LI LIU
YANMING PI
YING HE
ZHENXING ZHANG
ZETIAN MENG
and
ZHIPENG DAI

Chemical flooding experiment after the polymer flooding in offshore oilfield

The offshore oilfield are mostly viscous oil reservoirs. Tertiary oil recovery technology is mainly composed of the injection of the polymer solution. It is a problem to be solved for researchers to improve the oil recovery further. In the current study, we designed the heterogenetic physical model for the typical offshore area. The comparative study was carried out by experiments. In the meantime, we discussed the plan optimization of the chemical flooding after the polymer flooding in an offshore oilfield and evaluated the production level under different injection mode. The experimental results proved that the alkaline-polymer flooding is the preferred mode of chemical flooding after the polymer flooding in offshore typical area.

Key Words: Viscous oil, polymer flooding, chemical flooding, alkaline-polymer flooding.

1. Introduction

In recent years, the exploitation of offshore oilfields developed rapidly and was respected by people gradually. There have also been some problems that many main offshore oilfields enter high water-cut stage. However, it has become an important technical problem to be resolved that improving production in offshore oilfield production within the validity period of the platform due to the platform life span, complicated offshore conditions, geological conditions and other factors [1-4].

The Bohai oilfield is the viscous oil reservoir with wide well spacing, high porosity and high permeability. Due to the complexity of life span, space and offshore platform condition restriction, it is unable to mine from onshore oilfields in the same way. As much as possible, it is necessary to improve the speed and recovery of the reservoir. Many indoor experiments and ashore field practices demonstrate that alkaline-polymer flooding is an effective means of further improve oil recovery after the polymer flooding. It is more suitable for the characteristics of the offshore oilfield. So it has become one of key research directions to improve oil recovery of the offshore oilfield [5-8]. The 0.13 PV polymer solution had been injected since the end of 2007 in Bohai oilfields X well X9. Then it changed to inject alkaline-polymer solution in the early 2011. The field test result showed that alkaline-polymer flooding effectively suppressed adverse trends of the oilfield water cut rising and oil production declining. This led to a fall of 11% water cut and daily oil production increasing by 1.16 times. Alkaline-polymer flooding has now accumulated an increase of 16159.7m^{3}and brought huge economic benefit for oilfield[9-12].

We designed the heterogenetic physical model for the typical offshore area[10-11]. Additionally, the comparative study was carried out by experiments. We discussed the plan optimization of the chemical flooding, the opportune moment of conversion and the optimization of the injection mode. Then we evaluated the production level of different injection modes. This paper provides the basis for the further improvement of recovery measures for offshore oilfields [13-14].

2. Experiment part

2.1. Experimental conditions

Experimental temperature: 65ºC.

The physical model: the core with unequal thickness of heterogeneity of three layers in the layer. Core specification: 300mm×45mm×110mm. Permeability of three layers: 500×10^{-3} μm^2, 2200×10^{-3} μm^2, 4800×10^{-3} μm^2. Mean permeability: 2500×10^{-3} μm^2. The corresponding thickness: 30 mm, 30 mm, 50 mm.

Standard cylindrical core with demarcated porosity, permeability and saturation: 25 mm in diameter and 100 mm in length.

Saturated water and displacement water: the oil simulates the formation of water with the salinity of 9947.74 mg/L.

Experimental oil: simulated oil with viscosity 70 mPa·s at 65ºC.

Messrs. Li Liu*, Ying He and Zhipeng Dai, Northeast Petroleum University, Daqing 163 318, Yanming Pi, EnerTech-Drilling & Production Co., CNOOC, Tanggu 300 457, Tianjin, Zhenxing Zhang, CNOOC EnerTech-Safety & Environmental Protection Co., Toutai Company of Daqing Oil field.166 512 and Zetian Meng, No.6 Oil Production Company of Daqing Oilfield Co., Ltd. 163 114, China. E-mail: liuliduoduo@163.com

The polymer used in the step of polymer flooding: hydrophobic associating polymer AP-P4 (2000 mg/L).

