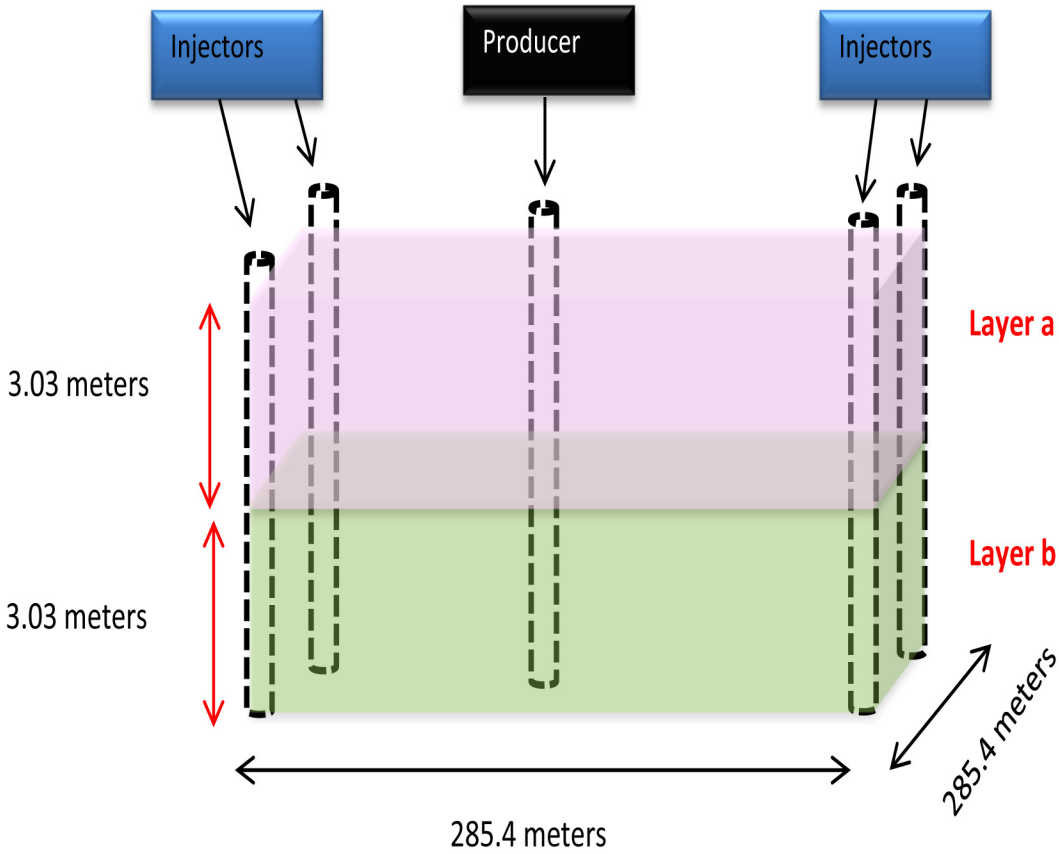

Figure 1—Schematic Well Pattern

The producing zone's length and width are assumed identical. A three-dimensional mesh is generated with 10 grid blocks in the x and y axes and 5 in the z axis, which is equivalent to 500 elements for a single quadrant. Therefore, the spacing between the grid blocks is as follows: x and y = 14.22 m and z = 1.212 m. In addition, both the injection and producing wells will be considered fully penetrating.

The Case Set B uses the same model as Case Set A to examine:

a. Four IOR methods, PF, LSWF, Conventional, water-flooding and PF + LSWF.
b. Short to Medium Term time scale to evaluate corresponding field development options.
c. Reservoir Heterogeneity (Areal and Anisotropic) for four IOR mentioned in item (a)
d. Different initial wetting and final wetting states (using validated models from literature) for the four IOR methods mentioned in item (a).

The injection duration is reduced from 127 years to about 20 years with shorter time intervals to represent recovery factor, this is due to the low injection rate used by Gaucher and Lindley (1960). Two cases are considered to evaluate reservoir heterogeneity (layered heterogeneity and areal heterogeneity). The 5 grid blocks/layers in the z axis (properties shown in Table 2) are assigned different permeability's, and different permeability's are assigned for vertical and areal, layers of the model, properties shown in Table 2. LSWF modeling is then, contrasted with conventional WF, PF and a combination of LSWF and PF, under different wetting conditions (initial and final capillary conditions), shown in Figure 2. Conventional water-flooding model assumes similar displacing water properties to the formation water.

Table 2a—Reservoir Properties for Five-Spot Water-Flooding Pattern

Vertical Pattern (Layer Thickness 4 ft)	Anisotropic Heterogeneity (md) 'x-y-z orientation'
Layer 1	0.016x0.016x0.016
Layer 2	1.6x1.6x1.6
Layer 3	0.0016x0.0016x0.0016
Layer 4	0.16x0.16x0.16
Layer 5	0.016x0.016x0.016

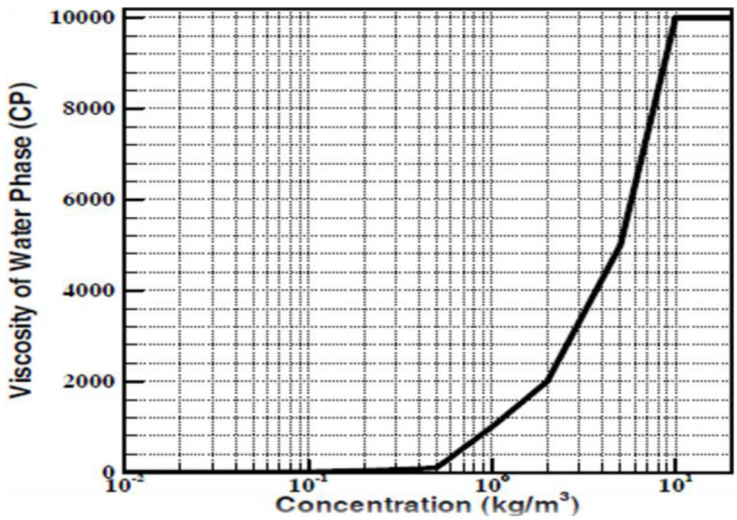

Figure 2—Polymer Viscosity Versus Concentration (Adopted from Wu and Colleagues, 1996)

