Physical Science International Journal
14(2): 1-12, 2017; Article no.PSIJ.30805
ISSN: 2348-0130

SCIENCEDOMAIN *international*
www.sciencedomain.org

Simulation Study of Polymer Flooding Performance: Effect of Polymer Rheology

O. A. Falode[1*] and K. I. Idoko[1]

[1]*Department of Petroleum Engineering, University of Ibadan, Nigeria.*

Authors' contributions

This work was carried out in collaboration between both authors. Author OAF designed the study and wrote the protocol. Author KII carried out the study under the supervision of author OAF. Author KII wrote the first draft of the manuscript while author OAF revised it. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/PSIJ/2017/30805
Editor(s):
(1) Thomas F. George, Chancellor / Professor of Chemistry and Physics, University of Missouri-St. Louis, Boulevard St. Louis, USA.
(2) Christian Brosseau, Distinguished Professor, Department of Physics, Université de Bretagne Occidentale, France.
Reviewers:
(1) Joel Obed Herrera Robles, Universidad Autónoma de Ciudad Juárez, Mexico.
(2) Yuhu Bai, Chinese Academy of Sciences, China.
Complete Peer review History: http://www.sciencedomain.org/review-history/18753

Original Research Article

Received 30th November 2016
Accepted 14th January 2017
Published 22nd April 2017

ABSTRACT

The use of enhanced oil recovery methods to improve oil productivity has grown and come to stay in the industry. This is as a result of its ability to improve productivity and sweep efficiency. Waterflooding, the most widely used method to recover oil becomes less effective when the mobility ratio is unfavorable and the displacement efficiency is low. This leads to viscous fingering or channeling that leads to significant bypassing of residual oil.

Augmenting injected water with polymer will increase the effectiveness of a conventional waterflood. However these Polymers used in the industry are pseudoplastic (shear thinning). This property is not a correct reflection of the sweep displacement. Polymer's non-Newtonian behavior needs to be taken into account for the successful design and evaluation of polymer flooding projects. The objective of this work is to study the performance of polymer rheology on oil recovery under different fluid and rock properties.

This project uses ECLIPSE 100 to study the performance of polymer flooding on oil recovery. Sensitivity runs was made on polymer concentration, polymer injection rate, rock wettability, polymer rheology, heterogeneous reservoir, stratified reservoir with crossflow.

Based on the simulation studies and the hypothetical model built, Polymer flooding and

**Corresponding author: E-mail: falodelias@gmail.com;*

waterflooding case was compared in which there is an increase of oil recovery by 20% over water flooding. Polymer flooding is effective in water-wet rock than oil-wet. This is because an oil-wet formation tends to hold back more oil in its minute pores and produce reservoir water. Increasing polymer concentration will lead to higher sweep but reservoir pressure and economics should be considered. Non-Newtonian polymer leads to lower oil recovery. This is due to the decrease in viscosity at high shear rate as a result of velocity contrast and instability.

Keywords: Waterflooding; polymerflooding; non-Newtonian; simulation.

NOMENCLATURES

FOE : *Field Oil Efficiency*
FOPR : *Field Oil Production Rate*
FWCT : *Field Water Cut*
K_{rw} : *Relative permeability to water*
K_{ro} : *Relative permeability to oil*
$S*$: *Normalized water saturation*
E_w : *Water relative permeability at residual saturation*
E_o : *Oil relative permeability at residual saturation*
nw : *Water Exponent of the relative permeability*
no : *Oil Exponent of the relative permeability*
P_c : *Capillary pressure*
P_b : *Constant*
C_{pc} : *Constant*
E_{pc} : *Constant*

1. INTRODUCTION

The word Rheology is defined as the science of deformation and flow. Rheology involves measurements in controlled flow, mainly the viscometric flow in which the velocity gradients are nearly uniform in space. In these simple flows, there is an applied force where the velocity (or the equivalent shear rate) is measured, or vice versa [1].

Rheologically, fluids are classified as Newtonian and non-Newtonian. Fluids whose viscosity value does not change at different shear rate are termed Newtonian fluid; fluids which have non constant viscosity value at different shear rate are called non-Newtonian fluid. Experiments show that the viscosity of polymer solution does not remain constant at various shear rates and therefore polymers are categorized as the non-Newtonian fluid.

Normally, polymer solutions used in EOR processes are shear-thinning or pseudoplastic fluids in a viscometer, whose apparent viscosity decreases in a reservoir with increasing shear rate. Some polymer solutions may exhibit pseudodilatant behavior in porous media [2]. The shear-thinning behavior is beneficial from the standpoint of injectivity, because the viscosity near the injection well is lower due to higher shear rate, which provides more favorable injectivity. Once the polymer moves far into the reservoir, shear rates decline and the viscosity increases, which provide the desired mobility control. However, shear-thinning may be undesirable in terms of sweep efficiency and resulting oil recovery, especially in heterogeneous reservoirs. Therefore, this work intends to study polymer rheology under different fluid and rock properties.

1.1 Previous Work

A three dimensional numerical simulation of polymer flooding in homogenous and heterogenous systems was conducted [3]. The purpose of the study was to determine the order and magnitude of waterflood pattern recoveries as affected by slug injection of viscous polymer. The results showed that injection of polymer at watered-out stage in the flood history has no effect on the 5-spot recoveries for the homogenous case but has a slightly favorable effect in the layered cases with thief zones.

Masuda et al. [4] simulated polymer flooding including the viscoelastic effect of polymer solution, They assumed the immiscibility of oil and polymer solution. Because the displacing fluid is non-Newtonian, the Buckley leveret equation was modified to calculate fractional flow curves. The rheological behavior of polymer solution was model with Ellis type model and viscoelastic model.

It was noticed that the assumption of polymer solution as Newtonian or a pseudoplastic is valid when the flow rate in pore space is so slow that the pseudoplastic effect of polymer solution can be neglected. Polymer viscoelasticity is to be considered in high shear-rate regions such as the vicinity of the injectors and producers and in reservoir having heterogeneous pore geometry.

