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Study of Profile Reversion in Early Stage Polymer Injection for Heavy Oil Recovery in China Bohai Bay

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ABSTRACT:

Polymer flooding of heavy oil proves successful in China offshore heterogeneous reservoir, how to improve polymer flooding efficiency is a critical challenge in economically field application of heavy oil polymer flooding. Field results show that single slug polymer injection can lead to profile reversion, excessive polymer flow most to high permeability reservoir, results in poor recovery efficiency in the low permeability reservoir. Parallel core physical simulation was used to study effect of permeability ratio、polymer concentration、water cut of polymer injection on profile reversion in heavy oil polymer flooding.“Profile reversion” in Bohai Bay heavy oil reservoir have much difference than Daqing light oil reservoir. First, effect of permeability ratio/injection timing/polymer concentration on “profile reversion” was studied by laboratory core flooding tests and simulation. It was found that injection of polymers at low water cut(<80%)、small permeability ratio(<3) and suitable polymer concentration(balance of polymer injectivity and profile modification) have vital importance on heavy oil recovery efficiency; different alternative injection methods and cycles was compared, results show that alternative injection of weak gel and polymer solution have less than 6.6% original oil in place(OOIP)recovery efficiency than single slug polymer injection, which means weak gel injection have detrimental effect on reservoir permeability; while alternative injection of 2250mg/L and 1750mg/L polymer in two cycle has more than 4.3%OOIP recovery efficiency than single slug polymer injection at the same dosage, increase alternative injection cycles have detrimental effect on recovery efficiency due to small slug size for mobility control. Another important finding show that "profile reversion " mechanism can be successfully simulated using CMG stars reservoir simulation software by assuming different polymer retention, inaccessible pore volume and residual resistant factor for different permeability layers. Finally, a single well block reservoir simulation show that alternative injection of polymer slug can decrease negative effect of profile reversion and improve heavy oil recovery.

KeyWords: polymer flooding of heavy oil ,profile reversion,alternative injection

■INTRODUCTION

Polymer flooding proved successful worldwide *[1]*. Injection of polymer in heavy and extra-heavy oil reservoirs has gained increasing attention *[2-4]* and promising results during the last few years*[5-7]*. Results from Daqing oilfield (China) shown polymer injection have caused adverse injection profile which called "profile reversion" after prolonged polymer injection *[8,9]*. This paper aims to understand the controlling factors of polymer flooding profile reversion and improve polymer flooding efficiency for heavy oil reservoir in China Bohai Bay.

Polymer injection "profile reversion" in Daqing oilfield was shown in Figure 1 *[9]*, it shows that polymer injection did not modify water injection profile, but make it even worse .Well test of polymer flooding profile show the relative amount of polymer intake in heterogeneous reservoir layers is fluctuating. At first, the polymer intake of low permeability layer increased due to profile modification of polymer solutions. After some time, it began to decline.

Polymer intake in low permeability layer first increase than decrease was called "profile reversion". The turning point of diversion ratio curve was called "profile reversion point", pore volume injected between two adjacent maximum(or minimum) diversion ratio was called "profile reversion cycle". In Daqing oilfield case, under certain circumstances, there will be 2 or more times "profile reversion cycle". In the process of polymer flooding, profile reversion leads to less polymer intake of the low permeability reservoir, thus low enhanced oil recovery efficiency.

Most of the injection wells occurred " profile reversion" in Daqing after several years of polymer injection, resulting in reduction of polymer flooding effectiveness *[10,11]*,to eliminate this problem, alternative injection of high concentration and low concentration polymer solution was used, and a 25% reduction of polymer usage and 1.48% OOIP was obtained compared with nearby injection wells which have the same reservoir character*[12-15]*.

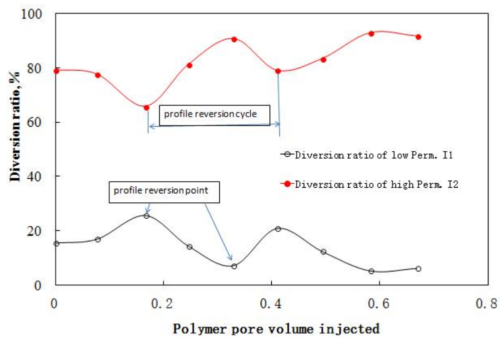


Figure 1. Profile reversion in Lanan3, Daqing oilfield*[9]*

Hydrophobically Associative Polymers(HAP) proved to have superior viscosity enhancement behavior and better mobility control *[16,17]*.In China Bohai bay, HAP polymer flooding was initiated in 2007 at water cut 80%,after three years' injection, 0.18 pore volume polymer was injected into this area, water cut decreased by a maximum of 70% while oil production rate increased by about 30%. After prolonged injection, polymer inefficient circulation and large amount of oil had remained in the reservoir *[8-9]*. We consider "profile reversion" occurs. Different from Daqing polymer injection project, which have low oil viscosity of 10 mPa.S and late stage polymer injection at water cut 99% , the Bohai polymer injection project has high oil viscosity 70mPa.S and early stage polymer injection at water cut 80%. Therefore, we present here a systematic study of "profile reversion" mechanism and control method for polymer flooding of heavy oil. This study will have profound value to enhance polymer injection effectiveness and reduce the amount of polymer used in polymer flooding of heavy oil.

■EXPERIMENTAL SECTION

Materials and Methods of Solution Preparation.