Binary system: the polymer ap-p5 with molecular weight 1100×10^4 (1750 mg/L) and the surface acting agent BH-M2 (0.2%) provided by CNOOC.

Injection rate: 1mL/min.

2.2. Experimental apparatuses

Incubator, agitator, beaker and Brookfield viscometer.

2.3. Experimental schemes

Scheme 1: Water drives until the water content rises to 95%.

Scheme 2: Water drives until the water content rises to 70% + 0.3PV polymer flooding (2000 mg/L) + follow-up water drive until the water content rise to 95%.

Scheme 3: Water drives until the water content rises to 70% + 0.3 PV polymer flooding (2000 mg/L) + 0.3 PV polymer flooding (2000 mg/L) + follow-up water drive until the water content rise to 95%.

Scheme 4: Water drives until the water content rises to 70% + 0.3 PV polymer flooding (2000 mg/L) + 0.24 PV high-concentration polymer flooding (2000 mg/L) + follow-up water drive until the water content rise to 95%.

Scheme 5: Water drives until the water content rises to 70% + 0.3PV polymer flooding (2000 mg/L) + 0.3 PV alkaline-polymer flooding (polymer 1750 mg/L and surface acting agent 0.2%) + follow-up water drive until the water content rise to 95%.

The price of each displacement agent is as follows:

The polymer AP-P4 used for polymer flooding: RMB 22000/t.

The price of polymer AP-P5 used for the alkaline-polymer flooding: RMB 25000/t.

The price of surface acting agent BH-M2: RMB 33000/t.

Through the calculation of the price, you can see that, the price of polymer flooding of is concentration and concentrated polymer flooding after the polymer flooding in scheme 3 and scheme 4 is the same.Meanwhile, the price of the alkaline-polymer flooding in scheme 5 is 2.49 times that in scheme 3 and scheme 4.

The viscosity of displacing agent and core parameters in the scheme are shown in Table 1.

Table1: Viscosity table of displacement agent

System	AP-P4 (2000 mg/L)	Concentrated AP-P4 (2500 mg/L)	Binary system (polymer 1750 mg/L, SAA 0.2%)
Viscosity (mPa·s)	42	65	34.6

There are parameters of the calibration core with the same formula in Table 2. This cylindrical core corresponds to the different layers of the three-layer heterogeneous physical model with unequal thickness used in the typical offshore oilfield.

Table 2: Calibration parameter table of core

Core permeability ($\times10^{-3}\mu m^2$)	Porosity (%)	Initial oil saturation (%)
500	25.2	68.1
2200	30.1	72.4
4800	34.5	78.5

3. Experimental results and discussion

The selection of injection mode after polymer flooding:

The overall results of different displacement schemes are shown in Table 3.

The total recovery rate is 31.0% when the water content is 95% in scheme 1. The total recovery rate is 42.52% after

Table 3: Experiment results in different scheme

Scheme	The specific scheme	Degree of reserve recovery (%)			Overall recovery efficiency (%)
		Water drive	Polymer flooding	Alkaline polymer flooding	
1	Water drives until the water content rises to 95%	31.0	-	-	31.0
2	Water drives until the water content rises to 70% + 0.3 PV polymer flooding + follow-up water drive	16.05	26.47	-	42.52
3	Water drives until the water content rises to 70% + 0.3 PV polymer flooding + 0.3 PV polymer flooding + follow-up water drive	15.03	29.90	-	44.94
4	Water drives until the water content rises to 70% + 0.3 PV polymer flooding + 0.24 PV high-concentration polymer flooding + follow-up water drive	15.17	31.05	-	46.22
5	Water drives until the water content rises to 70% + 0.3PV polymer flooding + 0.3PV alkaline-polymer flooding + follow-up water drive	15.59	18.10	31.48	66.29

injection of 0.3 PV polymer solution. It noted that the 0.3 PV polymer can produce 11.52% of the reserves.The total recovery rate of injection of 0.6 PV polymer in scheme 3 is 44.94% in scheme 3, which is only 2.42 per cent more than scheme 2. It shows that the polymer injection 0.3 PV is close to the limit of the polymer flooding production's effect. The overall effect of extending sweep volume and improving displacement efficiency is weakened after the polymer injection 0.3 PV. Irreducible oil cannot be greatly produced out of the ground if only the same concentration of the polymer solution were continued to inject. Therefore, the timing of the conversion of the polymer flooding is determined by injection 0.3 PV, and the subsequent chemical flooding should be considered for the end of the injection.