Abdulkareem Alsofi et al. [5] stated that most polymer used in EOR exhibit shear thinning behavior. Shear thickening will improve sweep while shear thinning (pseudo-plasticity) will impair it through exacerbating the velocity contrast and or inducing instability. Streamline simulator was used to handle the polymer flooding with Newtonian and non-Newtonian behavior. In their work, they investigated the thinning effect of polymer in a homogenous and heterogeneous reservoir 5 spot pattern. It was concluded that the pseudoplasticity nature of polymer leads to less recovery. Their work did not include the wettability of the reservoir rock.

Because most polymers used in EOR exhibit shear-thinning behavior, polymer solution is a highly nonlinear function of shear rate. Kun Sang Lee [6] studied Performance of a Polymer Flood with Shear-Thinning Fluid in Heterogeneous Layered Systems with Crossflow.

A reservoir simulator including the model for the shear-rate dependence of viscosity was used to investigate shear-thinning effects of polymer solution on the performance of the layered reservoir in a five-spot pattern operating under polymer flood followed by waterflood. The result show that oil recovery decreases a lot for larger shear thinning values due to velocity contrast among layers as reservoir heterogeneity becomes larger. This work attempts to capture the effect of polymer rheology in respect to the wettability of the reservoir.

A simulation study that illustrates the application of polymer flooding to an offshore heavy oil reservoir within the Niger delta was carried out [7,8]. Several full field scale sensitivities were run in an experimental design approach in an effort to optimize the injection strategy and flood pattern for both a water injection case and then polymer flooding case. All producers and injectors are either horizontal wells or deviated wells. The results show that polymer flooding is economical in the field under consideration and early injection is profitable.

This paper did not consider lithology and effect of polymer properties.

Chemical EOR techniques are challenge by the high salt concentration in the maturing field oil reservoirs. The high salinity encourages deficiencies in the performance of chemical EOR. Some authors proffer solution to this problem through Optimization of polymer flood performance by preflush injection [9-12]. The performance of polymer flooding, after preflush slug, in high salinity reservoir was investigated by numerical means. The results show that the preflush size results in more oil recovery especially during the early time. Their work concentrated on the reduction of salinity of reservoir fluid that negatively affects the performance of polymer flooding, the effect of polymer rheology was not considered.

2. METHODOLOGY

ECLISPSE 100 was used to evaluate the performance of polymer flood on oil recovery. Appropriate keywords describing the polymer flooding was imputed in the simulator and different sensitivity scenarios were investigated. Two Reservoir models were investigated. 3D flooding of stratified reservoir with communicating layers, 3D flooding of heterogeneous reservoir. All the cells are active with no faults. The result gotten was validated by comparison with literature results.

2.1 Method of Solution

The flow equations are actually partial differential equations (PDEs) since the unknowns, P(x,t) and Sw(x,t) say, depend on both space and time.

Simplified pressure equation is given by:

$$\frac{\partial P}{\partial t} = \frac{k}{\phi \mu c}\frac{\partial^2 P}{\partial x^2} \quad (1)$$

In this study, multiphase relative permeability is modeled with Corey-type functions. Corey-type relative permeability is expressed with relative permeability on residual saturation, exponent defining the curvature of relative permeability, and residual saturation determining normalized saturation. Corey-type relative permeability equation is given as follows:

$$K_{rw} = E_w . S^{*nw} \quad (2)$$

$$K_{ro} = E_o .(1 - S^*)^{no} \quad (3)$$

Where

$$S^* = \frac{S_w - S_{wc}}{1 - S_{wc} - S_{orw}} \quad (4)$$

Capillary pressure is strong function of saturation as presented by Leveret derived capillary pressure scaled by soil permeability and porosity for homogeneous reservoirs. Reflected on previous relations, Brooks and Corey capillary pressure-saturation is calculated as follows:

$$P_c = P_b \sqrt{\phi / k} \quad (5)$$

$$P_b = C_{pc}(1 - S^*)^{E_{pc}} \quad (6)$$

3. RESULTS

3.1 Polymer Concentration Sensitivity

To evaluate and optimize the injection according to concentration, simulation has been run with concentrations at 5 kg/m3, 2.5 kg/m3, 2 kg/m3, 1.5 kg/m3, 1 kg/m3. For all these specific cases injection has been planned for 500 days, and then continuing with only pure water injection. Concentration at 5 kg/m3 gives higher incremental oil production because of higher viscosity.

Study of concentration effect, Figs. 1 and 2, shows the rate of reservoir pressure is opposite dependent with polymer concentration where concentration at 5 kg/m3 leads to lower reservoir pressure.

For the concentration at 5kg/m3 recovery is highest but highest bottom-hole pressure makes it unfavorable case.

3.2 Injection Rate Sensitivity

In this case rate sensitivity includes polymer flooding for rate at 500 Sm3/day, 700 Sm3/day, 800 Sm3/day, 900 Sm3/day, 1000 Sm3/day, 2000 Sm3/day and 4000 Sm3/day. Injection rate for the well was 1000 Sm3/D in the base case model. Fig. 3 illustrate that oil production increases from 500 Sm3/day to a maximum of 1000 Sm3/day. Injection rate of 2000 Sm3/day and 4000 Sm3/day reduces oil recovery. Oil recovery is highest for the tested rate at 1000 Sm3/D.

