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Reservoir simulation study of enhanced oil recovery by sequential polymer flooding method

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Abstract:
As a reservoir reaches depletion stage there will still be a varying amount of residual oil saturation in the reservoir pore volume that is too heavy to be moved and produced. This undesirable phenomenon occurs due to adverse mobility and/or viscosity ratio between displacing phase (water) and displaced phase (residual oil). A solution to that is polymer injection which has been considered as one of the most effective and successful method to improve oil recovery. Moreover polymer flooding also showed limited success when applied in heterogeneous reservoir. This is because single polymer injection cannot sweep entire porous media efficiently, therefore in this research work the effectiveness of sequential polymer injection is studied and compared with conventional single polymer injection. The reservoir property model was developed from the available well data of an example field using stochastic approach. From the base case two more property models were developed to cover the heterogeneity from slightly to very heterogeneous reservoir rock. The degree of heterogeneity was obtained for each property model using Dykstra-Parson technique. The magnitude of Dykstra-Parson coefficient for Slightly, Moderate and Very heterogeneous were 0.24, 0.59 and 0.69, respectively. Our results indicated that injecting polymers sequentially with varying in concentrations is an effective technique for enhanced oil recovery in heterogeneous reservoir rock.

1. Introduction

Enhanced oil recovery (EOR) is the using of various techniques and methods for increasing the production of residual oil saturated zones that cannot be extracted by primary and secondary recovery mechanism. There are three primary techniques for EOR: Thermal recovery, gas injection, and chemical injection. Sometimes, in some cases the term quaternary recovery is used to refer to more advanced and speculative EOR techniques.

A survey of literature has been conducted and several studies were found. Muggeridge et al. (2014) suggested that by using EOR techniques recovery efficiency factor for heavy oil may increase to 50-70%. Tunio et al. (2011) indicated that through the usage of advanced modern EOR techniques such as gas flooding, water alternating gas (WAG), or polymer flooding, recoverable oil amounts can reach up to 60-65%. Other methods such as gas injection could also have issues such as gas overriding effects, gas channeling and early breakthrough, and high cost (Mogensen et al., 2010; Mousavifar et al., 2012).

On the other hand, Loahardjo et al. (2010, 2012) showed that after several cycles of injecting water sequentially residual oil saturation was reduced significantly. They also observed same result with aging oil in the porous media. Injecting three different polymers concentration from low to high molecular weight can prevent channeling or fingering effects (Lohardjo et al., 2013). Whilst in a number of lab tests injecting polymers sequentially has increased residual resistance factor to water by 5 times and 2.5 times if compared to single polymer injection. Similarly the residual resistance factor to oil reduced by 2 times in comparison to single injection (Sidiq and Amin, 2008). In another study by Sun et al. (2012), he showed that with increasing polymer concentration FoE increases to a level then decreases.

One of the main factors that affect the success of any EOR is heterogeneity. It has also considerable effect on polymer distribution and stability in the reservoir formation as its being injected. The same affect will naturally be even truer for sequential polymer injection. In this paper the magnitude of heterogeneity effect on recovery efficiency was investigated in details. Fig. 1 shows the schematic of polymer injection sequentially and highlights the effect of heterogeneity on polymer propagation in reservoir rock.

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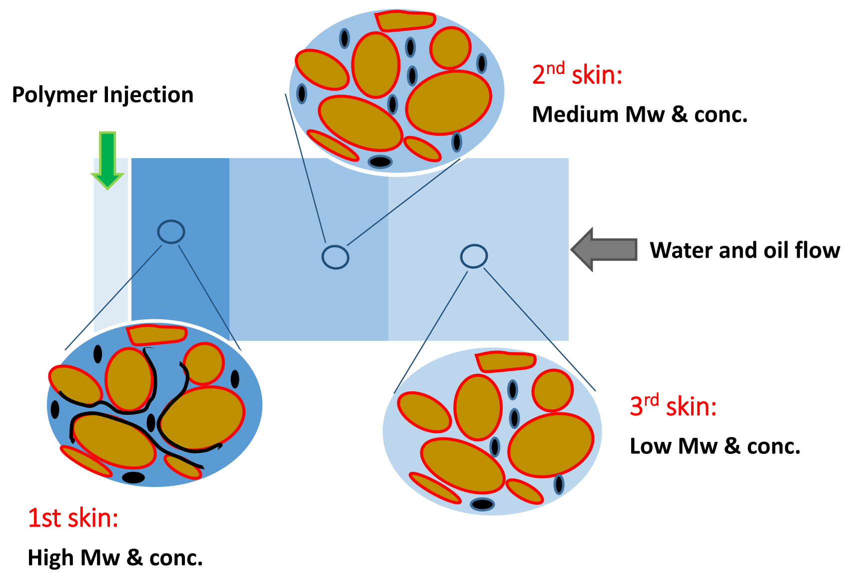