The polymer used in this study is Hydrophobically Associating Polymer(HAP) with a brand name AP-P4 with intrinsic viscosity [η]=1800 cm^3/g, which was supplied by Sichuan Guangya Polymer Company. Crude oil was collected from a heavy oil reservoir SZ36-1 in China Bohai Bay. Basic water from the crude oil was removed by thermal enhanced high-speed centrifugation and diluted with diesel oil and passed through 200 meshes stainless filter to remove sand. The measured oil viscosity was 70cP at 45 °C. Oil viscosity was checked using Brookfield DV-III Rheometer each time before the experiment to maintain consistency. Water was synthesized according to Table 1, the solution was stirred for 2 h until it became completely transparent and no filtration was needed. The mother polymer solutions (0.5wt % concentration) were prepared by adding them to synthetic sea water. Polymer powders were added with constant stirring and were maintained under gentle mechanical stir overnight, then diluted to required concentration and stirred overnight until homogeneous, the temperature kept at 45℃ use a water bath. Proper care was taken to ensure that polymers are not added too rapidly in order to avoid lumping of the powder.

Table 1. Synthetic water Composition of SZ36-1 resevoir

Ion	Concentration(ppm)
Na^++K^+	3092
Ca^{2+}	276
Mg^{2+}	159

CO_3^{2-}	14.2
HCO_3^-	311
SO_4^{2-}	85
Cl^-	5436

Rheological Experiments. Polymer rheology measurements were carried out by a Brookfield DV-III Rheometer measured at 65 °C at a low shear rate of $7.34s^{-1}$ for the sample solutions, every sample was read 1 hour to a constant value.

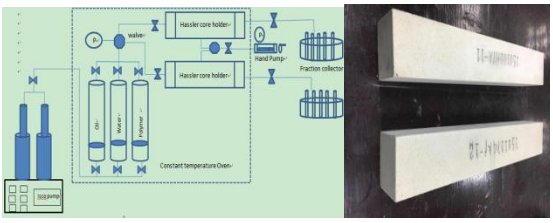


Figure 2. Schematic of core experimental setup and synthetic cores

Core Flooding Experiments: As shown in Figure 2, high temperature and high pressure core flooding experiments made up of an Constant flow pump, constant temperature oven, piston accumulator, one cylinder short core for shear degradation of polymer before injection, two rectangular Hassler core holder for simulation profile reversion in heterogeneous reservoir, overburden pressure was maintained at 5MPa by a hand pump. Epoxy cemented sandstone cores have two kinds: cylinder (2.5cm×7cm) and Rectangular (4.5cm×4.5cm×30cm). Epoxy cemented sandstone cores, which have gas permeability of 300mD, 900mD, 1800mD, and porosity of 30%.All the experiment was kept in an constant temperature oven kept at 65°C.

(1)Polymer solutions were shear degraded by porous media under Hassler core holder at 20ml/min before injecting to the reservoir;

(2)Synthetic sandstone core was evacuated for 4 hours and imbibition saturated with synthetic formation water then measure porosity and water permeability;

(3)The core was saturated with heavy crude oil and aged for 1 week before experiment.

(4)The oil saturated core was flooded first with formation water to rich water cut 80%, then associate polymer solution was injected for 0.6 pore volume, subsequently water flood to water cut 98%.In this process, produced liquid was collected in a 10ml glass tube every 5 minutes and the produced liquid was heated in a water bath at 80℃ to separate the produced oil. Injection pressure was recorded every 5 minute by a high precise pressure gauge.

■Simulation

Polymer flooding results was simulated using CMG STARS software, we simulated laboratory core flooding results and then extended to a typical single well block. A three layers 20×1×3 grid blocks model with middle layer set as impermeable layer , one injector and one producer was used to simulate our laboratory results. Modeling polymer flooding in a layered viscous oil reservoir is challenging because of two major concerns: First is how to correctly allocate flow rates from wellbore to multiple layers; Second is how to capture the viscous fingering effect without using unrealistically fine grids*[18]*. Due to the dependence of polymer retention, inaccessible pore volume, and polymer shear degradation on permeability, Each layer can have a different resistance factor, retention, inaccessible pore volume, and shear degradation*[19]*. With this method, simulation results show it can simulate polymer flooding “Profile reversion” at acceptable error , as shown in Figure 4.

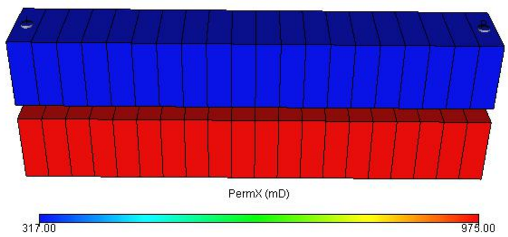
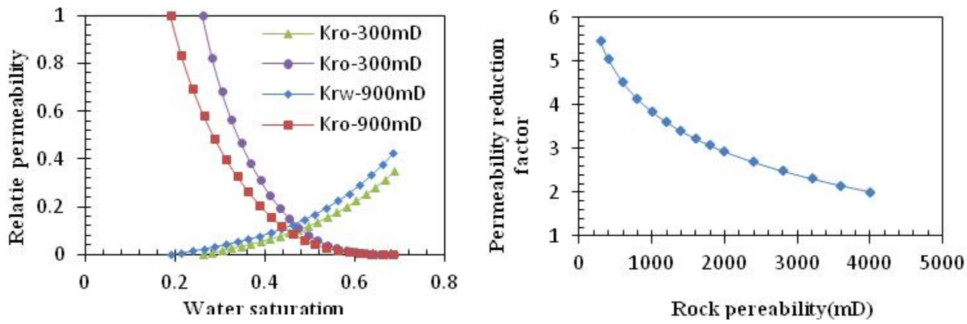
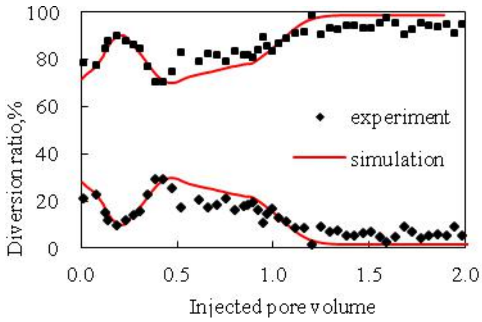


Figure 3. Simulation model of parallel core flood.