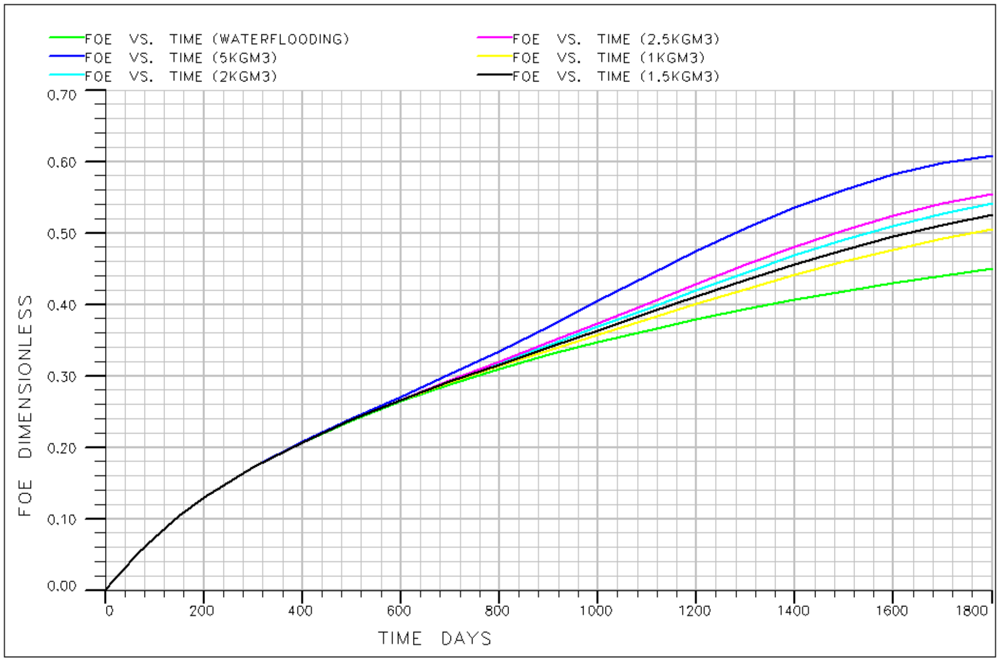

Fig. 1. FOE vs. time for different polymer concentration

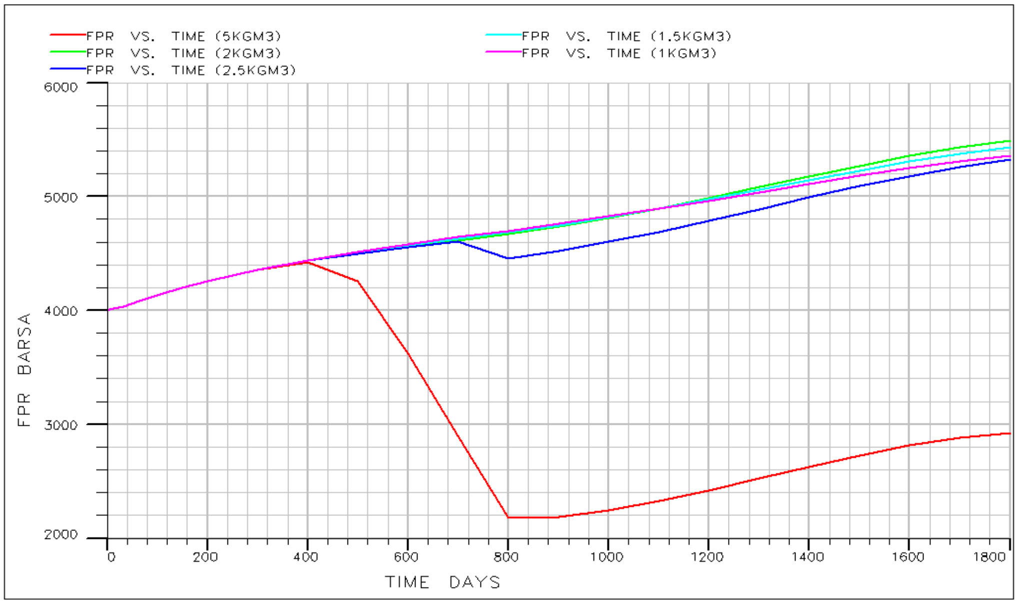

Fig. 2. Field pressure vs. time for different polymer concentration

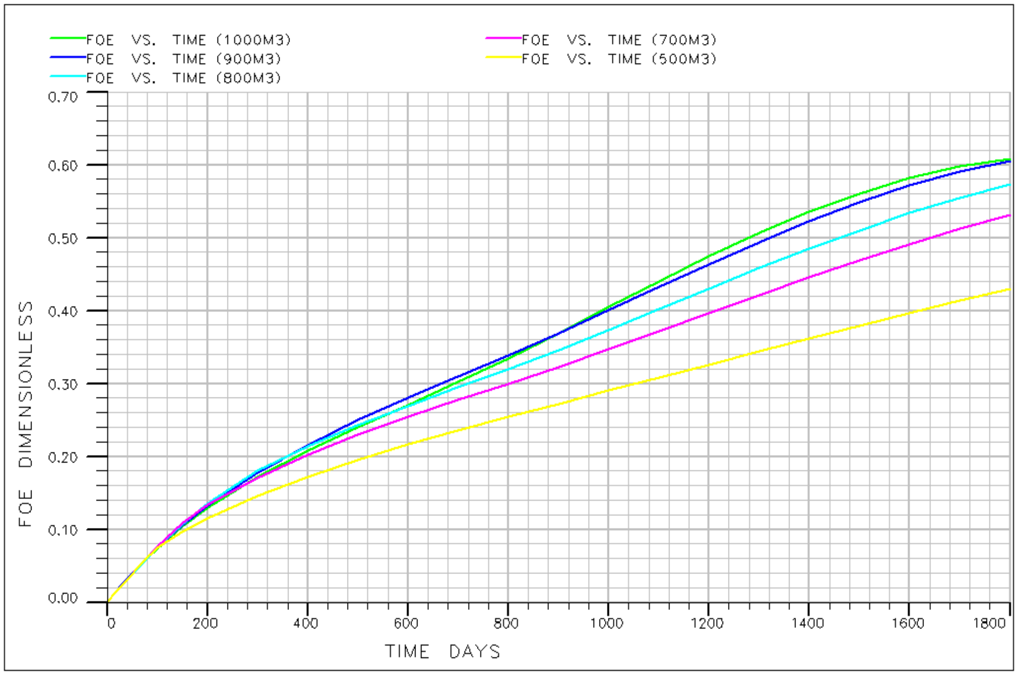

Fig. 3. FOE VS. time for different injection rate

3.3 Heterogenous Reservoir

For the heterogeneous reservoir, the permeability ranged from 200 md to 1000 md and porosity ranged from 0.18 to 0.22. From Fig. 4, Non-Newtonian polymer under recover 3% of oil. It also delays recovery. It shows that more pore volume must be injected to attain full sweep. Fig. 5 shows the oil-phase saturation at the end of the simulation for Non-Newtonian polymer. For the Non-Newtonian case some oil has been trapped and unrecovered due to shear thinning of the polymer.