TABLE 4: RATIO OF PRODUCED OIL TO THE TOTAL RESERVES IN EACH LAYER OF THE MODEL OF THE TERTIARY RECOVERY AND TERTIARY INJECTION WITH UNAQUAL THICKNESS IN DIFFERENT STAGES

The stage of displacement	The percentage of the total reserves of oil produced (%)		
	Low permeability layer	Mid -permeability layer	High permeability layer
Water flooding stage	0.72	4.78	11.21
Polymer flooding stage	1.30	5.21	11.60
Alkaline-polymer flooding stage (including subsequent water flooding)	3.17	10.30	18.00
The percentage of the total reserves of intrastratal production	5.19	20.29	40.8
Overall recovery efficiency of the model		66.43	

In scheme 4, we used the high concentration polymer flooding after polymer injection 0.3 PV. The high concentration polymer 0.24 PV was injected after the concentration increased by 2000mg/L to 2500mg/L in the ordinary polymer flooding stage. The recovery rate was only 3.7 per cent higher than that in scheme 2 with equivalent polymer in scheme 3. The result showed that the effect of the method of the high concentration polymer flooding was very small, but it was better than the condition of the same concentration and the degree of reserve recovery increased by 1.28%.

The binary solution 0.3 PV was directly injected after the polymer flooding and then carry on the following water flooding in scheme 5. The experiment showed that a binary system can greatly enhance oil recovery after the polymer flooding. The injection of binary solution used the irreducible oil that cannot be used only by the polymer viscoelasticity and displacement efficiency. The ultra-low interfacial tension has played a key role. The irreducible oil rejoins the flow because ultra-low interfacial tension causes the emulsification, decomposition, and the formation of the emulsion. Low interfacial tension also reduces the capillary force of the irreducible oil, making the extraction of the irreducible oil less difficult. The polymer solution in the binary system also plays a role in reducing the mobility ratio, allowing the irreducible oil to be carried out. It can be confirmed from the experimental data that it is an effective method of production that uses the alkaline-polymer flooding after the polymer flooding, especially for the efficient development of offshore oilfields. Although the input of scheme 5 is 2.49 times the scheme 3 and 4,the degree of reserve recovery is 9.82 times the polymer flooding of isoconcentration, and 6.42 times the concentrated polymer flooding. It is visible by both enhancing oil recovery and the contrast of economic input and output, the alkaline-polymer flooding is the preferred method for the chemical flooding of the typical block in the offshore oilfield.

According to Table 4:

The dynamic recovery curve and analysis of each scheme:

Characteristics and analysis of dynamic recovery in different modes after the polymer flooding:

The characteristics and analysis of dynamic recovery of the concentrated polymer flooding after the polymer flooding is indicated. The slug of concentrated polymer flooding (2500 mg/L) is 0.24 PV. The experimental recovery curve is as follows:

Fig.1 shows that the pressure keeps rising, while the water content ratio keeps rising on the stage of high concentration polymer flooding. The overall recovery rate is slightly up, about 2%. It is indicated that the concentrated

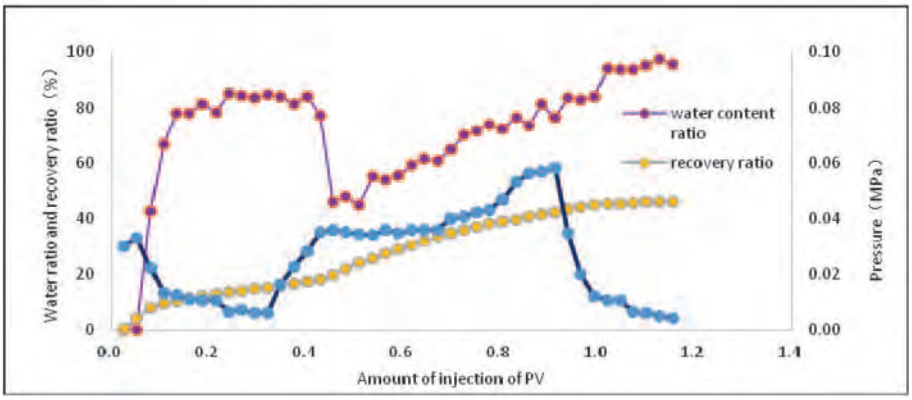

Fig.1 The relation of amount of injection of PV with composite water cut, recovery ratio and pressure