4a 4b



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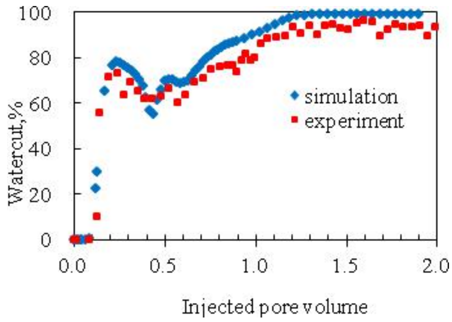


4d

Figure 4.History matching of labrotorary results: 2a):Relative permeability curve varied with different permeability layer. 2b): Permeability reduction factor with rock permeablity.2c): Matching of diversion ratio of high and low permeability with experiment results. 2d): Matching of water cut in heterogeneous layers with experiment results.

■RESULTS AND DISCUSSION

Two separated linear layer model of displacement with Newtonian Fluid*[20]*.

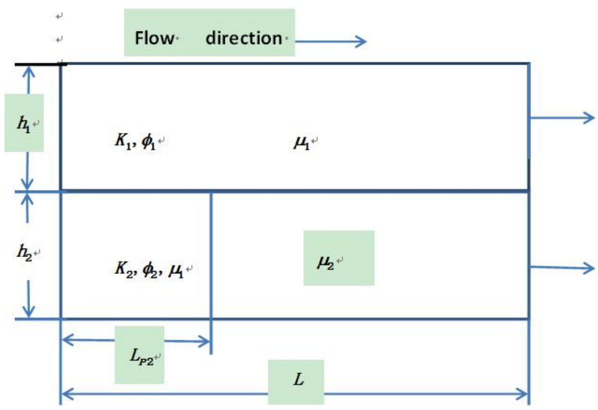


Figure 5. Schematic illustration of two linear layer model of displacement with no crossflow.

The analysis presented here considers the fortuitous case in which reservoir layers are separated by impermeable barriers without crossflow. Because crossflow allows injected fluids to circumvent small or moderate-sized slugs placed in the high-permeability zones and made profiles meaningless.

Homogeneous Cores without mobile oil: Consider a simple case of injecting a Newtonian fluid(polymer solution) for miscible displacement of water from two parallel linear cores that have the same length and that share a common injection port. It is assumed that the displacement is piston-like, that fluids are incompressible, that no adsorption or dispersion occurs. When the injected fluid reaches the outlet (L) of the high permeable core (core 1), the degree of penetration (L_{p2}/ L_t) into a low-permeable core (core 2) was described by a equation derived by Seright [20]

$$\frac{L_{p2}}{L_t} = \frac{\left[1 + (F_r^{\ 2} - 1)\frac{\phi_1 k_2}{\phi_2 k_1}\right]^{0.5} - 1}{F_r - 1} \quad (1)$$

In equation (1), resistant factor(F_r) is assumed to be independent of permeability (k). The degree of penetration (L_{p2}/ L_t) of polymer into a low-permeable core is depend on permeability ratio(k_1/k_2), resistance factor can be modified by polymer concentration. In our experiment,φ_1/φ_2 approximately equal to 1 because of large permeability of our synthetic cores.

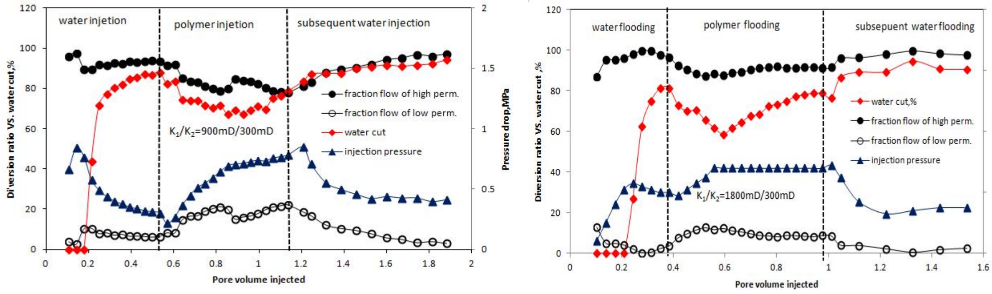
Homogeneous Cores with mobile oil: Liang and Seright use fractional-flow theory and material-balance calculations to study factors affecting gel placement in production well without crossflow [21], neglect viscous fingering. "Gelant" refer to polymer (with cross linker)solution before gelation. Several conclusions reached in this study: First, the degree of polymer penetration into the less permeable cores decrease with increasing permeability ratio; Second, an increase in resistance factor(increase polymer concentration)with increase the degree of penetration into the less permeable layer, and this trend is moderated by increase polymer viscosity; Third, water saturation can affect the degree of polymer penetration; and the degree of penetration is fairly insensitive to the endpoint relative permeability to water.

Based on previous research by Seright[20, 21] , in the same case of our study with oil saturated cores, three main factors affect profile reversion in polymer injection is considered in our experiment: permeability ratio、polymer injection concentration(affect F_r) and polymer injection water cut(water saturation).