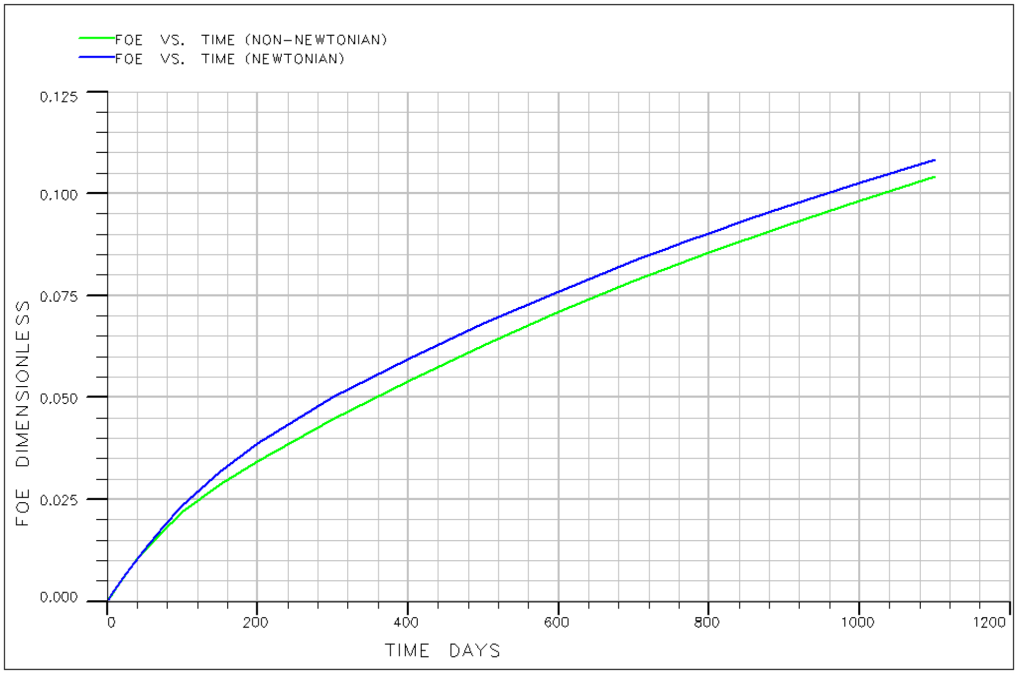

Fig. 4. Field oil efficiency a heterogeneous reservoir

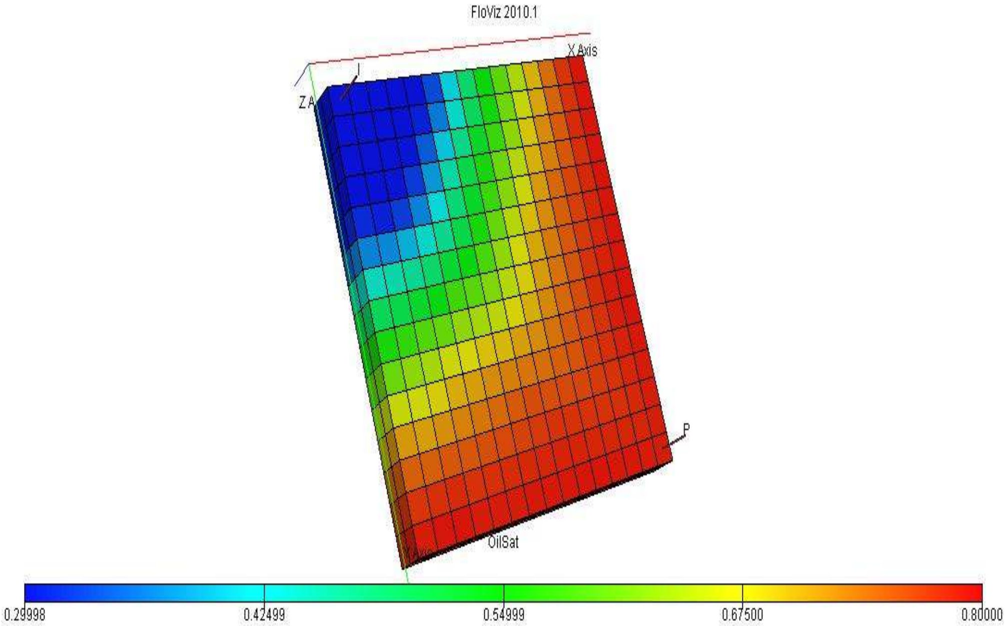

Fig. 5. Oil saturation in heterogeneous reservoir for non-Newtonian polymer

3.4 Stratified Reservoir with Cross Flow

A 3D simulation consisting of 15 by 15 by 5 grids with different permeability contrast was created to study the effect of polymer Rheology in stratified reservoir with cross flow. The modeled system used to study the stratified reservoirs with cross flow is a square reservoir with horizontal area of 450*450 square feet and a vertical thickness of 25ft. vertically, the simulation domain consists of 5 layers of 739 md, 272 md, 100 md, 37 md and 14 md. The Kv/Kh was varied to incorporate contrast between layers.

Figs. 6 and 7 shows that lower oil recovery and rapid increase in FWCT are obtained with smaller Kv/Kh value. When polymer solution is injected into a stratified reservoir with layers of widely differing permeability, the oil recovery is dominated by crossflow due to combined effects of viscosity-derived pressure gradients and gravity.