polymer flooding cannot effectively use the irreducible oil after the polymer flooding. This method that concentrated polymer flooding after polymer flooding cannot solve the problem of effective use of the irreducible oil, and other chemical drive methods should be considered.

Fig.2 shows that after the polymer flooding, the concentrated polymer flood, the hypertonic diffluent ratio keeps rising while the mid-penetrative diffluent ratio keeps gradually declining, without the effect of profile modification. Although the pressure is increasing, it is only the movement of the concentrated polymer in the reservoir, which does not greatly increase the displacement efficiency.

The characteristics and analysis of dynamic recovery of the alkaline-polymer flooding after the polymer flooding is indicated. The experimental recovery curve is shown in Fig.3.

As shown in Fig.3, at the stage of the polymer flooding, the composite water cut begins to drop to the lowest value, and the pressure rises to the highest level of the polymer flooding stage. In the stage of the alkaline-polymer flooding, the composite water cut decreases firstly and then increases and the pressure kept going up. After the end of the alkaline-polymer flooding, the composite water cut decreases to 15.1% and then increases, the pressure goes down to 0.016MPa, which is 25% higher than the water drive final pressure of 0.012 MPa. It proves that the chemical agent was stranded in the core.

As shown in Table 5, in the model of the tertiary recovery and tertiary injection with unequal thickness, most of crude oil produced from the high permeability layer on the stage of the water flooding, polymer flooding and alkaline-polymer flooding. It is associated with the thickness ratio of the high permeability layer that the mid-permeability layer and low permeability layer are less used during the injection phase. The high permeability layer accounts for 54.5% of the total thickness, and the pore volume accounts for 0.51 PV of the total volume of the model. While the mid permeability pore is 0.26 PV, and the low permeability pore is 0.23 PV. Combining with the above situation of the diffluent ratio on the stage of the polymer injection, after the start of the polymer injection, the polymer solution mostly flows into high permeability layers. About 10% of the polymer solution flows into the permeability layer, around 3% of the polymer solution flows in the low permeability layer. As the injection goes, the injection pressure gets bigger. The high permeability diffluent ratio and the injection rate of the polymer solution decreases. The diffluent rate and injection rate increases in the mid-permeability layer while it is unchanged in the low permeability layer. At the time of the injection of 0.15 PV, the pressure hits the maximum and begins to decrease, indicating that the polymer solution which has been injected into high permeability is breaking through the high permeability wells. Since then, the composite water cut begins to rise, fluid ratio of high permeability is gradually rising, and the ratios of mid and low permeability are decreasing on the stage of polymer injection. At the time of the injection of 0.3 PV, the fluid ratio of high permeability is 87.2%, and the rate is 10.15% in mid-permeability layer, while the composite