Results

Case Set A

Case A-1 examined metrological properties identical to Gaucher and Lindley (1960), and the result of the simulation is compared with their experimental results. Two additional Cases are considered, Case A-2 for a water-wet reservoir and Case A-3 for an oil-wet reservoir; in both cases, HSWF and LSWF are simulated. The oil recovery factor provided by Gaucher and Lindley's (1960) experiment for Reservoir 4 is 90.4% after injecting 3 pore volumes. Additionally, because the sum of oil and water's residual saturations is 0.5, the residual oil saturation must equal 0.048. Therefore, Reservoir 4 can be considered to have intermediate wetting conditions. The result of the simulation in Case A-1 is compared with the experimental results from Gaucher and Lindley (1960), as shown in Figure 2.

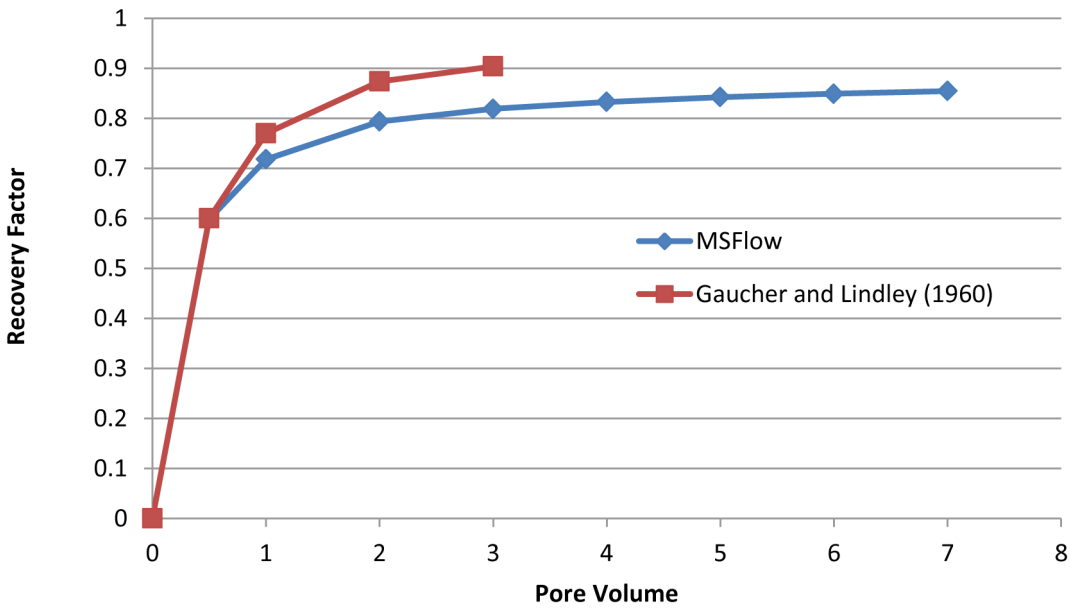

Figure 2—Three-Dimensional, Five-Spot Well Pattern (Mixed Wettability Reservoir)

The breakthrough recovery is identical for both the simulation and experimental results. The final recovery results agree well; the simulation final recovery is 85.5%, and the experimental final recovery is 90.4%. However, the variance between the simulation and experimental results can be attributed to oil relative permeability correlations. Case A-1 underlines the importance of the initial wetting conditions on LSWF recovery. When the residual oil saturation is very low due to intermediate wetting conditions, there is little or no incremental recovery (Skrettingland colleagues 2011).

Therefore, Case A-2, and Case A-3 consider water-wet conditions with a 60° contact angle and oil-wet conditions with a 120° contact angle, Simulation results for Case A-2 consider HSWF and LSWF. It is assumed that during LSWF, the contact angle shifts to intermediate wetting conditions as the salinity decreases, whereas in HSWF, the contact angle remains constant. The recovery curves are shown in Figure 3.

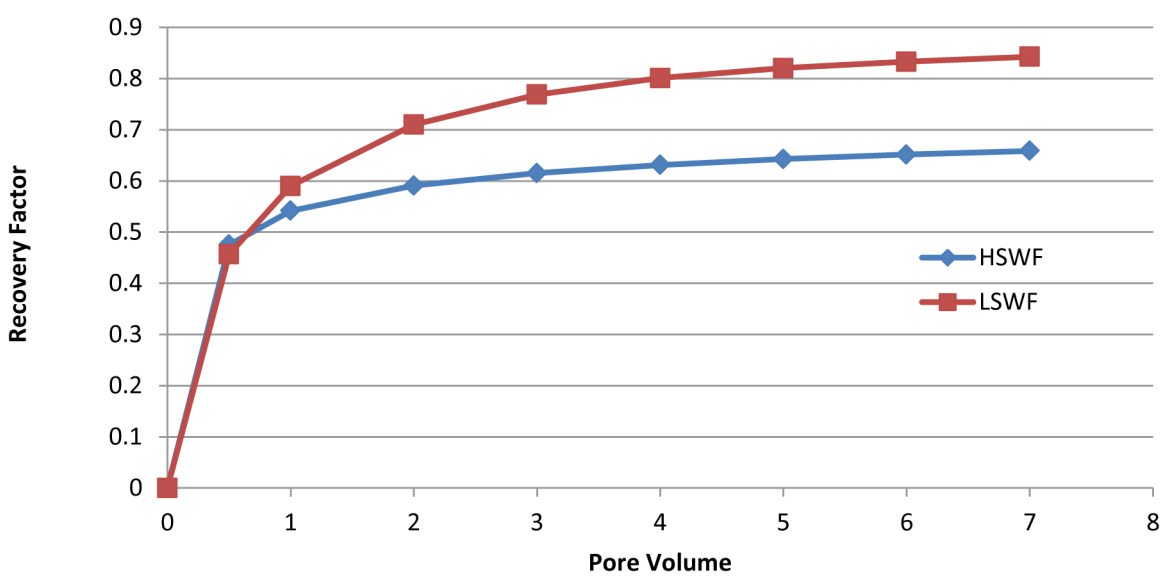

Figure 3—Three-Dimensional, Five-Spot Well Pattern (Water-Wet Reservoir)