Fig. 1. Schematic representation of a sequential injection treatment (Chung et al., 2012).

The main objective of this research work was to investigate the effect of sequential polymer injection method at field scale using reservoir simulation. The aim is to see to what degree increases the sweep and recovery efficiency for the studied field.

2. Preparing simulation data

The key inputs of the geo-model were acquired from the existing well data. Due to confidentiality only some well data were provided. Based on these data a two dimensional sector model is developed having the rock property distribution (porosity, permeability and saturation) reflects the field data.

Three static models are developed representing different degree of heterogeneity, the dimension of the model is (N_x = 20, N_y = 20, N_z = 1), refer to Fig. 2. The aim of this work is to disclose the impact of heterogeneity on recovery efficiency, polymer distribution, sweep efficiency, etc. Details of research work-flow is explained in below points:

1. Well data (porosity and water saturation) and their location is collected and fed to reservoir model software.

2. Porosity and Sw is scaled up and distributed in the reservoir model using Kiriging technique.

3. Permeability is calculated using Tixer's, Timur's, and Coate's methods. Average permeability is selected from the results of abovementioned methods.

$$K = \frac{62.5\phi^6}{S_{wi}^2} \tag{1}$$

$$K = \frac{8.58\phi^{4.4}}{S_{wi}^2} \tag{2}$$

$$K = \frac{4.9\phi^4(1-S_{wi})^2}{S_{wi}^4} \tag{3}$$

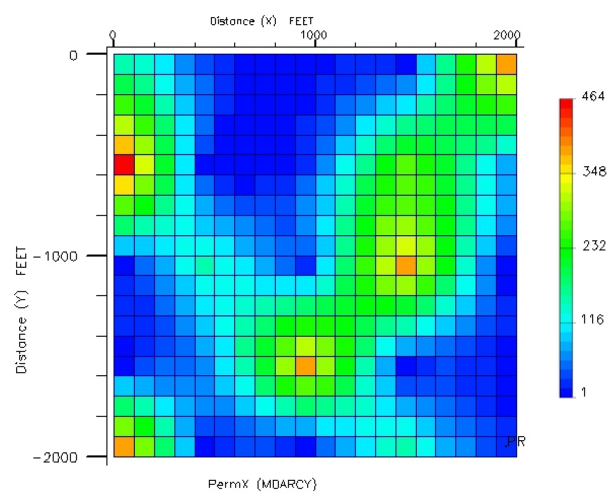


Fig. 2. Grid model (20, 20, 1) of the studied oil field representing the heterogeneous permeability distribution.

where ϕ is porosity, S_{wi} is initial water saturation and K is permeability.

4. Dykstra-Parsons methods is used to generate three reservoir model (*Slightly* V_K = 0.24, *Moderate* V_K = 0.59, *Highly* Heterogeneous V_K = 0.59) refer to Fig. 2 and Table 1. For more details in relation to static model refer to permeability distribution map in Fig. A1 in appendix which represents V_K = 0.24 and V_K = 0.59, respectively.