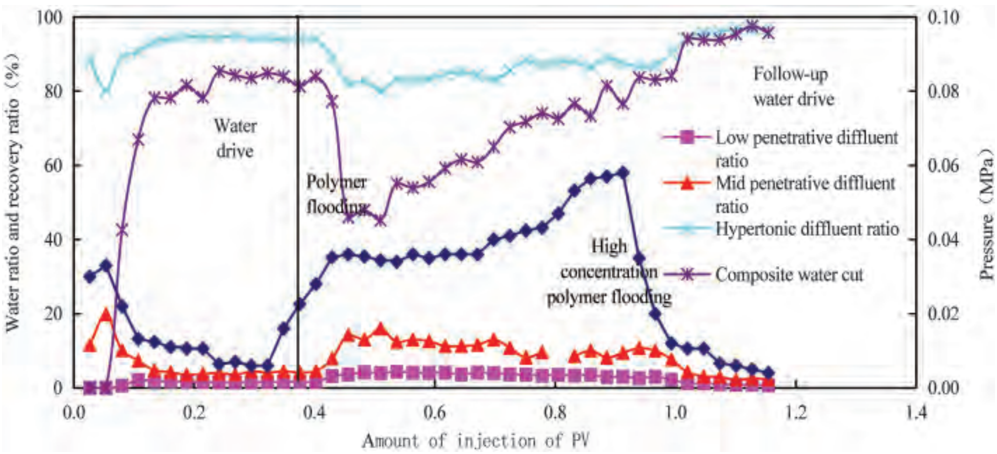

Fig.2 The relation of amount of injection of PV with diffluent ratio composite water cut, recovery ratio and pressure

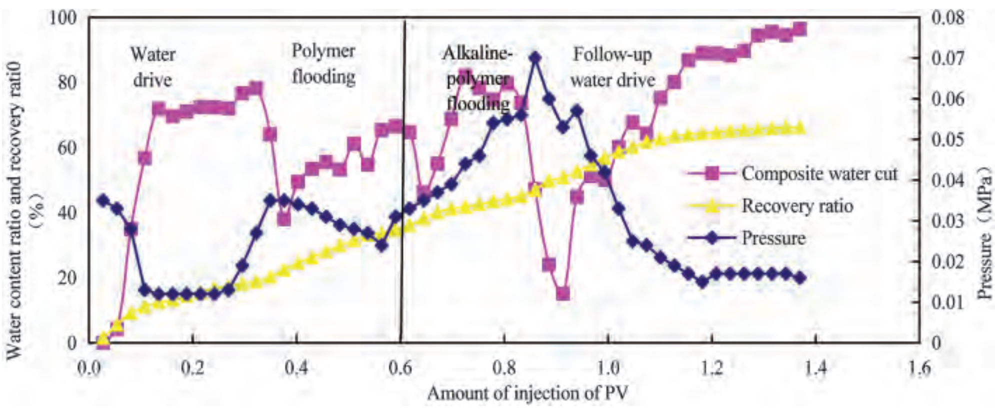

Fig.3 The relation of amount of injection of PV with diffluent ratio composite water cut, recovery ratio and pressure in scheme 5

TABLE 5: INTRASTARTAL RECOVERY RATIO ON EACH STAGES OF DISPLACEMENT

The stage of displacement	Degree of reserve recovery (%)		
	Low permeability layer	Mid -permeability layer	High permeability layer
Water flooding stage	3.53	18.43	20.88
Polymer flooding stage	6.37	20.10	21.61
Alkaline-polymer flooding stage (including subsequent water flooding)	15.53	39.74	33.53
The percentage of the total reserves of intrastratal production	25.43	78.23	76.01
Overall recovery efficiency of the model		66.43	

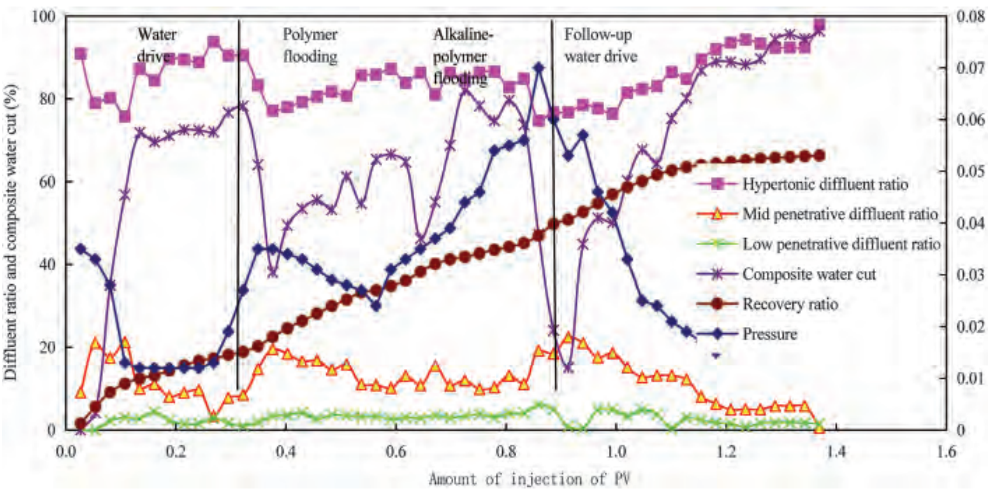

Fig.4 The relation of amount of injection of PV with diffluent ratio composite water cut, recovery ratio and pressure