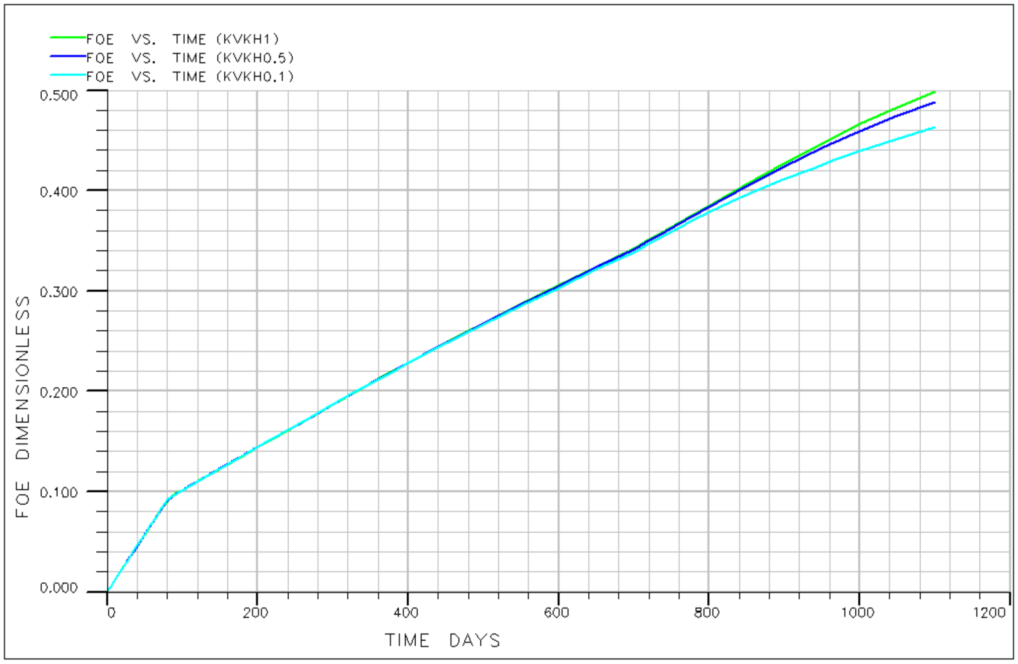

Fig. 6. Field oil efficiency for Newtonian polymer at different Kv/Kh

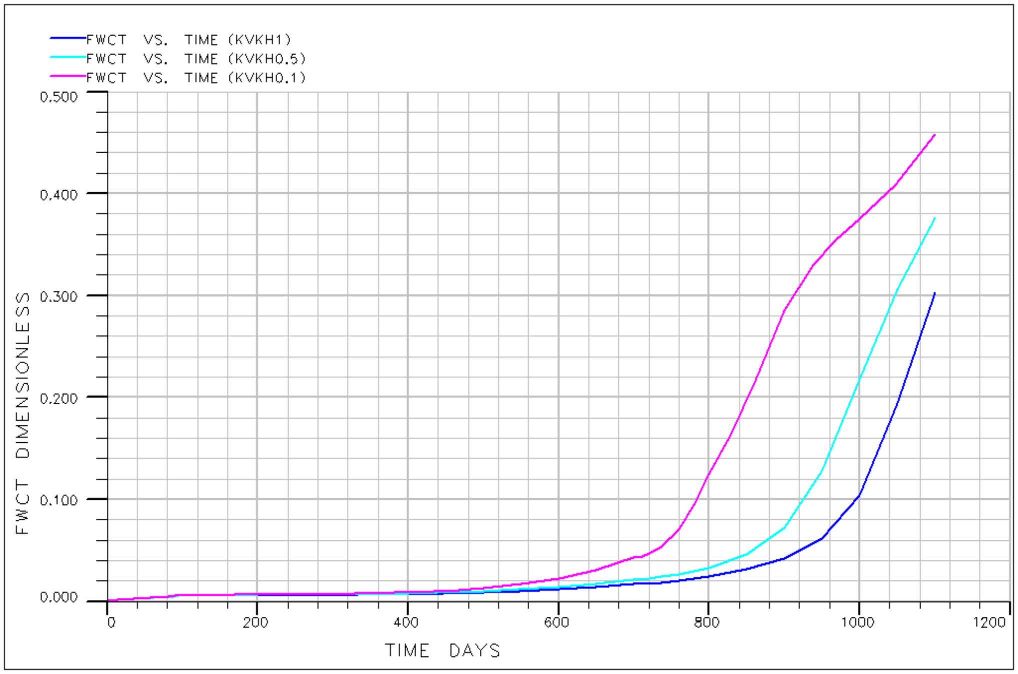

Fig. 7. Field water cut for Newtonian polymer at different Kv/Kh

3.5 Non-Newtonian Effect of Polymer

Polymers used in EOR exhibit shear thinning. Shear thinning (pseudoplasticity) impairs sweep. It is important to take polymer non-Newtonian behavior into account for the successful design and evaluation of polymer flooding projects. This is because pseudoplasticity will diminish sweep which deteriorates the whole economic picture of the polymer flood projects. As shown from Fig. 8 and Fig. 9, pseudoplastic fluid decrease oil recovery by 5% and it delays recovery. Polymer solution unlike water does not show same viscosity at all flow rate. At low flow rate, the viscosity of the solution is approximately constant and depends only on the concentration of the polymer in the solution. With increase in flow rates, the solution viscosity reduces in a reversible manner. At even higher rate, large molecules begin to break up and the viscosity approaches a limiting value. The effect tends to be greatest in the vicinity of the injection wells where fluid velocity is greatest and so is the shear rate.

3.6 Rock Wettability Effect on Polymer Flood Performance

In attempts to study the effectiveness of polymer flood in oil-wet reservoirs, relative permeability and capillary pressure curve were generated from Corey-Type Function.

Figs. 10 and 11 present the cumulative oil recovery and water cut for Newtonian flow of polymer for water-wet and oil-wet reservoirs. As can be seen, the cumulative oil recovery in water-wet is 0.48, which is considerably higher than the oil recovery in oil-wet, 0.32, at the end of production.

From the water cut graph, it can be seen that oil-wet reservoir produces more water than water-wet in excess of 8% at the end of the simulation. For water-wet reservoirs, water was not produce until 600 days of the simulation before which oil was recovered which was not the case for oil-wet.