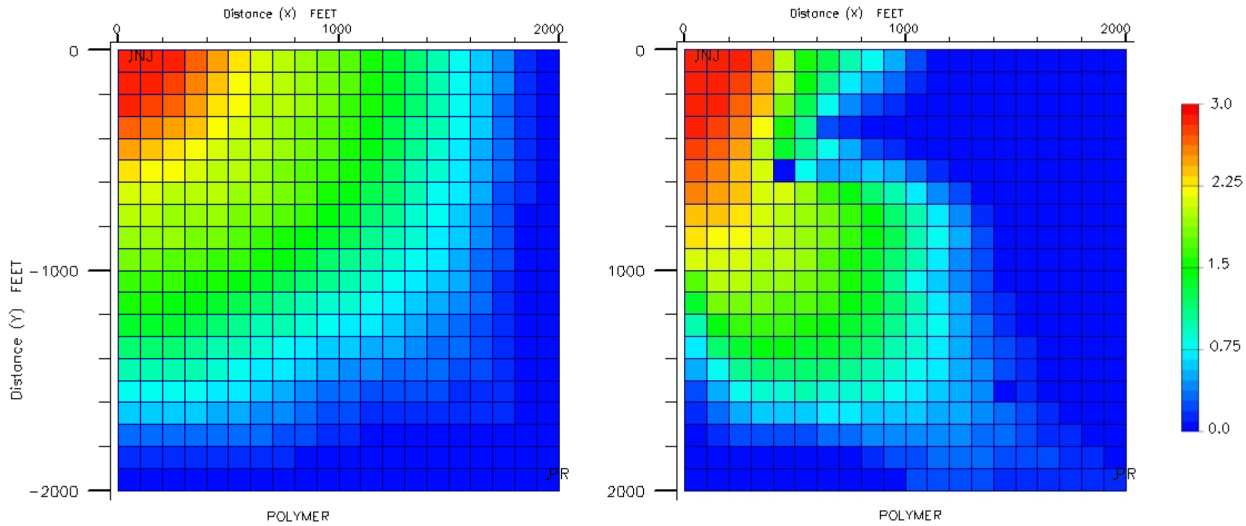
$$V_K = \frac{K_{50} - K_{84.1}}{K_{50}} \tag{4}$$

5. Reservoir simulation case scenarios were run for the developed reservoir model as follow:

a) natural recovery mechanism;

b) water flooding;

c) single polymer injection;



(a) (b)

Fig. 3. Sequential polymer injection propagation in (A) homogenous V_K = 24 and (B) heterogeneous V_K = 69.

Table 1. Dykstra-Parson coefficient for three different reservoir models.

Reservoir model	Dykstra-Parson coefficient V_K	Heterogeneity scale
1	0.24	Slightly
2	0.59	Intermediate
3	0.69	Very

Table 2. Reservoir model descriptions.

S.N.	Model	Description
1	Grid block size	20×20×1
2	Cell size	100 ft
3	Swi	0.248
4	Initial reservoir pressure	4150 psi
5	Reservoir temperature	72 °C
6	API	31.2
7	GOR	987 scf/stb

d) sequential polymers injection.

The initial data used in preparation of the reservoir model is shown in Table 2. Relative permeability curves for wetting and non-wetting phase can be seen in Fig. A2 in appendix.

3. Polymer properties

There are a number of factors that can affect the success of polymer injection procedures. The factors that need to be addressed before the initiation of injection operations include: Type of the reservoir fluid, wettability of the reservoir rock, presence of fractures in the formation, concentration and amount of the injected polymers (Olajire, 2014). Furthermore, polymer concentration and viscosity are other factors that influence the distribution of polymer in porous medium while displacing oil, Table A1 in appendix shows polymer concentration versus viscosity at reservoir temperature.

The propagation of injected polymers in two reservoir models (V_K = 0.24 and V_K = 0.69) is shown in Fig. 3. It is apparent heterogeneity significantly affects the sweep efficiency of polymer in reservoir rock.

The properties of injected polymers for sequential injections can be found as follow:

1-Low polymer concentration (1 Lb/Stb): This type of polymer known by having a low concentration, high injectivity during injection, and low resistance factor. It reduces water permeability by 20% and low concentration polymer is also used in the first stage of sequential injection that will mobilize the residual oil trapped in the pore space (Chung et al., 2012).

2-Medium polymer concentration (2 Lb/Stb): This type is known to have a relatively higher concentration and lower injectivity. This type reduces water relative permeaby to almost 40%, and can displace the remaining trapped oil in the porous media (Sidiq and Amin, 2008).

3-High polymer concentration (3 Lb/Stb): It is known to have a high concentration and very low injectivity, and this makes to have a sufficient gelation time to over-displace the low and medium polymer concentration.

