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Feasibility Study of Secondary Polymer Flooding in Henan Oilfield, China

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Abstract: After polymer flooding, it is necessary to find relay technology to retain oil yield. In this paper, laboratory experiments were conducted to investigate feasibility of secondary polymer flooding, in which injecting more polymer with higher concentration and relative molecular mass. It is necessary to determine enhanced recovery range and optimum concentration. With microscopic visible glass physical models, further start up of oil drops with secondary polymer can be observed distinctly. In the mean time, macroscopic heterogeneous core tests were carried out with permeability range of 2, 5 and 8. Polymer concentration effective and economical for flooding is optimized. It is shown that 3%~8% of further enhanced recovery and 20% decreased water cut can be obtained, and water profile can be improved to some extent after secondary polymer flooding. Thence, it is proved that secondary polymer injection after primary polymer can indeed further improve recovery and the technology of secondary flooding is feasible. Moreover, laboratory optimum concentration of 2200mg/L is determined. On the basis of laboratory results, from 2007 to 2008, field trial with above optimum parameters were implemented. Up to 2008.12, water cut decreased from 92% to 83%, and cumulative increased crude oil of 5.71×10^4 t. The success of secondary polymer flooding technology provides reference for the development of oil fields after primary polymer flooding in China and other regions in the whole world.

Key words: secondary polymer flooding; feasibility study; microscopic mechanism; polymer concentration optimization; after polymer flooding

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1. INTRODUCTION

Polymer flooding, as one of effective technologies to enhance oil recovery about 8%-12%, has been widely used and developed in many oilfields in China including Daqing oilfield, Shengli oilfield and Henan oilfield [WANG, 1998;WANG,2000;]. It is generally recognized that the predominant displacement mechanism is improving sweep efficiency through increasing viscosity of aqueous phase. In addition, it is indicated that polymer solution can improve microscopic displacement efficiency because of excellent viscoelasticity [XIA,2001; HUANG, 1990;]. However, in the course of re-injecting water after polymer flooding, water cut rises again rapidly, and a large amount of residual crude oil exists in rock pore throat. Because of limit ability of polymer solution to control mobility, formation heterogeneity can not be improved remarkably, even aggravated. It is urgent to find a new technology to maintain production through enhancing sweep efficiency or displacement. Up to now, the technologies to further enhance oil recovery after polymer flooding include low-alkali ASP flooding, non-alkali SP flooding, foam and microbe flooding [ZHAO 2006; LIU, 2007; YU, 2007; LIU, 2005; WANG, 2006].

During 1996~2006, polymer flooding was implemented in Henan Oilfield, with average 70mPa.s of crude oil viscosity and reservoir temperature of 55°C, polymer of 0.42PV~0.44PV was injected with above 8% of enhanced recovery. In the next water flooding, water cut arise rapidly, and part of lower permeability zones were not development, therefore it is necessary to employ relay technology to retain yield. In the other hand, the total produced degree is less than 35%, that is to say, more than 65% of residual crude oil still exists in underground, and both vertical and plane heterogeneity are serious. Therefore, according to characteristic of crude oil and formation, a series of laboratory experiments to study the feasibility of secondary polymer flooding were carried, including microscopic mechanism study and macroscopic physical modeling. In addition, the polymer concentration must be optimized to ensure recovery effect and economics. Filed trial with above optimum parameters was implemented. Up to 2008.12, water cut decreased from 92% to 83%, and cumulative increased crude oil of above 50000t.

1. EXPERIMENT MATERIALS AND METHODS

1.1 Materials

Polymer

MO4000 (Japan, with viscosity 21.6mPa·s with concentration of 1000mg/L); Polymer model I (Zhengzhou, China, with viscosity 29.2mPa·s and 70.0mPa·s with concentration of 1800mg/L and 2200mg/L);

Crude oil and water

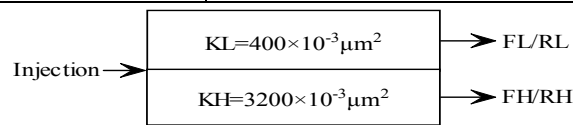
Model oil made up xia'ermen crude oil and aviation kerosene; Model injected water with total salinity 2282mg/L, Na⁺655mg/L, Ca²⁺ 20mg/L and HCO₃⁻1159mg/L;