The breakthrough recovery of HSWF is 47.5%, in contrast to LSWF, which is 45.7%. This difference is due to an increase in the mobility ratio that occurs because the injected brine viscosity is proportional to salinity concentrations. However, Lemon and colleagues, 2011 suggested that desorption and migration of fine particles during LSWF may improve sweep efficiency. After breakthrough recovery as wettability is modified, the capillary pressure decreases, and the incremental recovery of LSWF increases as the contact angle shifts to intermediate wetting conditions, as shown in Figure 3. Favorable wettability modification may not be the case for LSWF with an initial water-wetting state.

Case A-3 considers HSWF and LSWF in a three-dimensional, five-spot well pattern in an oil-wet reservoir. The contact angle is assumed to remain at a constant value of 120° for HSWF but to decrease linearly with salinity during LSWF, as shown in Figure 4. The results in Figure 4 underline the impact of wettability modification in oil-wet conditions. LSWF's incremental recovery is more rapid and overshadows an adverse mobility ratio resulting from a decrease in injected brine salinity.

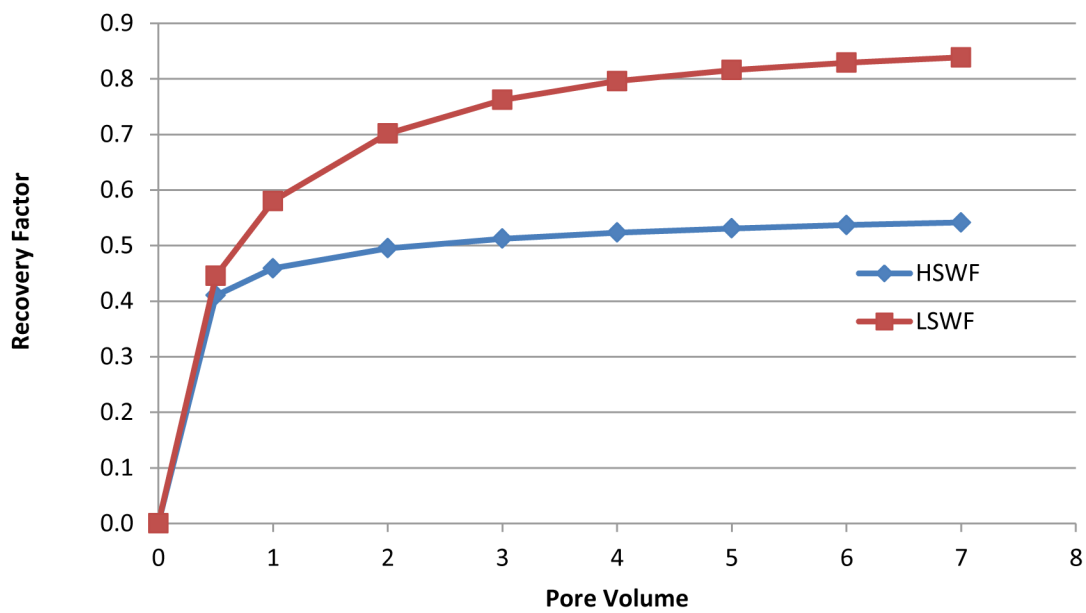

Figure 4—Three-Dimensional, Five-Spot Well Pattern (Oil-Wet Reservoir)

The initial wetting state is an important criterion for LSWF. The incremental recovery in oil-wet systems, or "typical carbonate reservoirs," is more rapid and thus requires less dilution of the injected brine salinity. This has been proven by core-flooding experiments and up-scaled simulation results. Water-wet systems, or "typical sandstone reservoirs," can achieve slightly higher incremental recovery than "oil-wet" reservoirs; however, it take higher salinity dilution ratios and higher injection pore volumes to achieve the final recovery. There is less benefit from LSWF in reservoirs with intermediate wetting conditions. In addition, simulation results indicate substantial un-swept quantities of available oil saturation, as has been validated by three-dimensional simulations. Therefore, the role of polymer flooding is examined along with conventional water-flooding in wetting conditions where LSWF may not achieve significant incremental recovery.

Case Set B Results

The Case Set B uses the same model as Case Set A to examine LSWF, PF, WF and LSWF + PF (Case B-1). The following summarized the guidelines of the study in this paper:

3.2.1 The relative permeability formulation is revised from Corey's (1954) to Buckley and Leveret's (1942) to achieve a better agreement with Gaucher and Lindley's (1960) recovery factors (Case B-1).

3.2.2 The model time scale is than reduced to evaluate potential changes to short term field development plans. (Case B-2)
3.2.3 Anisotropic and volumetric reservoir heterogeneity is studied under 'water wet conditions'. (Case B-3)
3.2.3 Anisotropic and volumetric reservoir heterogeneity is studied for LSWF in addition to PF + LSWF under 'weak oil wet conditions'. (Case B-4)
3.2.4 Under 'strong oil wet conditions' (Case B-5) anisotropic and volumetric reservoir heterogeneity is studied for WF, PF, LSWF and PF + LSWF, IOR methods.