4. Results and discussion

4.1 Natural recovery model

The recovery efficiency of the No-Flood model "the base case scenario (a)" will be used as a reference to compare results from other scenarios (b-d) water flooding, single polymer injection and sequential polymers injection. This is to unders-

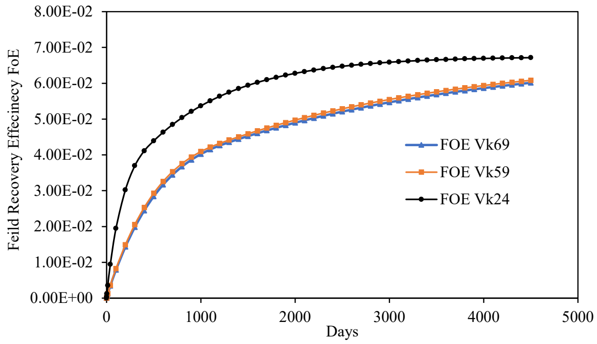


Fig. 4. Field recovery efficiency of no-flood model vs time in different heterogeneous rocks.

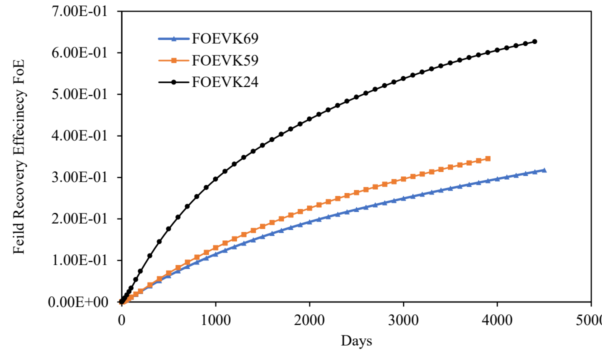


Fig. 5. Field recovery efficiency of water-flood model vs time in different heterogeneous rocks.

tand the degree of effectiveness of different EOR methods on recovery efficiency. Fig. 4 shows FoE (field recovery efficiency) for the no-flood scenario on three reservoir models (V_K = 0.69, V_K = 0.59, V_K = 0.24). Results indicate that with increasing V_K recovery FoE decreases by 18%.

Since no flood is selected the recovery efficiency is extremely low and indicates that most of the oil trapped in the pore space as immobile. The recovery rate obtained for each reservoir model (V_K = 0.24, V_K = 0.59, V_K = 0.69) were 6.71%, 5.9% and 5.5%, respectively.

4.2 Water flood model

With water flooding method recovery efficiency has increased significantly as the water immiscibly displaces oil in the pore space in which increases oil production rate (Willhite, 1986). Fig. 5 shows FoE vs time for all three reservoir models in which FoE is noticeably higher if compared to No-Flood model and there is significant increase in recovery efficiency (RE). The improvement occurred with each reservoir model by factor 10, 6.5 and 5.4 times when compared with No-Flood scenario. An approximate maximum (RE) of (61.1%, 37.4% and 30.2%) achieved for (V_K = 0.24, V_K = 0.59, V_K = 0.69) respectively. Maximum recovery efficiency is achieved with most homogeneous formation.

4.3 Single stage polymer injection model

The conventional method ”single polymer injection” was carried out by injecting single polymer having a constant concentration through the simulation run. The aim of this method was to compare and evaluate the effectiveness new method when compared to conventional methods. Fig. 6 shows the recovery efficiency versus time for all three different heterogeneity models. If it is compared to water flood the recovery efficiency improved with all reservoir models. This is an evidence of polymer effects on FoE in all case scenarios. The recovery rates achieved with single polymer injection were 63.2%, 41.2% and 36.4% for (V_K = 0.24, V_K = 0.59, V_K = 0.69) respectively. The incremental increase of FoE if compared to water flood were 5%, 9% and 8% for (V_K = 0.24, V_K = 0.59, V_K = 0.69) respectively.