Figs. 12 and 13 compare the oil saturation distribution at 1100 days for Newtonian polymer for both water-wet and oil-wet Reservoirs. Due to the favorable mobility ratio by polymer flood in water-wet reservoir, relatively higher contrast of oil saturation between swept and unswept regions exits in reservoir. On the other hand, there is a lower contrast between swept and unswept region in the oil-wet reservoir. For oil-wet reservoirs, remained oil saturation is still higher than residual oil saturation for both cases of polymer flood.

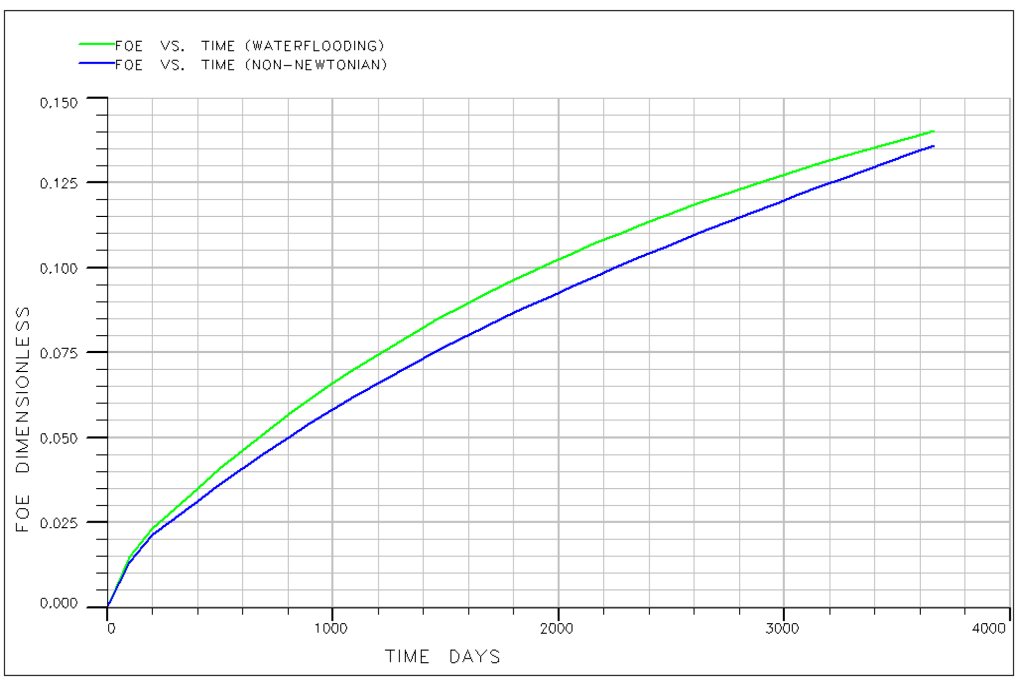