Permeability ratio

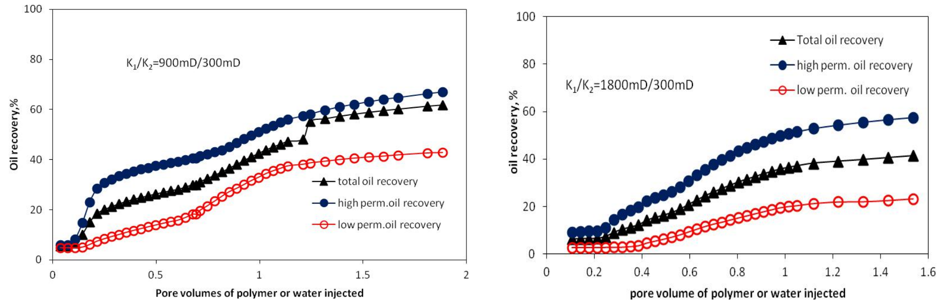
The low permeability layer is fixed at 300mD, permeability ratio are 3 (900mD)and 6 (1800mD), Water flooding to water cut 80%, inject 0.6 pore volume 2000ppm polymer, subsequent water flooding to water cut 98%; to investigate effect of permeability ratio on profile reversion. Due to the unfavorable mobility ratio during water flooding of heavy oil, water quickly breakthrough the high permeability layer, leave the low permeability layer immobilized. As shown in Figure 6, under permeability ratio 3, 0.6 pore volume polymers was injected at water cut 85%, then water flooding to water cut 92%. Polymer injection does not significantly lower the diversion ratio in high permeability core (0.8 times the original), but improve flow heterogeneity so that oil production increased two times in high permeability core. Water intake and oil production increased to about 2 times the original in the low permeability reservoir. In polymer injection, water intake in low permeability undergoes "increase-decrease-increase" process. Diversion ratio of low permeability layer has two distinct turning points, which means that under the permeability ratio 3, profile reversion occurred two times. As shown in Figure 7, under permeability ratio 6, 0.6 pore volume polymers was injected at water cut 82%, then water flooding to water cut 92%. Polymer injection does not significantly lower the diversion ratio in high permeability (0.9 times the original), but improves sweep efficiency in high permeability so that oil production increased 2 times. Water intake and oil production increased to 2-3 times original production in the low permeability reservoir. Diversion ratio in low permeability increases first and then decreases. Diversion ratio of low permeability layer has only one turning point, which means that under the permeability ratio 6, profile reversion occurred only once.

As seen from Figure 6 to 8, as permeability ratio increase, the diversion curve become sharper during polymer injection, the recovery factor of low permeability core decreased; oil recovery factor of permeability ratio 3 has 18% higher than the permeability ratio 6. Increase permeability ratio has detrimental effect on mobilization of the low permeability reservoir. In our experiment, further increase permeability ratio (>6) will lead to poor recovery in the low permeability reservoir.



6a 6b

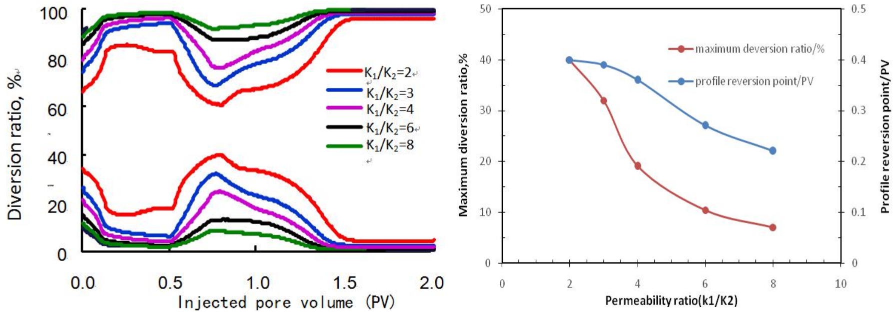
Figure 6.Experiment results of diversion ratio and water cut at permeability ratio 900mD /300mD(6a)1800mD/300mD(6b)



7a 7b

Figure 7. Experiment results of Polymer flooding under different permeability ratio.900mD /300mD(7a)1800mD/300mD(7b)

Polymer flooding "profile reversion point" determination: **we can see from experiment results in Figure 6 that profile reversion point was consistent with water cut minimum turning point and injection pressure maximum turning point.** Under permeability ratio 3, profile reversion point is 0.28PV; polymer intake of low permeability layer attain its' highest value 21% at this point. Under permeability ratio 6, profile reversion point is 0.14PV; polymer intake of low permeability layer attain its' highest value 13% at this point. With the increase of permeability ratio, profile reversion point occurred in advance; polymer intake of low permeability get worse, which make poor recovery of the low permeability reservoir at large permeability ratio, it was comparable with simulation results use CMG software.



7a 7b

Figure 8. Simulation result of profile reversion (2000ppm). Diversion ratio profile at different permeability ratio (7a) effect of permeabiity ratio on profile reversion point and maximum diversion ratio of low layer(7b). Simulation condition:water flooding to water cut 80%, inject 0.6 pore volume 2000ppm polymer, subsequent water flooding to water cut 98%; the low permeability layer is fixed at 300mD.

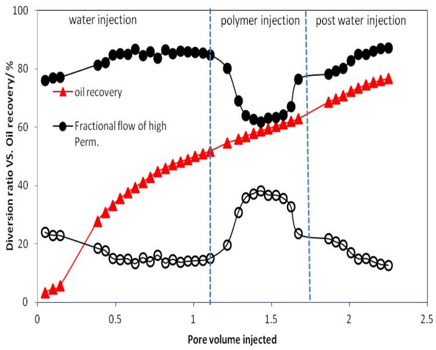
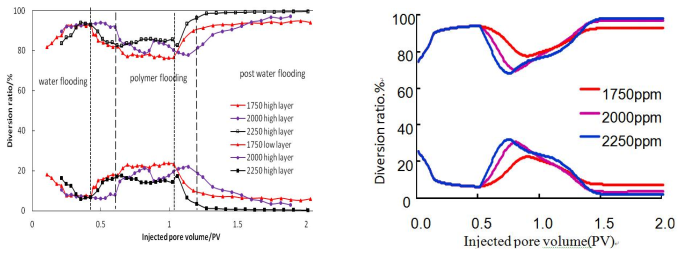


Figure 9.Experiment study of Polymer flood profile reversion in Daqing case with light oil.