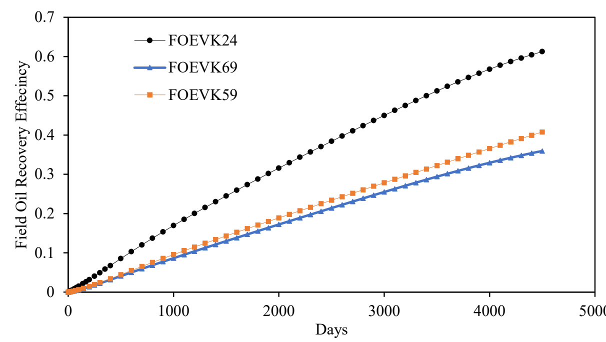


Fig. 6. Field recovery efficiency for single polymer injection model in different heterogeneous rocks.

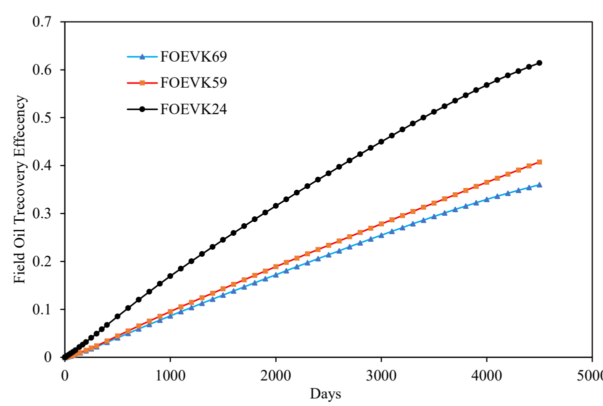


Fig. 7. Field recovery efficiency for single polymer injection model in different heterogeneous rocks.

4.4 Three stage polymer sequential flood model

In this model polymer was injected sequentially in three stages where each stage had a different concentration of polymer injected. Fig. 7 shows results of injecting polymer sequentially for all three reservoir models. With polymer concentration increases the recovery efficiency improved if compared to conventional polymer flooding method. The achieved FoE with sequential injection was 64.4%, 42.8% and 39.2% (V_K = 0.24, V_K = 0.59, V_K = 0.69) respectively.

Table 3. Comparison of recovery efficiency for no-flood, water-flood, single & three stage polymer flood models.

Models	Maximum recovery efficiency (Dimensionless)		
	V_K = 0.24 (Slightly-heterogeneous)	V_K = 0.59 (Medium-heterogeneous)	V_K = 0.69 (Very-heterogeneous)
No-Flood	0.0671	0.059	0.055
Water-Flood	0.611	0.374	0.302
Single stage polymer injection	0.632	0.412	0.364
Three stages polymer injection	0.644	0.428	0.392

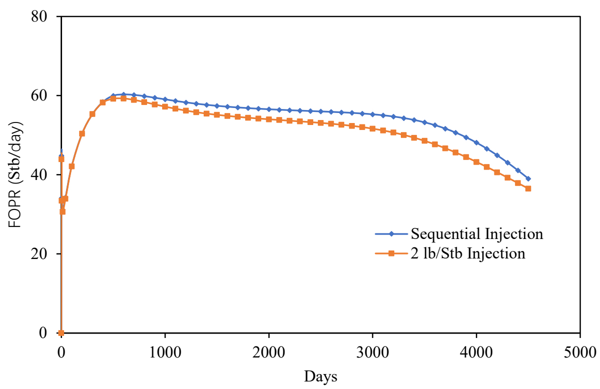


Fig. 8. Field oil production rate for sequential and 2 lb/Stb polymer injections.

The incremental increase can be noticed with sequential polymer injection if compared to conventional method polymer injection, the increment rate were 3%, 5% and 8% for (V_K = 0.24, V_K = 0.59, V_K = 0.69) respectively. The slight increase of FoE can be related to heterogeneity effect on the polymer dispersion and porosity-permeability distribution. These results are in agreement with experimental observations discussed in the introduction section.

Another run also conducted to compare the results of sequential polymer injection with medium polymer concentration (2 Lb/Stb), see Fig. 8. Results showed that better recovery efficiency can be obtained if compared to low polymer concentration. The FoE is nearly the same as achieved with sequential injection. The reason of obtaining high FoE with 2 Lb/Stb is that pore scale heterogeneity cannot be captured by the simulator, so the differences between pore throat and pore body is difficult to be represented by the differences in permeability of two adjacent cells.