Fig. 8. FOE vs. time for Newtonian and non-Newtonian fluid

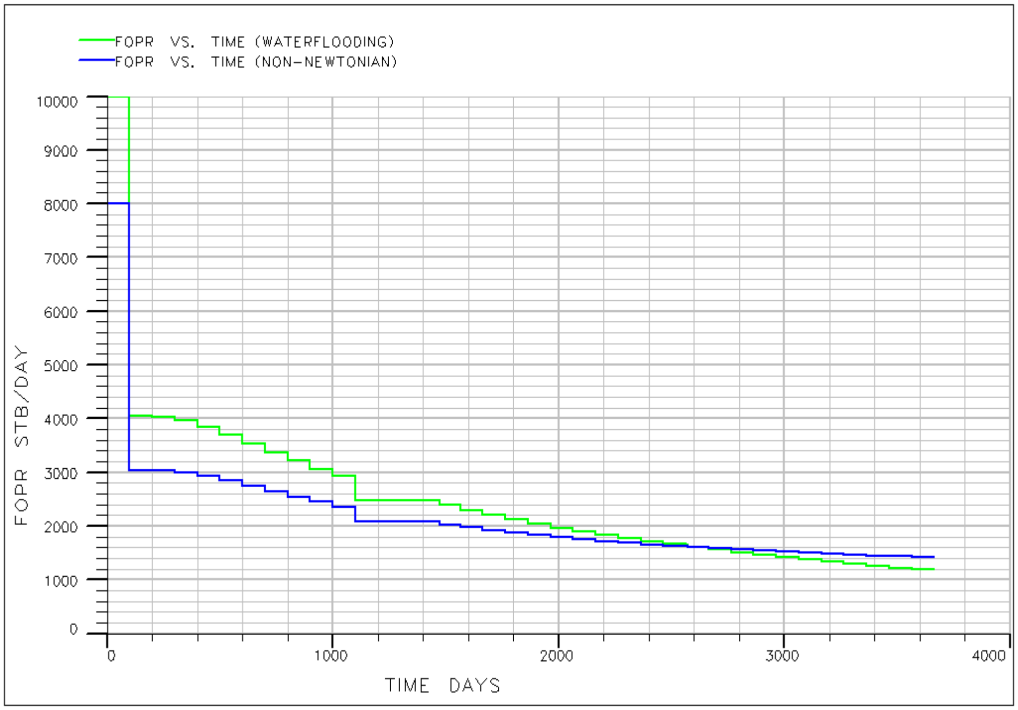

Fig. 9. FOPR VS. time for Newtonian and non-Newtonian fluid

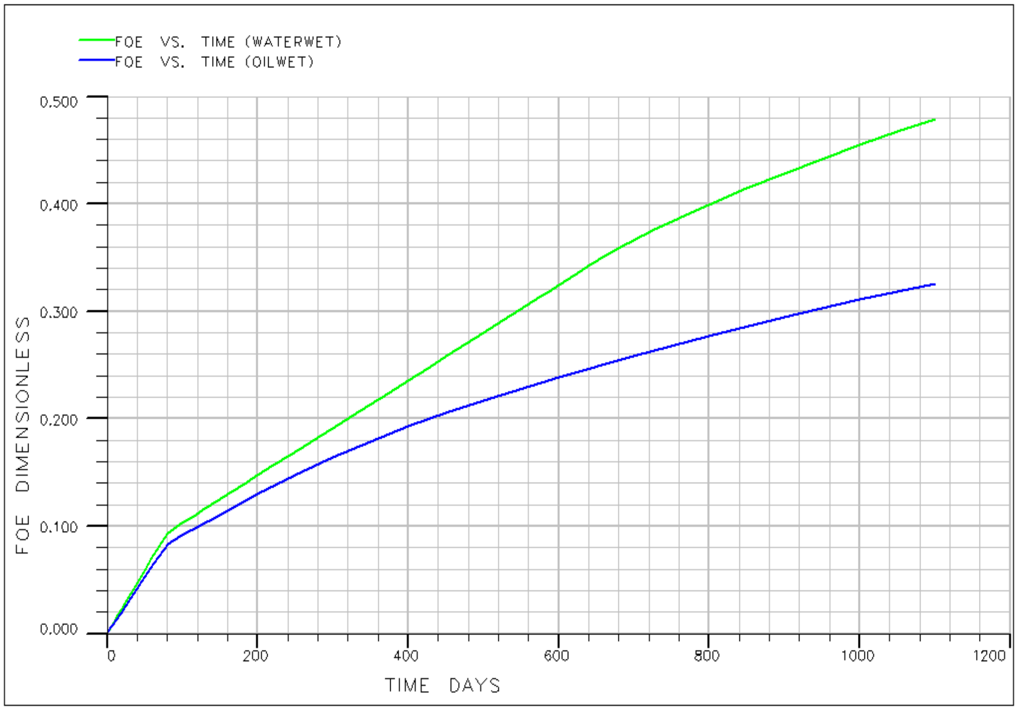

Fig. 10. FOE for Newtonian polymer flooding in oil-wet and water-wet reservoir

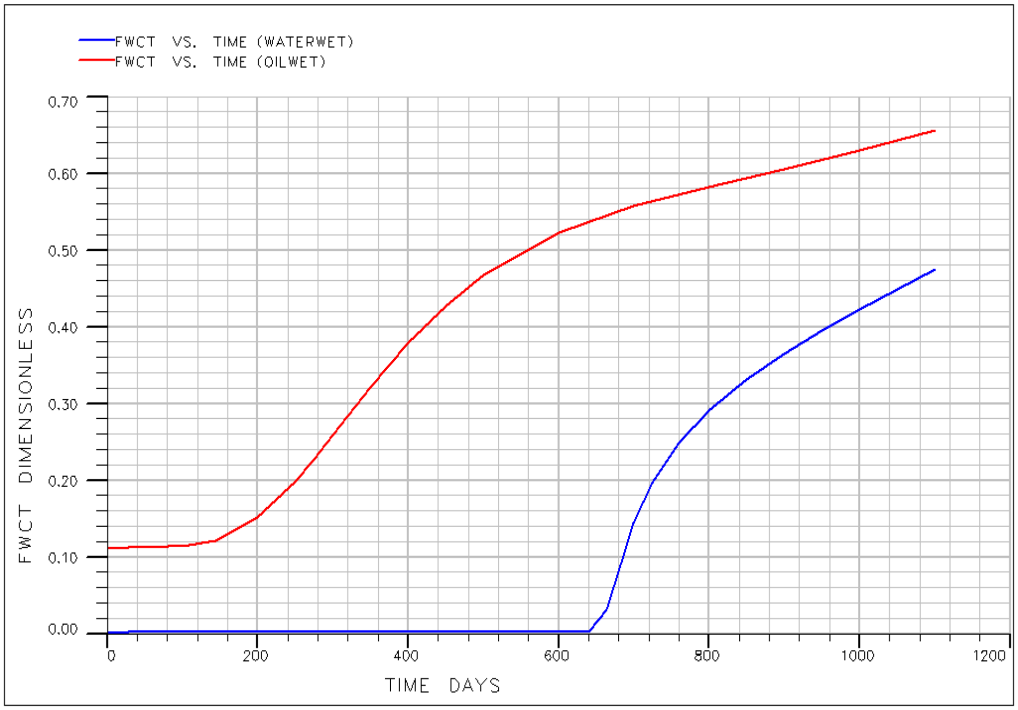

Fig. 11. Field water cut for Newtonian polymer flooding in oil-wet and water-wet reservoir

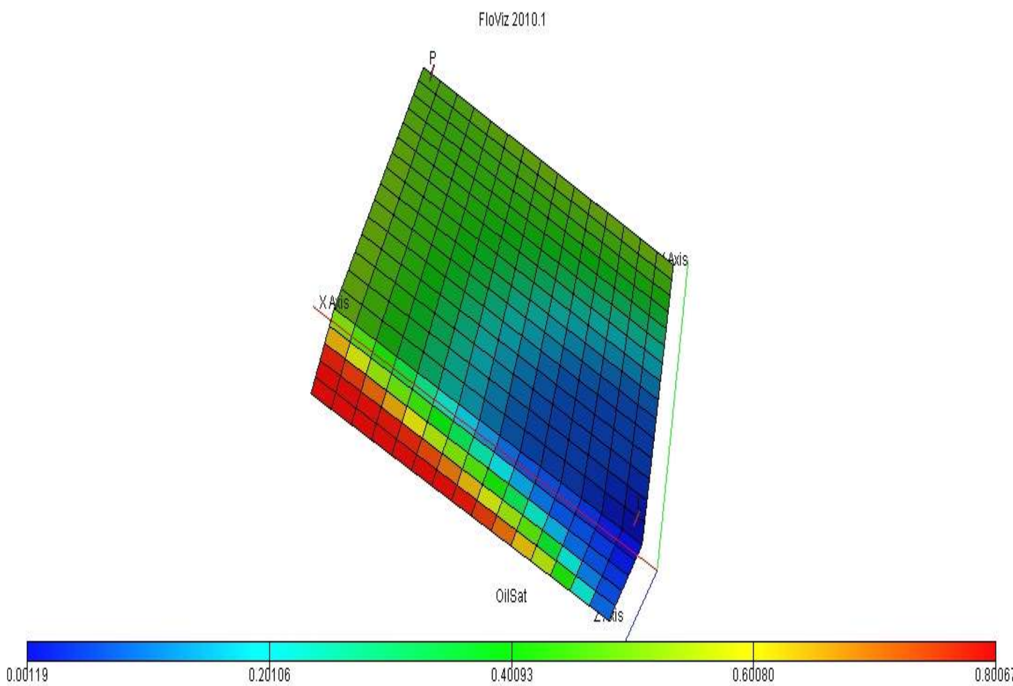

Fig. 12. Oil saturation distributions at 1100 days for Newtonian polymer in oil-wet reservoir