Case B-1 Results Case B-1 model is characterized as a homogenous reservoir under intermediate wetting conditions, similar to Case A. However, four IOR methods have been included along with a reduction of the simulation time interval. The results in Figure 5 indicate no benefit from LSWF since the recovery curve is similar to conventional water-flooding. The performance of LSWF under intermediate wetting conditions has been studied previously for screening some North Sea reservoirs (Aladasani, and colleagues 2012a) and a similar conclusion to Figure 5 was reached. In addition, polymer flooding and a combination of polymer + LSWF yield similar recovery curve that outperform convention water-flooding by 12% recovery factor at 3 PV injection. The aforementioned PF results are comparable to field pilots carried out in China, reference to Aladasani and Bai, 2010. Therefore, under intermediate wetting conditions, polymer flooding is a suitable candidate based on the results of this study.

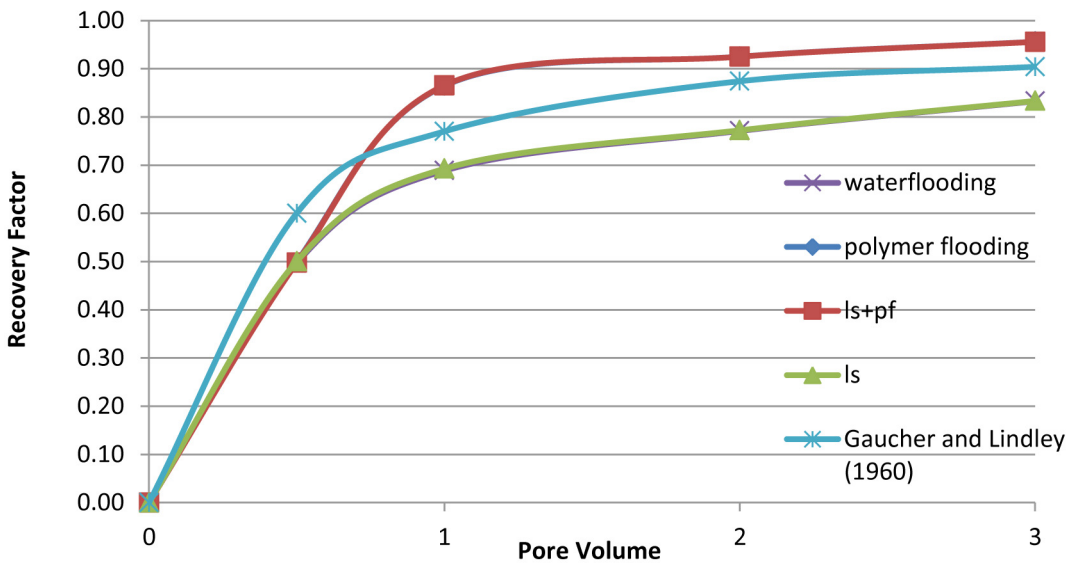

Figure 5—Three-Dimensional, Five-Spot Well Pattern (Mixed Wettability Reservoir)

Case B-2 Results The Case B-2 is divided into sections. In the first section anisotropic reservoir heterogeneity is considered by incorporating five layers with different permeability's to the reservoir model, refer to Table 2a. The adopted permeability magnitudes are intended to represent formation damage resulting from fine migration or participation. Therefore, no distinction is made between sandstone and carbonate reservoir in Case B-2-1 and the initial wetting condition is assumed as 'strong water wet conditions'.

The results in Figure 6 indicate a general decrease in the recovery factors by up 34% OOIP (compared to Case B-1 at 2 PV injected) mainly due to a substantial decrease in permeability resulting for example from the incorrect application of LSWF. In such a case, PF provides the highest incremental recovery at (12% Recovery Factor, 2 PV injected) over conventional water-flooding. Therefore, it is suggested that

the highest recovery in a strong wetting state is expected from PF (it should be noted that high salinity water may favorably modify the wetting state to intermediate conditions and possibly avoiding formation damage).

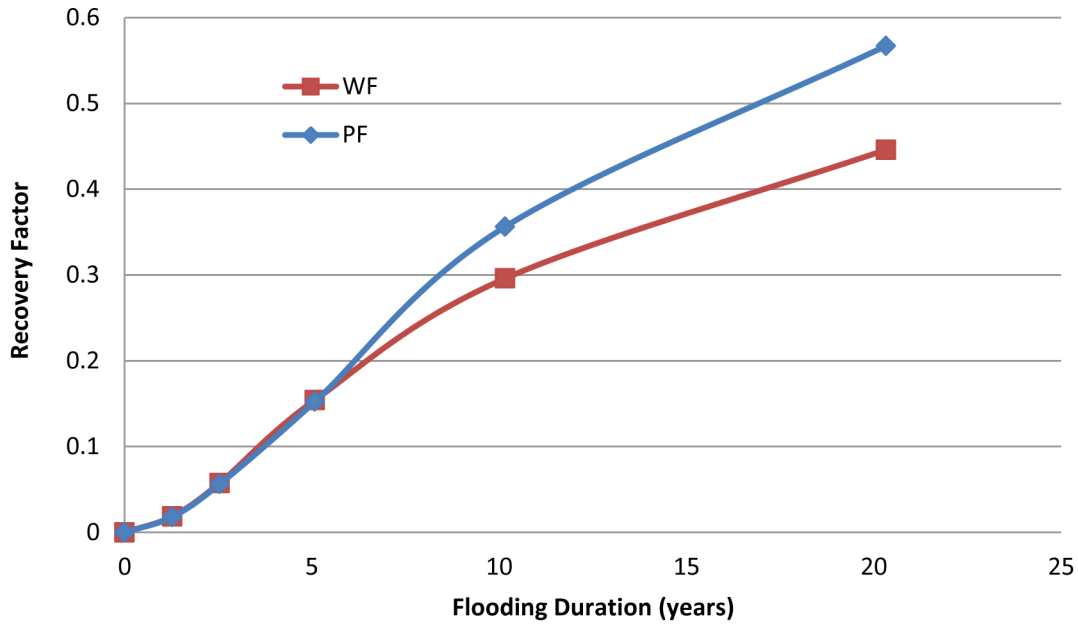

Figure 6—3D, 5-Spot Pattern, Heterogeneous, Low Permeability (Wetting Condition – Strong Water Wet)