Figure 9 show the experiment results of profile reversion in Daqing ,light crude oil viscosity 10mPa.S at 45°C. The permeability of low permeability layer is fixed at 300mD, permeability ratio is 3, water flooding to water cut 85%, inject 0.6 pore volume 2000ppm Daqing polymer with viscosity of 34mPa.S, subsequent water flooding to water cut 98%. As show in Figure 9, In Daqing light oil reservoir case, profile reversion occurs only once at 0.28PV polymer injection; at this point, polymer intake of low permeability layer attain its' highest value 38%, compared with Figure 6a and Figure 9, profile reversion of Bohai heavy oil reservoir occurs quickly, polymer intake of low permeability was much lower than conventional light oil reservoir, thus it is more urgent to control profile reversion for heavy oil reservoir for efficiently mobilize of heavy crude oil in low permeability layer.

polymer concentration

The permeability of low permeability core is fixed at 300mD, permeability ratio are 3 (high permeability core 900mD), Water flooding to water cut 80%, inject 0.6 pore volume polymer, subsequent water flooding to water cut 98%; study effect of permeability ratio on profile reversion. According to Bohai field application and considering polymer injectivity, three polymer concentration 1750ppm(viscosity of 67mPa.S),2000ppm (viscosity of 76mPa.S)and 2250ppm(viscosity of 240mPa.S) are used in the experiment. All polymer solutions were subject to high flow rate core shear degradation before experiment to modeling polymer undergoes high shear rate degradation in the near wellbore region. In our experiments, we have found that 2500ppm polymer solution have poor injectivity. While 1500ppm polymer solution which has poor mobility control in the high permeability reservoir led to low oil recovery.



(10a)Experiment results (10b)Simulation results

Figure 10.Effect of Polymer concentration on profile reversion.

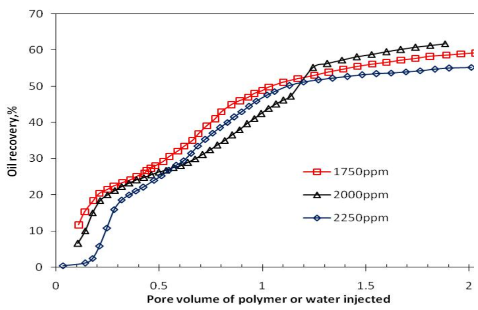


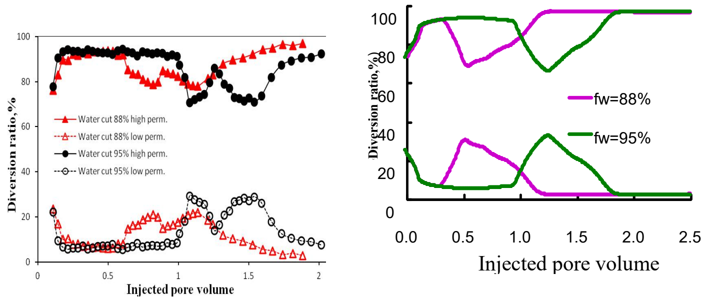
Figure 11.Experiment results of Polymer concentration effect on oil recovery.

Table 1：Effect of polymer concentration on profile reversion

Polymer concentration mg/L	Profile reversion point （1st）	Profile reversion times	Profile reversion cycle	Low perm. Max.diversion ratio	Fraction of cumulative water or polymer intake in low perm.	Oil recovery	
1750	0.26PV	1	-	22.9%	57%	58.2%	High perm. 66.2%
							Low perm. 49.3%
2000	0.22PV	2	0.32PV	22%	45%	62.1%	High perm. 70.3%
							Low perm. 52.8%
2250	0.20PV	2	0.32PV	17.2%	31%	54.6%	High perm. 65.6%
							Low perm. 41.8%

As seen from Table 1、Figure 10 and Figure 11, with the increase of polymer concentration, profile reversion advance; At profile reversion point, polymer intake of low permeability reaches the maximum value. As polymer concentration increase, maximum diversion ratio at profile reversion point in low permeability decrease. oil recovery maximum at polymer concentration of 2000ppm. It means that polymer concentration has an optimum value 2000ppm for permeability ratio 3; 2250ppm polymer may have injectivity problem in low permeability 300mD and cannot mobilize the residual oil in low layer and lead to poor recovery in low permeability cores. During polymer flooding and subsequent water flooding, little oil was produced. Thus effective polymer concentration should have better mobility control in high layer plus good injectivity in low layer[22] thus can mobilize residual oil in low layer. We can calculate from the experiment data that profile reversion cycle was 0.32PV.

Injection water cut



(12a)Experiment results (12b)Simulation results

Figure 12.Effect of injection water cut on profile reversion.

The permeability of lower layer is fixed at 300mD, permeability ratio is fixed to 3 (higher layer 900mD), Water flooding to a certain water cut, inject 0.6 pore volume polymer, subsequent water flooding to water cut 98%; study effect of injection water cut on profile reversion.

As injection time advanced from water cut 95% to water cut 88%, profile reversion point delayed from 0.09PV to 0.28PV; at "Profile Reversion Point", diversion ratio of low layer decreased from 26.5% to 21%. Cumulative water or polymer intake in low permeability decreased from 65.2% to 45.5%, oil recovery of the low layer increased from 35.1% OOIP to 42.8% OOIP. Total oil recovery of two layers increased from 41.2% to 61.7%. Polymer injection at high water cut benefits for polymer intake of low layer, but poor total oil recovery, this is because polymer injected more to high permeability reservoir cause post water flooding directed more to low layer to mobilize residual oil. Thus, polymer injection at low water cut will have higher oil recovery.

Alternative injection of different polymer or gel solution for profile reversion improvement

Field results in Daqing prove that alternative injection of high and low concentration polymers can divert more polymer solution to low permeability reservoir, thus improve oil recovery and reduce polymer used. The basic idea of alternating injection for Profile

Reversion Control is: Choose different polymer concentration at different reservoir condition for efficient transport in porous media and good mobility control; high viscosity polymer slug preferentially inject to high permeability layer, reducing high permeability layer's mobility, forcing the subsequent injected low viscosity polymer solution into the low permeability layer, reducing viscous finger of polymer solution and achieve more uniform displacement front in heterogeneous layer.