4.5 Recovery efficiency comparison

The results attained with each scenario are summarized in Table 3. The comparison between different recovery efficiencies for all methods investigated by this study is displayed. The magnitude of field recovery is shown in fractions. This makes the interpretation of data much easy and comparable between water and two EOR approaches. More importantly, the sequential polymer injection method is preferable technique particularly in heterogeneous reservoir since the recovery rate with sequential injection is much higher when compared to water and single polymer floods.

5. Conclusion

The main conclusion with this study is that injecting polymer sequentially in three stages with different concentrations can be considered as a viable alternative to conventional polymer flooding methods particularly in reservoir rock considered as heterogeneous to very heterogeneous (high V_K).

The sequential flooding of polymers proved to improve the overall mobility ratio, oil relative permeability, and areal sweeping efficiency of residual oil in the pore space compared to conventional polymer flooding.

Further study requires optimizing sequential polymer flooding method that could reduce the overall operating and capital cost of most EOR operations.

Nomenclature

EOR = Enhanced oil recovery
FoE = Field recovery efficiency
V_K = Dykstra-Parsons coefficient
RE = Recovery efficiency
PVT = Pressure volume temperature
FVF = Formation volume factor
STB = Stock tank barrel

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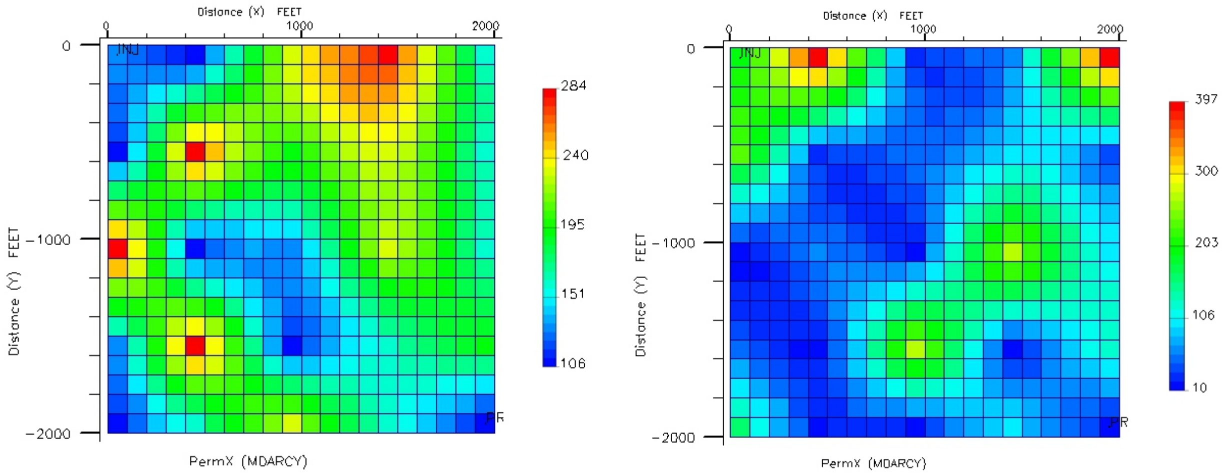
Appendix



(a) (b)

Fig . A1. Permeability distribution, (a) low heterogeneity (V_K = 0.24); (b) medium heterogeneity (V_K = 0.59).

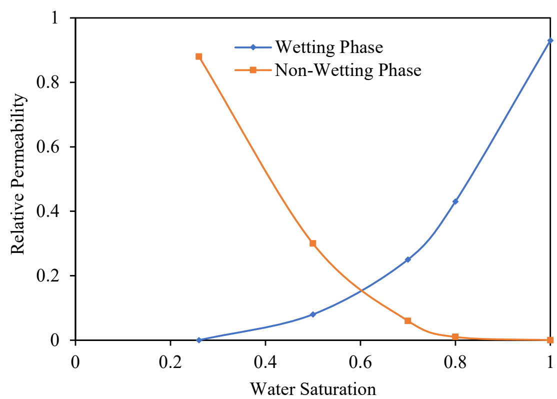


Fig . A2. Relative permeability of wetting and non-wetting phase.

Table A1. Polymer concentration versus viscosity under reservoir condition.

lb/stb	Vis (cp)
0	1
0.25	3.55
0.5	6.77
0.75	9.45
1	12.55