In the second section, Case B-2-2 is constructed with areal heterogeneity is added to the model and is representative of sandstone formation, shown in Table 2b. No formation damage is considered. The results in Figure 7 indicate a general decrease in the recovery factors by up to 14% OOIP (compared to Case B-1 at 2 PV injected) due to the added volumetric heterogeneity.

Table 2b—Reservoir Properties for Five-Spot Water-Flooding Pattern

	Areal Heterogeneity (md)		Ansiotropic Heterogeneity (md)	
Vertical Pattern (Layer Thickness 4 ft)	Sandstone	Carbonate	Sandstone	Carbonate
Layer 1	1600x16	16x16	16	16
Layer 2	160x16	1.6x0.16	1600	0.16
Layer 3	16x1600	0.16x1.6	160	16
Layer 4	1600x160	16x16	160	1.6
Layer 5	160x1600	1.6x1.6	1600	1.6

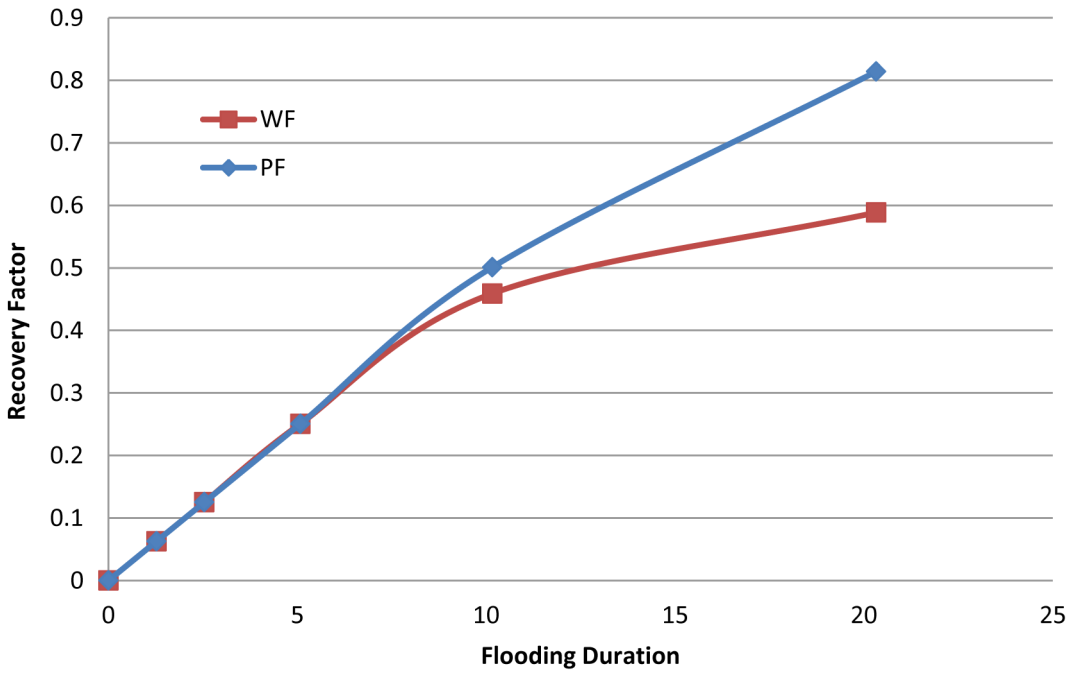

Figure 7—3D, 5-Spot Pattern, Heterogeneous (Wetting Condition – Strong Water Wet)

Case B-3 Results The Case B-3 is divided into two sections, similar to Case B-2. In the first section anisotropic reservoir heterogeneity is considered by incorporating five layers to the model, refer to Table 2a. Formation damage is assumed, no distinction is made between sandstone and carbonate reservoir in Case B-3-1 and the wetting condition is considered as 'weak water wet conditions'. The results in Figure 8 indicate a general decrease in the recovery factors by up 31% recovery factor (compared to Case B-1 at 2 PV injected) mainly due to the formation damage. Polymer flooding improves recovery factor by 12% recovery factor (2 PV injected). In the second section, areal heterogeneity is added to the model, similar to Case B-2-2. The permeability's are selected to represent sandstone formation, refer to Table 2b. The difference between Case B-3 and Case B-2 is the wetting condition. The results in Figure 9 indicate a general decrease in the recovery factors by up 10% recovery factor (compared to Case B-1 at 2 PV injected) due to the added areal heterogeneity. In addition, Figure 9 indicates PF results in incremental recovery of 21% compared to conventional water-flooding.