water cut of recovery wells raises to 66.7%. The degree of reserve recovery is 18.1% in the whole injection stage, while still some of the polymer solution is not found in the model.

The composite water cut of the model is reduced by the time of the injection of 0.05 PV on the stage of the alkaline-polymer flooding. The injection recovery pressure difference continues to rise after the injection of binary compound solution. On the stage of injecting binary solution to 0.24 PV, there is no significant change in the fluid ratio in high and mid permeability layer. It is dependent on the viscoelasticity of the undeveloped polymer solution and the synergies of the binary solution in the model that has produced 22.65% of the total reserves. The pressure difference rapidly increases and the ratio of mid and low permeability is increased significantly between the injection binary system of 0.24 PV -0.27 PV. The low permeability layer is used, and the pressure difference gradually decreases between the injection binary system of 0.27 PV to 0.3 PV.,which should be the alkaline-polymer flooding used to produce from the high permeability layer. At this time, the composite water cut has fallen to 15.1%, and the production of oil on the injection binary solution is 16.03% of the total amount of oil, and then some of the binary solution has remained in the model. Overall, the fluid ratio does not change significantly for a long time in each layer, while the water content had declined sharply in binary solution injection stage. It is proved that the displacement efficiency of a binary solution is so high that can help to emulsify and produce crude oil extensively. Thus, the purpose of oil controlling water is realized. Although the total oil production in binary compound flooding stage is 16.03% less than the 18.1% of the stage of the polymer flooding stage, the difficulty of drilling in binary solution injection stage is greatly increased. It is shown that the alkaline-polymer flooding is the effective displacement mode of the typical offshore block because the solution of a binary solution is the oil that cannot be produced with the polymer's displacement efficiency.

In the subsequent water flooding stage, the fluid ratio and pressure in high and mid permeability layers gradually decrease because there is still some binary solution working in the model, while composite water cut increases gradually. The final recovery efficiency is 66.29%, and 15.44% of oil is produced from the subsequent water flooding stage.

According to the data of the porosity and initial oil saturation corresponding to the permeability of core sample (Table 2) and the displacement experiment of the tertiary recovery and tertiary injection in different stages, which is where the oil is produced from which layer, this approach does not consider the impact of the channeling. The recovery data of the three layers of non-homogeneous cores calculates by this method are shown in Table 5.

According to the above table, the intrastratal recovery in the high permeability layer is 76.01%, which is 78.23% in the mid permeability layer and 25.43% in the low permeability layer. The actual endpiece data shows that the recovery in the mid permeability layer is higher than that in the high permeability layer, because this is the case where the channeling is not considered. In the actual stage of the intrastratal heterogeneous displacement process, the high permeability layer is blocked in the stage of the chemical flooding experiment after the polymer flooding and the oil flows to the mid-permeability layer. And the oil in the low permeability layer could also flow into to the mid-permeability layer and be produced.

As the experimental model has uniform thickness, the high permeability layer accounts for 45.5% of the total thickness, and the resource in the high permeability layer is large, so the contribution of the high permeability layer is the largest on the whole stage of production. The high permeability and mid-permeability layer of the polymer flooding stage were effectively used. In the alkaline-polymer flooding stage, the high permeability layer and the mid-permeability layer were greatly used, and the use level of the low permeability layer was also very high. As you can see, the alkaline-polymer flooding effectively used the irreducible oil of the polymer flooding.