According to Bohai oilfield results, we choose two injection strategy: (1) High concentration polymer and low concentration polymer alternate injection (2) Phenol-formaldehyde polymer-gel *[23]*and polymer alternate injection. Previous report*[24]* that the phenol-formaldehyde gelant display good injectivity in core flood and slim-tube experiments at temperatures up to 140°C. In this study, we use a weak gel formulation.2500ppm Associating Polymer AP-P4+ 500ppm phenol + 250ppm resorcinol + 500ppm Hexamethylenetetramine+ 750 ppm Acetic acid. After stay in the bottle kept in an oven at Bohai reservoir temperature 65°C, after 24h it forms a Sydansk strength code C gel*[25]*, it kept at strength C and D Level. After 3 months aging at reservoir temperature not obvious syneresis detected. Before the gel formation, the injected gel formula transport like polymer in porous media thus has good injectivity in high permeability cores. After age in the oil saturated cores for 7 days, gel formation in the high layer obviously not flowing because in post alternative injection of polymer injection, pressure climbed from 0.52MPa to 1.05MPa and polymer breakthrough in the outlet, as shown in Figure 12 and Table 2, fluid flow was diverted from high perm layer to low perm layer, and obviously a formation damage coursed production reduced, we think weak gel at this large injection pore volume 0.3PV have detrimental effect on high perm layer.

Then we carry out alternate injection of polymer slug injection. The permeability of low permeability layer is fixed at 300mD, permeability ratio are 3 (high layer permeability 900mD), Water flooding to reach water cut 80%,then inject 0.6 pore volume polymer, subsequent water flooding to water cut 98%, cumulative injection 2PV;study effect of injection system and alternating cycle on enhanced oil recovery. As shown in Table 2, in the case of the high concentration / low concentration polymer alternating injection, proper choice of high and low concentration polymer is crucial, alternative injection 2250ppm and 1750 ppm polymer is better than 1750ppm and 15000ppm polymer, as shown in table 2. High concentration polymer slug can establish effective flow resistance in high permeability layer of heavy oil, effectively direct subsequent low concentration polymer flooding to the low permeability reservoir, thus improve oil mobilized in low permeability reservoir.

As show in Figure 13 to Figure 14,alternative injection of phenol-formaldehyde-based 2250ppm polymer weak gel (shut in for 7 days at 65℃ for gel code D formation)and 1750ppm polymer have poor oil recovery efficiency than alternative injection of the 2250ppm and 1750ppm polymer. Due to polymer injection at low water cut, there are large amounts of oil remained in the high permeability layer, weak gel injection cause plugging and a significant reduction in production, oil recovery of the high permeability layer significantly reduced . Weak gel injection successfully directs subsequent fluid to low-permeability layer and makes it the main oil production layer. However, oil recovery of low permeability layer increases slightly. This make gel/polymer alternate injection has 6.8% less oil recovery than high/low concentration polymer alternative injection, show in Figure 12. Therefore, weak gel are not suitable for alternative injection system in improve polymer injection performance of heavy oil recovery because it is not flowing after gelation in reservoir. Seright*[26]* reveals that weak gel injection is most appropriate for high permeability ratio(e.g.10:1),and relatively low oil viscosities. Because of the high cost of the weak gel, economics favors small bank size (e.g. 5% of the pore volume in the high-permeability layer), although oil recovery during weak gel injection is higher than polymer injection, ultimate recovery is much less than polymer flooding at the same polymer concentration used, this is well corresponded to our experiment results.

We compared the effects of alternate cycles on oil recovery; we found that high concentration polymer slug (0.15PV, 2250ppm)/low concentration polymer slug(0.15PV,1750 ppm) alternately injection twice proofed to be most effective. As alternate injection cycles increase, polymer mobility control effect gets worse. As show in table 2, at the same polymer dosage 1200mg/(L PV) injected, high concentration / low concentration polymer alternative injection twice increased oil recovery higher than directly polymer injection by 4.3%OOIP. In Daqing case, oil recovery after alternative polymer injection increased a value of 2.2% OOIP at two alternate injection cycles[12,14], which shows better performance of alternative injection of polymer slug for heavy oil recovery at low water cut.

Table 2: Effect of polymer or injection method on oil recovery

Polymer or gel injection method[1,2]	Total oil recovery	Oil recovery of high perm.	Oil recovery of low perm.
2000ppm polymer 0.6PV, direct injection	44.7%	61%	16.1%
2250ppm 0.3PV+1750ppm 0.3PV, Alternate injection once	44.9%	72.4%	14.4%
2250ppm 0.15PV+1750ppm 0.15PV, Alternate injection twice	50%	69.1%	29.4%
2250ppm 0.10PV+1750ppm 0.10PV, Alternate injection 3 times	42.1%	67.9%	13.1%
1750ppm 0.3PV+1500ppm 0.3PV, Alternate injection once	40.4%	66.9%	10.8%
Weak gel 2250ppm 0.3PV+1750ppm 0.3PV, Alternate injection once	38.1%	26.9%	52.6%

[1]Water flooding to water cut 80%, inject 0.6 PV polymer or gel, subsequent water flooding to water cut 98%, cumulative injection 2PV.

[2]Polymer gel was directly injected in cores after mixing and Shut in for 7 days under the reservoir conditions for gel formation.