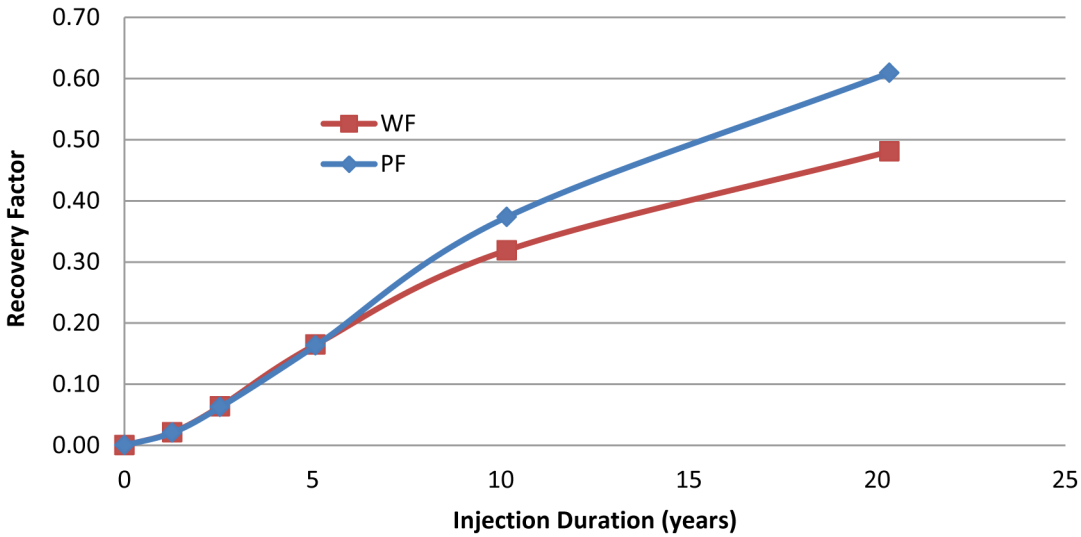

Figure 8—3D, 5-Spot Pattern, Heterogeneous, Low Permeability (Wetting Condition – Weak Water Wet)

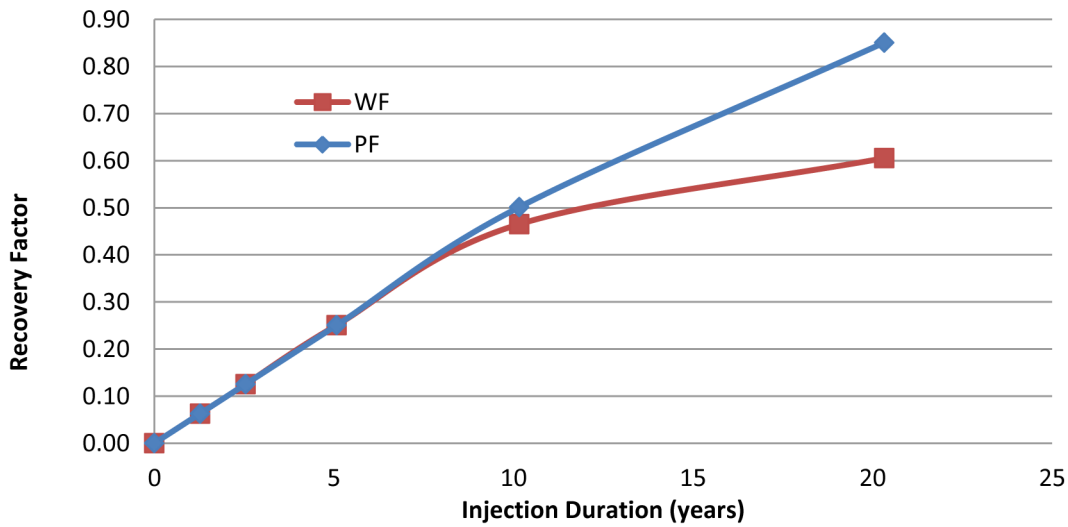

Figure 9—3D, 5-Spot Pattern, Heterogeneous (Wetting Condition – Weak Water Wet)

Case B-4 Results The Case B-4 is divided into two sections, similar to Case B-2. In the first section anisotropic reservoir heterogeneity is considered by incorporating five layers to the reservoir model, refer to Table 2a. In Case B-4-1 the permeability's are selected to represent carbonate formation. The initial wetting state is assumed as ″weak oil wet condition' and as a result of wettability modification the final wetting state is assumed as ″intermediate wetting conditions″. The results in Figure 10 indicate a general decrease in the recovery factors due to the appreciable decrease in the formation permeability and oil wetting conditions. PF yields 15% incremental recovery contrasted with LSWF under weak oil wet conditions.

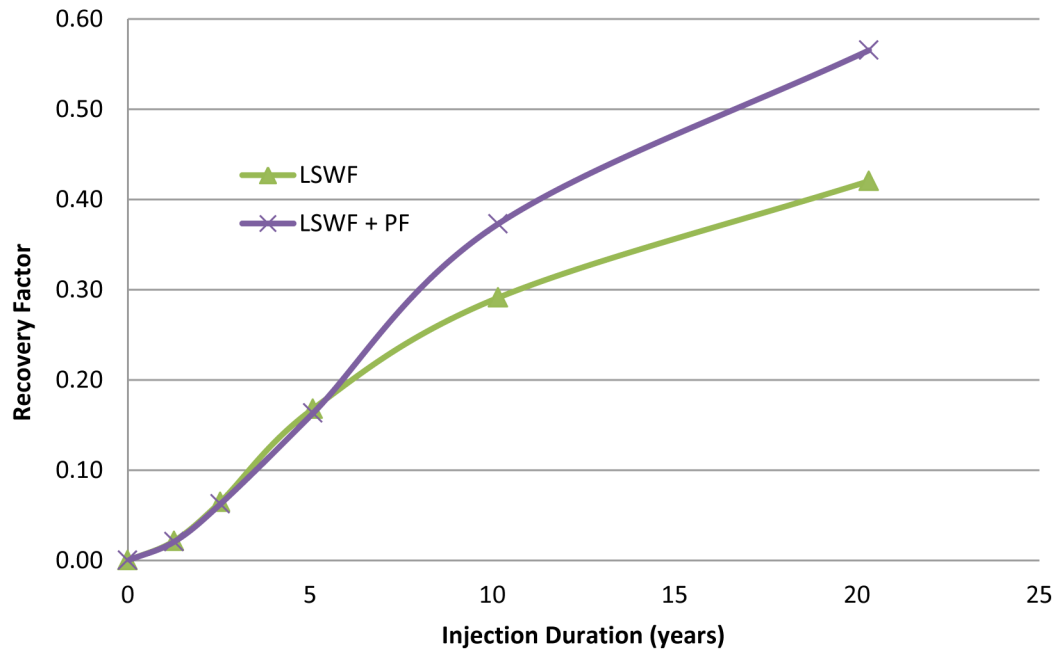

Figure 10—3D, 5-Spot Pattern, Heterogeneous, Low Permeability (Wetting Condition – Weak Oil Wet)