5. Conclusions

In this paper, the chemical flooding optimization method was carried out after the polymer flooding by using the three-layer non-homogeneous thickness model, which was developed for the offshore oilfield block. Experimental results show that the recovery ratio of the isoconcentration polymer flooding after polymer flooding can be increased of 2.42%. High concentration polymer flooding can enhance oil recovery of 3.7%. While the injection 0.3 PV of binary system can improve the recovery rate of 23.77%. Combined with the economic comparison, the alkaline-polymer flooding is the preferred mode of chemical flooding in the typical offshore block.

Acknowledgements

The research work was both supported by the Natural Science Foundation of Heilongjiang Province, China (The research of the oil-displacement mechanisem of fuctional polymer (polymer surfactant) in reservoir conditions) (E2016016) and the Innovation Fund Petro-China "The research of the influence of the polymer fuctional groups to the oil-displacement mechanisem and permeability rules" (2015D-5006-0214).

References

1. Carpenter, C. (2015):"Fracture Optimization in the Valdemar Field Offshore Denmark," *Journal of Petroleum Technology*, 67(9):130-133.
2. Maizeret, P. D., Rocha, P. S. and Danemberg, Marsili M. et al. (2015)::"Multiphase Flowmeter for Testing Heavy-Oil Wells in Offshore Brazil," *SPE Production & Operations*, 30(3): 1-10.
3. Sheng, James J., Leonhardt, Bernd and Azri, Nasser (2015): "Status of polymer flooding technology," *Journal of Canadian Petroleum Technology*, 54 (2): 116-126.
4. Oliveira, L. F. L. D., Schiozer, D. J. and Delshad, M. (2016): "Impacts of Physical Phenomena on Polymer Flooding Projects," *Journal of Petroleum Science & Engineering*, 147:346-355.
5. Kim, T. W., Vittoratos, E. and Kovscek, A. R. (2016): "An Experimental Investigation of Viscous-Oil Recovery Efficiency as a Function of Voidage-Replacement Ratio," *Society of Petroleum Engineers Journal*, 21(4): 1-18.
6. Clemens, T., Tsikouris, K. and Buchgraber, M. et al. (2013): "Pore-Scale Evaluation of Polymers Displacing Viscous Oil-Computational-Fluid-Dynamics Simulation of Micromodel Experiments," *SPE Reservoir Evaluation & Engineering Journal*, 2013(2):144-154.
7. Clarke, A., Howe, A. M. and Mitchell, J. et al. (2015): "How Viscoelastic-Polymer Flooding Enhances Displacement Efficiency," *Society of Petroleum Engineers Journal*, 21(3), 1-13.
8. Wilson, A. (2015): "New Technologies Maximize Production in Viscous-Oil North Slope Field," *Journal of Petroleum Technology*, 67(10):72-73.
9. Khorsandi, S., Qiao, C. and Johns, R. T. (2016): "Simulation of Surfactant/Polymer Floods with a Predictive and Robust Microemulsion Flash Calculation," *SPE Journal*, 22(2): 1-10.
10. Fortenberry, R. P., Kim, D. H. and Nizamidin, N. et al. (2013): "Use of Co-Solvents to Improve Alkaline-Polymer Flooding," *SPE Journal*, 20(2).
11. Wang, Z., Ye, Y. and Ma, D. et al. (2013): "A New Method of Numerical Simulation for Viscoelastic Polymer Flooding," Proc. of SPE Reservoir Characterization and Simulation Conference and Exhibition.
12. Mogollón, J. L., Tillero, E. and Gutiérrez, I. et al. (2016): "Numerical Maximization of the Secondary Polymer Flooding Value in a Mature, Offshore, Heavy Oil Reservoir," Proc. of Offshore Technology Conference.
13. Olajire, A. A. (2014): "Review of ASP EOR (alkaline surfactant polymer enhanced oil recovery) technology in the petroleum industry: Prospects and challenges," *Energy*, 77(C): 963-982.
14. Sharma, A., Azizi, A. and Clayton, B. et al. (2012): "The Design and Execution of an Alkaline-Surfactant-Polymer Pilot Test," *Society of Petroleum Engineers Journal Reservoir Evaluation & Engineering*, 16(4):423-431.