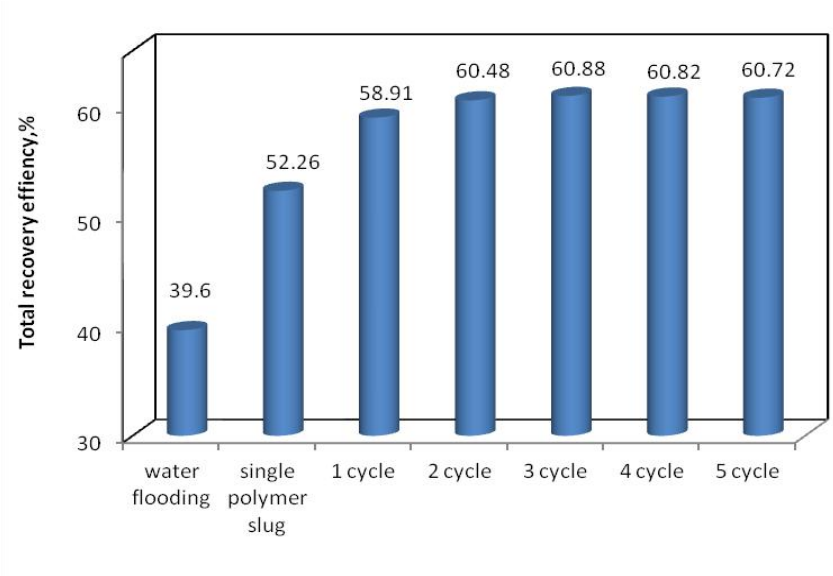


Figure 13.Resevoir simulation results of total recovery efficiency of water flooding ,0.6 PV polymer flooding ,alternative injection of 2250ppm Polymer and 1750ppm polymer. **1 cycle**(0.3PV 2250ppm polymer +0.3PV 2250ppm polymer), **2 cycle**(0.15PV 2250ppm polymer +0.15PV 1750ppm polymer， alternate twice) ,**3 cycle**(0.1PV 2250ppm polymer +0.1PV 1750ppm polymer，alternate 3 times), **4 cycle**(0.075PV 2250ppm polymer +0.075PV 1750ppm polymer， alternate 4 times),**5cycle**(0.06PV 2250ppm polymer +0.06PV 1750ppm polymer，alternate 5 times)

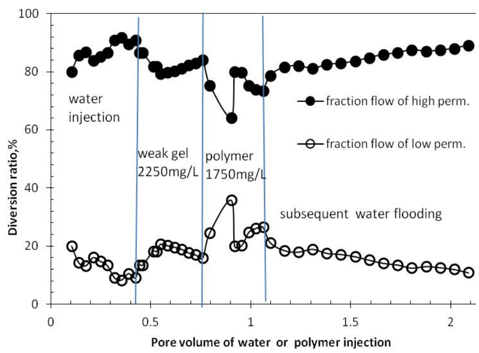


Figure 14. Diversion ratio of weak gel and polymer alternative injection.

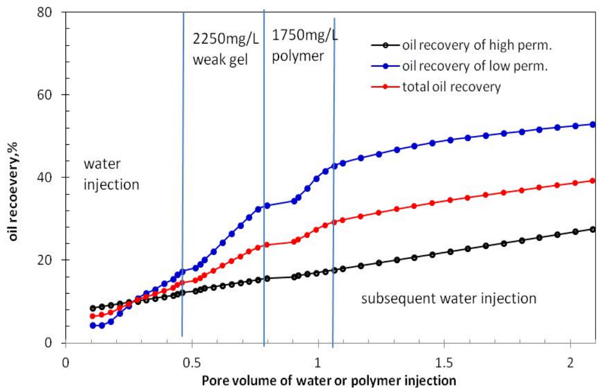


Figure 15. Oil recovery of weak gel and polymer alternative injection.

Figure 16 compared high concentration and low concentration aqueous polymer alternative injection cycles on water cut curve, polymer injection decrease water cut, the lager and longer duration of the water cut decrease, the larger oil recovery performance. In our experiment, alternate injection twice in 0.6PV total polymer injection have the largest and longest duration of water cut decrease, thus have the best oil recovery performance, 4.3%OOIP larger than direct polymer injection. Proper selection of polymer alternate injection cycles can built an effective mobility control barrier in heterogeneous reservoir, thus improves post water flooding sweep efficiency.

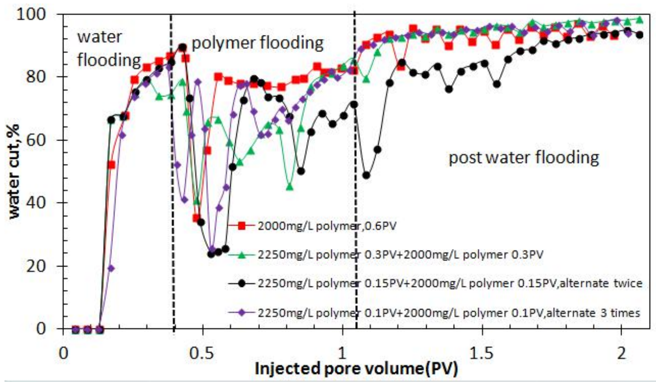


Figure 16. Effect of alternative times on polymer flooding Water cut curve.

Reservoir geological model and history matching

As show in Figure 17, the A13 well group in China Bohai offshore oil reservoir was selected to evaluate the effect of alternative polymer injection on oil recovery. The A13 well group include oil production well A12、A20、A14、A07、K07、K25、K11，water injection well

A13、A19、A21、J03、A08、A02。X direction have 25 grids, Y direction have 32 grids, the vertical direction have 56 small layers, the grid node is 32 * 25 * 56=44800.