In Case B-4-2 the reservoir permeability is revised based as shown in Table 2b, where higher magnitudes of permeability are adopted for carbonate formation. The results in Figure 11 indicate a 7% incremental recovery compared to Case B-4-1 and similar recovery curves for LSWF and PF. Furthermore, the is a dependency between PF and LSWF recovery variance and the change in reservoir permeability (Case B-4-1 Verses Case B-4-2).

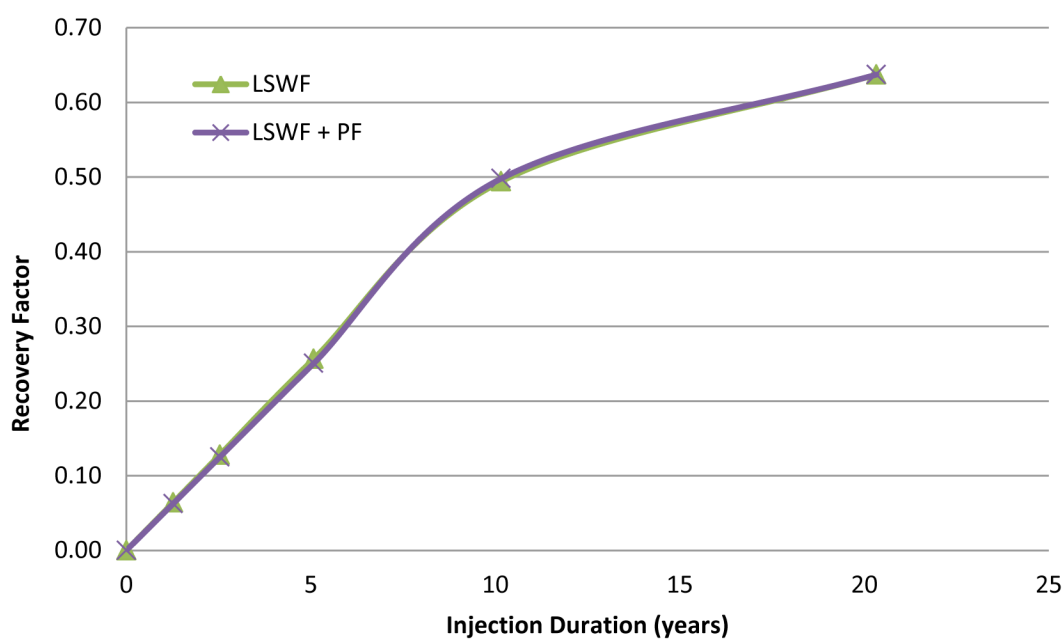

Figure 11—3D, 5-Spot Pattern, Heterogeneous (Wetting Condition – Weak Oil Wet)

Case B-5 Results The Case B-5 is divided into two sections, similar to Case B-2. In the first section anisotropic reservoir heterogeneity is considered by incorporating five layers to the reservoir model, refer

to Table 2a. The initial wetting state is assumed as ″oil wet condition' and as a result of wettability modification the final wetting state is assumed as ″intermediate wetting conditions″. The results in Figure 12 indicate LSWF incremental recovery of 2.5% recovery factor over PF. The combination of PF + LSWF achieved the highest recovery factor with variance of 20% over LSWF.

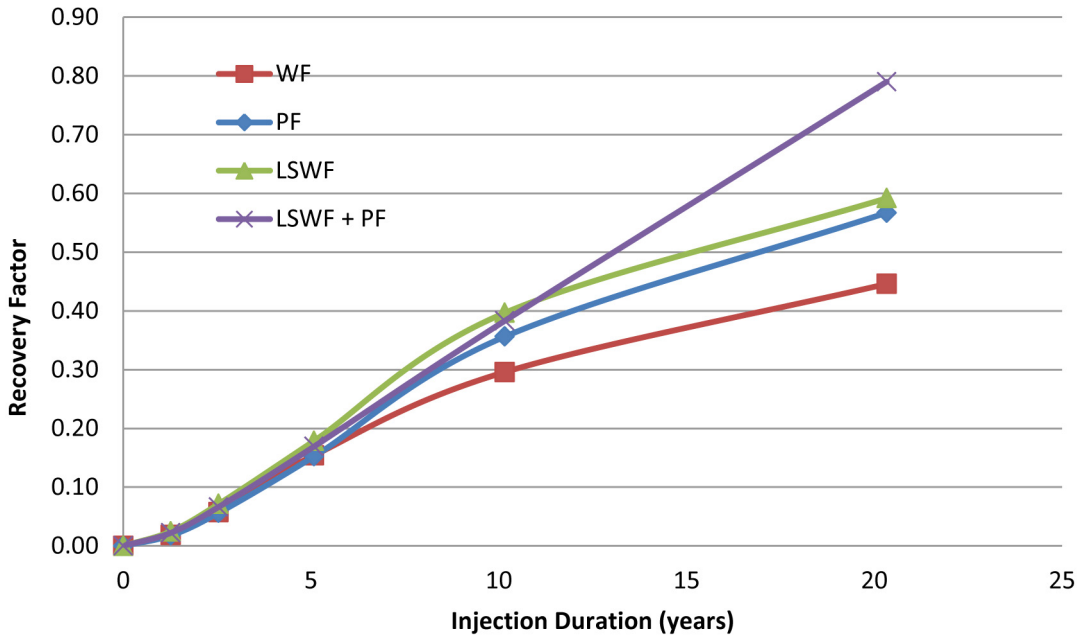

Figure 12—3D, 5-Spot Pattern, Heterogeneous, Low Permeability (Wetting Condition – Oil Wet)