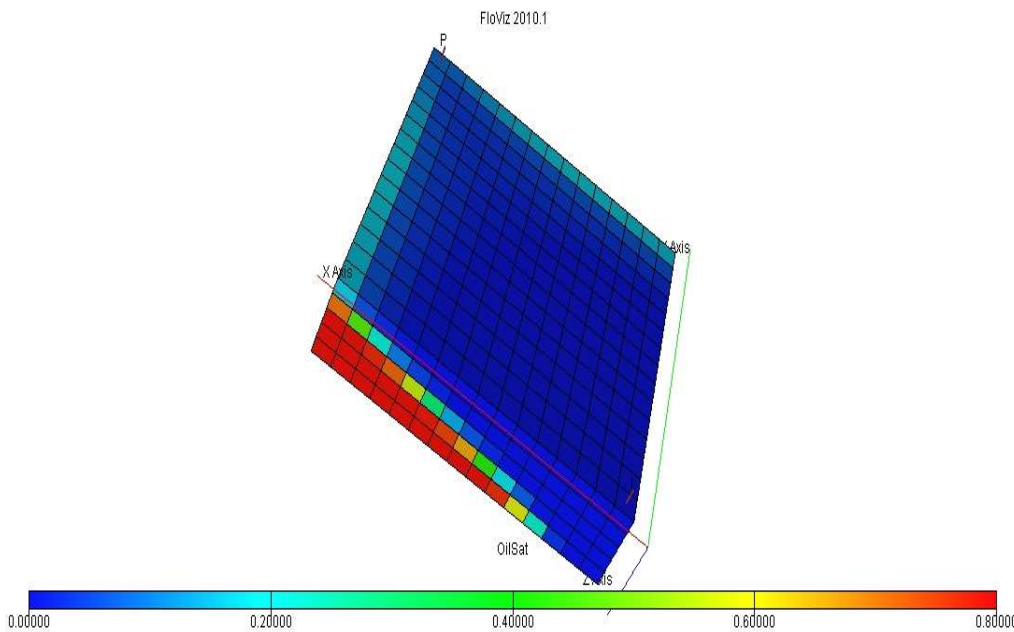

Fig. 13. Oil saturation distributions Newtonian polymer in water-wet reservoir

4. CONCLUSION AND RECOMMENDATION

4.1 Conclusion

Polymer flooding is effective in water-wet rock than oil-wet. This is because an oil-wet formation tends to hold back more oil in its minute pores and produce reservoir water. Increasing polymer concentration will lead to higher sweep but reservoir pressure and economics should be considered.

Non-Newtonian polymer leads to lower oil recovery. This is due to the decrease in viscosity at high shear rate as a result of velocity contrast and instability. Based on the analyses of the model developed, the case at 5 kg/m3 polymer concentration is unfavorable; the case at 2 kg/m3 can be optimal proposal because it gives least incremental pressure at lesser water cut.

4.2 Recommendation

For more accurate results, it is recommended that detailed laboratory work should focus on the reservoir to be polymer flooded. Core samples from the reservoir should be analyzed and different sensitivity studies on polymer flooding should be carried out in order to determine the suitability of the EOR method on it and also the optimum polymer properties to be used.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Barnes HA, Hutton JF, Walters K. An introduction to rheology. Elsevier, Amsterdam; 1989.
2. Seright RS, Fan T, Wavrik K, Balaban RC. New insights into polymer rheology in porous media. SPE J. 2011;16:35–42.
3. Zeito GA. Three dimensional numerical simulation of polymer flooding in homogenous & heterogenous system. Society of Petroleum Engineering of AIME SPE 2186; 1968.
4. Masuda Y, Ke-Chin T, Masashi M. 1D simulation of polymer flooding including the viscoelastic effect of polymer solution. SPE Reservoir Engineering. 1992;7(02): 247-252.
5. AlSofi AM, LaForce TC, Blunt MJ. Sweep impairment due to polymers shear thinning. In Proceedings of the SPE Middle

East Oil and Gas Show and Conference, Bahrain, Bahrain, 15–18 March; Paper Number SPE 120321-MS; 2009.

6. Kun SL. Performance of a polymer flood with shear-thinning fluid in heterogeneous layered systems with crossflow. Energies. 2011;4:1112-1128.
DOI: 10.3390/en4081112
7. Obuekwe M. Polymer flood simulation in a heavy oil field: Offshore Niger-Delta experience. SPE Enhanced Oil Recovery Conference, Kuala Lumpur, Malaysia, Jul. 19-21, SPE 145027; 2011.
8. Niu G. Simulation study for improving seawater polymer flood performance in stratified high temperature reservoirs. Master's thesis, Texas A & M University; 2014.
9. Goudarzi A, Delshad M, Sepehrnoori K. A critical assessment of several reservoir simulators for modeling chemical enhanced oil recovery processes. Paper presented at the the SPE reservoir simulation symposium. Woodlands, Texas, USA, 18-20 February 2013. SPE 163578; 2013.
DOI: 10.2118/163578-MS.
10. Abedi M, Algharaib M. Optimization of polymer flood performance by preflush injection - Numerical investigation. Presented at the 2012 SPE Kuwait International Petroleum Conference and Exhibition. SPE-163280 MS; 2012.
11. Pope GA, Wang B, Tsaur KA. Sensitivity study of micellar/polymer flooding. Society of Petroleum Engineers Journal. 1979; 19(6):357-368.
12. Al-Sofi AM, Blunt MJ. The design and optimization of polymer flooding under uncertainty. Presented at the SPE Enhanced Oil Recovery Conference. SPE-145110-MS; 2011.

Peer-review history:
The peer review history for this paper can be accessed here:
http://sciencedomain.org/review-history/18753