Physical models

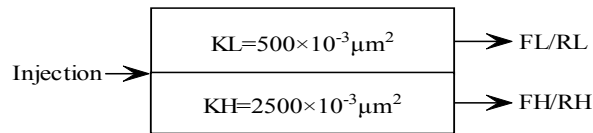
Microscopic light craved models (40mm*40mm), including homogeneous and heterogeneous models; macroscopic physical models of vertically heterogeneous models, as shown in Table1, and interstratal and intrastratal heterogeneous models are shown in Fig 1.

Table1: Basic characteristic of models

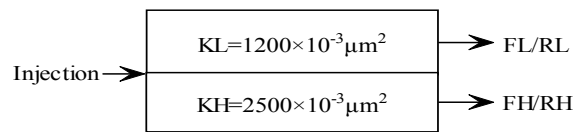
	Model type	Permeability, $\times 10^{-3} \mu\text{m}^2$	Permeability ratio
Microscopic physical models	homogeneous	3000	---
		2000	---
		1000	---
	heterogeneous	3000/2000/1000	3
Macroscopic (vertical heterogeneous models)	interstratal	3200/400	8
		2500/500	5
		2500/1200	2
	intrastratal	2500/1800/1200	2



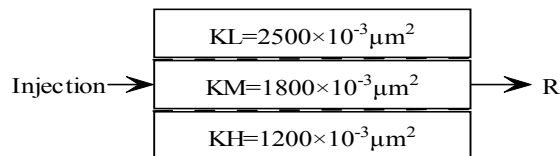
(a) 3200/400 interstratal heterogeneous models



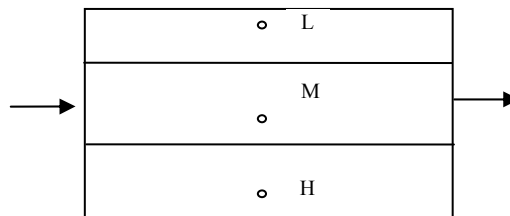
(b) 2500/500 interstratal heterogeneous models



(c) 1200/2500 interstratal heterogeneous models



(d) 2500/1800/1200 intrastratal heterogeneous models



(e) Microscopic model

*Notes: points L, M and H are observation location.

Figure1: Sketch of heterogeneous cores

1.2 Equipments

Stereo microscope; micro pump; constant temperature bath; HPHT displacement pump; high pressure piston container and etc, flow chart is shown in Fig. 2.