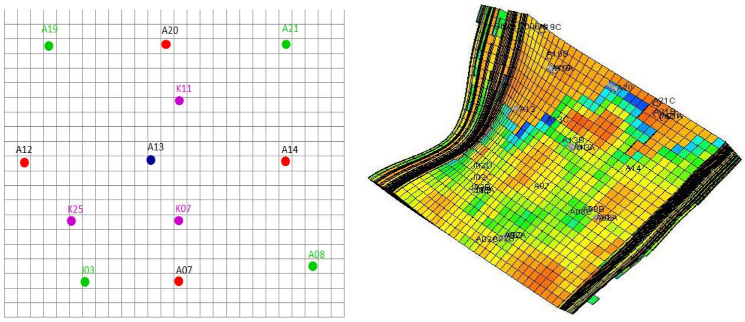


Figure 17. Well placement and Grid distribution in A13 well group in China offshore oil company

A13 well group was produced from the year 1993, associating polymer flooding since the year 2005.In the process of history matching, oil production well is produced at constant rate and water injection well is injected at const rate to simulate single well and well group. As show in Figure 18.

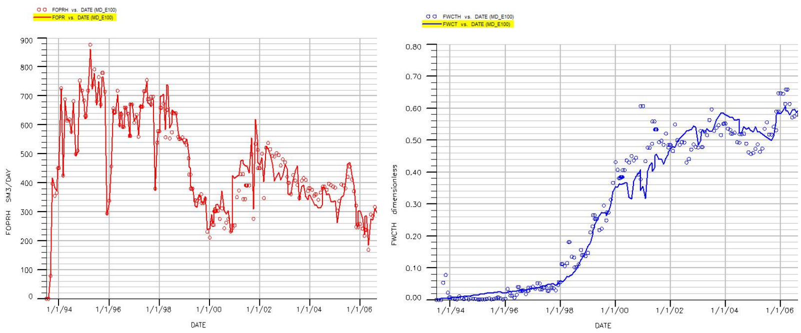


Figure18 History matching of oil production rate and water cut in A13 well group Simulation evaluation results of production well

As show in Figure 19, Production well simulation results of water cut and cumulative oil production between water flooding, single slug polymer injection, and alternative polymer injection. At the same dosage of polymer used，alternative injection of different concentration polymer solution have the sharp decline of water cut, and have the largest oil production volume(over 20m^3 cumulative oil production), thus prove alternative injection of high and low concentration polymer slug can significantly improve heavy oil recovery. Based on our results, a field scale experiment of alternative injection is undertaking in Bohai heavy oil reservoir and its results will be reported later.

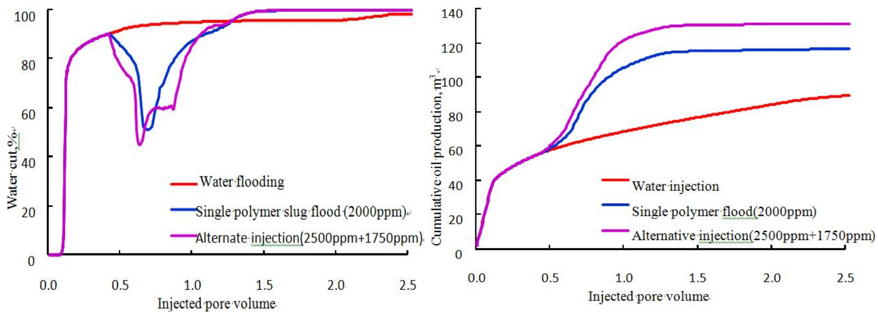


Figure 19　Simulation results of water cut and cumulative oil production of different injection strategy

■CONCLUSION

(1) Polymer flooding of heavy oil at low water cut in Bohai Bay has much difference profile reversion mechanism than Daqing oilfield, which has light oil and Polymer injection at high water-cut. In polymer flooding of heavy oil, low permeability layer has more oil remained in the porous media at the profile reversion. It is more need to control profile reversion, and more oil could be recovered by alternative injection than light oil case in Daqing.

(2)In our experiments, we use two parallel cores flooding to study polymer flooding profile reversion mechanism in the heterogeneous reservoir. We found that profile reversion point was concurrent with water cut minimum and the turning point of pressure drop. It have practical importance for offshore oil reservoir which polymer injection profile cannot be determined; in the future field application, profile reversion point can be achieved by monitor pressure using a precise pressure gauge combined with monitoring of water cut in production well.

(3) With the increase of permeability ratio, profile reversion advance, polymer diversion ratio in low permeability layer decrease at the profile reversion point. With the increase of polymer concentration, profile reversion point advance, polymer diversion ratio of low permeability layer reduced at profile reversion point. The cumulative oil recovery first increases then decreases, which indicate the polymer must be matched with heterogeneous reservoir. With polymer injection water cut decrease, profile reversion point came later, polymer intake and

diversion ratio of low-permeability layer decrease, but oil mobilized in low permeability layer increase, and cumulative oil recovery increase. In general, for efficient recovery of heavy oil, polymer injection at low water cut, small permeability ratio(<6), proper mobility control in the heterogeneous reservoir (proper polymer concentration) will benefit oil recovery efficiency.

(4) Gel/polymer alternate injection has 6.8% less oil recovery than high/low concentration polymer injection. Therefore, weak gel is not suitable for alternative injection system in improve polymer injection performance of heavy oil recovery under small permeability ratio3. High/low polymer alternative injection two times has the best oil recovery performance.

(5)By assuming different polymer retention, in accessible pore volume and resistance factor in different permeability layers, polymer flooding "profile reversion " was successfully simulated using commercial software, and extended to field scale, which prove alternative injection of polymer slug can significantly improve heavy oil recovery.

In conclusion, laboratory results and reservoir simulation show "profile reversion " occurs in polymer flooding of heavy oil, it depends on several factors like permeability ratio, timing of injection and polymer concentration. Alternative injection of polymer slug can significantly improve oil recovery performance. "Profile reversion" was based on polymer flooding experience in China Daqing oilfield with light oil, this paper extend the profile reversion mechanism and control strategy to heavy oil reservoir, and will pave a way for new polymer flooding techniques for heavy oil.

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Notes

The authors declare no competing financial interest.

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