In Case B-5-2 the reservoir permeability is revised as shown in Table 2b, where higher magnitudes of permeability are adopted for typical carbonate formation. The results in Figure 13 indicate a comparable performance for all IOR methods being evaluated up to 2 PV injection subsequently a distinction is observed that is summarized as follows. The microscopic and macroscopic displacement efficiency improved by LSWF and PF are comparable in their incremental recovery, as wettability is favorably modified to intermediate wetting conditions. The combinations of PF + LSWF results in similar effect as Steam Injection or Miscible flooding where both, displacement efficiencies are rehabilitated. Therefore, (a) an optimal time (incremental recovery versus cost of EOR implementation) exists to initiate EOR methods, (b) a criteria is developed for optimal PF + LSWF performance in candidate reservoir 'at specific wetting conditions'. (c) fractures and the impact of diffusion rates have not been considered in this study and will be a subject of future work especially inclusive of completion programs for multi-stage fracture wells (Aladasani and colleagues, 2014b)

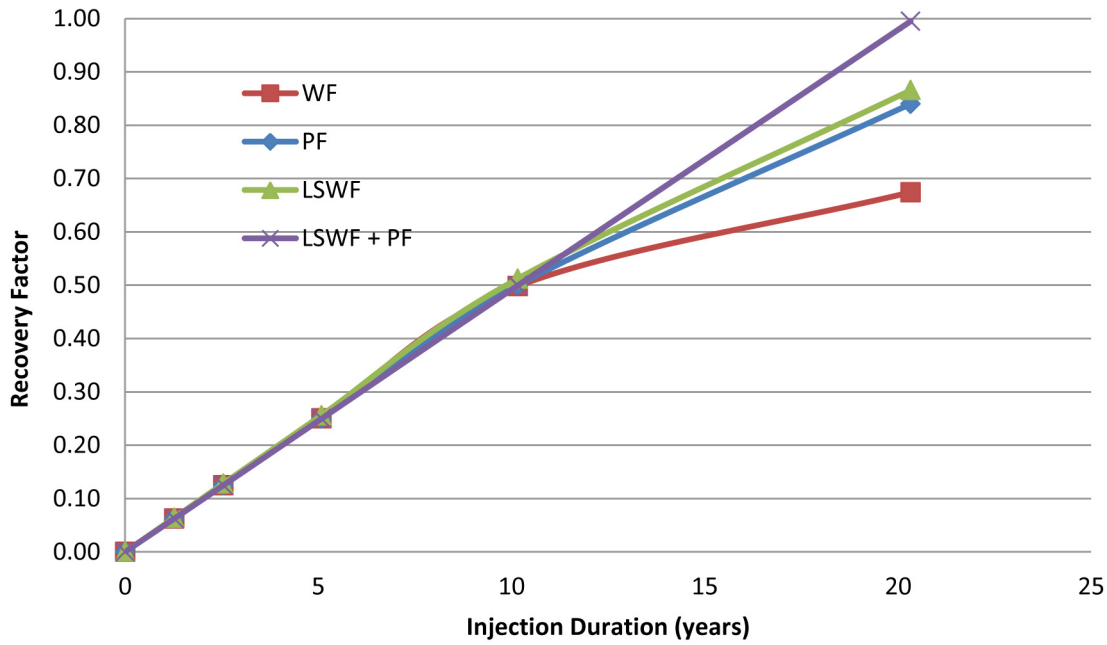

Figure 13—3D, 5-Spot Pattern, Heterogeneous (Wetting Condition – Oil Wet)

Summary

Overview

Oil recovery is a function of reservoir forces. Effective IOR implementation requires the proactive identification, and contribution of the dominating reservoir forces over the course of the field development. The work in this paper uses a validated, compositional simulator in addition to validated relative permeability and capillary formulations to simulate LSWF, PF, WF and combination of PF + LSWF in a multi-dimensional, anisotropic and aerially heterogeneous model, under various wetting conditions. Wettability modification is also simulated using start and end relative permeability end points, captured and validated from literature.

Conclusions

a. The initial wetting state is an important criterion for LSWF. The incremental recovery in oil-wet systems, or ″typical carbonate reservoirs,″ is more rapid and thus requires less dilution of the injected brine salinity. In addition, simulation results indicate substantial un-swept quantities of available oil saturation, as validated by three-dimensional simulations. Therefore, alternatives such as polymer flooding are examined along with conventional water-flooding in wetting conditions where LSWF may not achieve significant incremental recovery.
b. LSWF is not effective in intermediate wetting conditions and Polymer flooding yields higher recovery factors in all water wet conditions.
c. The impact of reservoir damage has an adverse effect on the field development and polymer flooding yields the highest incremental recovery in case of low permeability formations.
d. In oil wet conditions the performance of PF and LSWF is similar especially in weak oil wet systems due to the equal contribution of their respective displacement efficiencies or governing reservoir force.
e. In strong oil-wet conditions the combination of PF + LSWF yields the highest recovery factor.
f. The wetting conditions, formation heterogeneity and permeability magnitude all impact IOR selection and suggest that each oil reservoir has a unique ionic environment that changes naturally

and by human intervention, therefore it is important to study different IOR methods at different stages of the reservoir development

Fractures and the impact of diffusion rates have not been considered in this study and will be a subject of future work especially, inclusive of completion programs for multi-stage fracture wells.

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