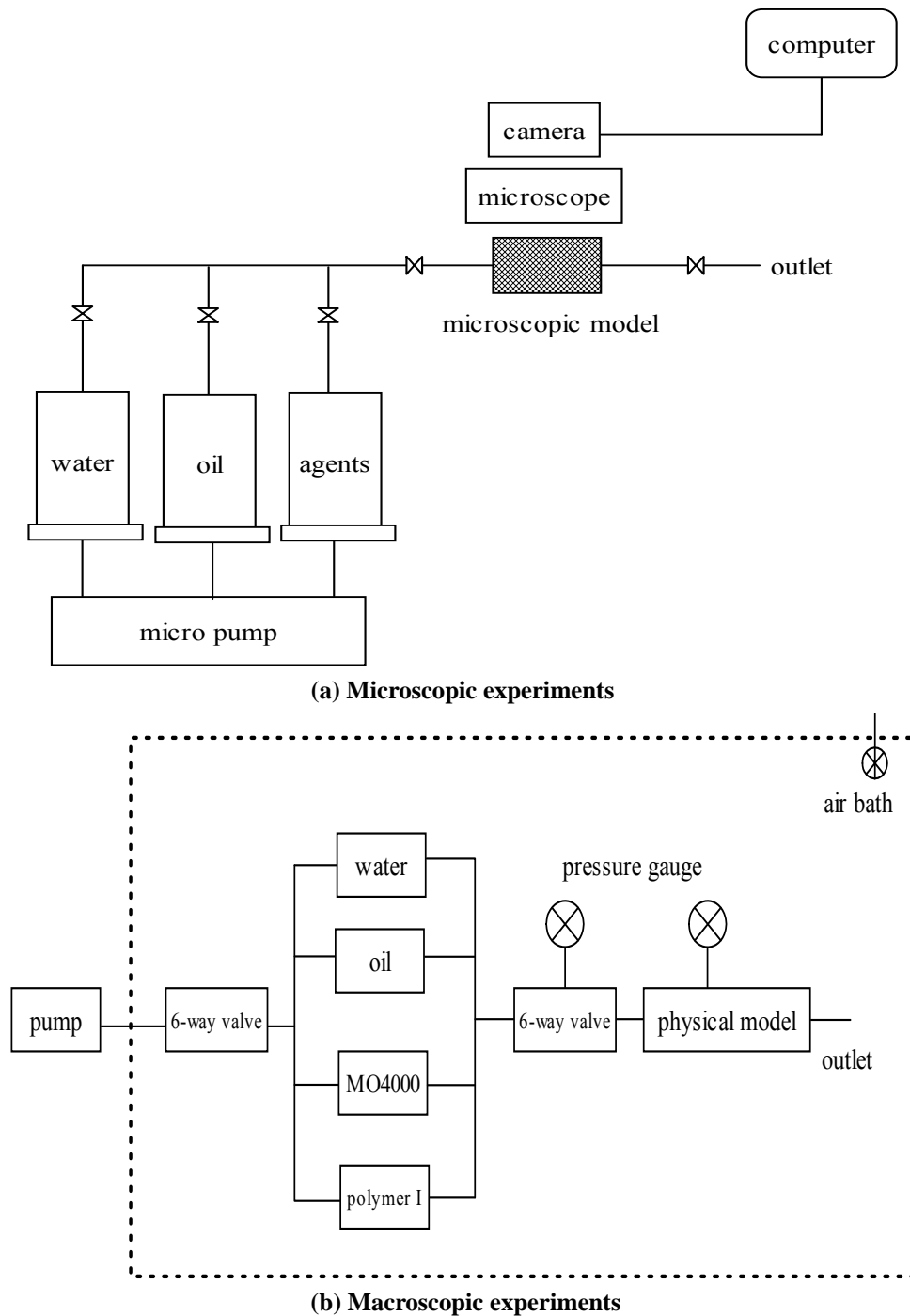


Figure2: Flow chart of experiments

1.3 METHODS

Macroscopic experiments

For the purpose of simulating practical field production stage, the macroscopic experiments were conducted as following.

---models were treated with evacuation and saturated with formation water, then pore volume PV and porosity ϕ could be obtained;

---saturating models with model oil until no more water, and then initial saturation of oil S_{oi} ;

---after aging for above 24h in constant temperature bath, flooding with water to water cut of 92%(WF);

---injecting polymer 4000 of 0.4PV (PPF) then water flooding to water cut of 94%;

---conducting secondary polymer flooding with Polymer model I (SPF);

---finally injecting water to water cut of 98%, the whole course finished;

---recovery degrees of different stages can be calculated and curves of water cut, recovery and pressure with injected PV can be drawn.

With different polymer concentration of secondary polymer flooding (C_p), different experimental model, the number of macroscopic experiments is 14, and detailed planning is showed in Table2.

Table 2: Designed experimental plan and model parameters

Serials number	C_p (mg/L)	PV(mL)	ϕ (%)	S_{oi} (%)	Permeability ratio
1	2500	148	27.2	81.1	8 (3200/400)
2	1800	154	27.1	83.1	
3	1500	154	26.2	80.2	
4	2500	154	27.1	82.3	5 (2500/500)
5	1800	154	26.2	81.2	
6	1500	154	27.2	81.1	
7	2500	158	27.7	79.7	2 (2500/1200)
8	1800	153	27.5	79.1	
9	1500	162	28.4	79.6	
10	1300	172	28.1	75.8	2 (2500/1800/1200)
11	1500	171	28.1	78.4	
12	1800	174	28.8	77.0	
13	2200	170	27.9	75.3	
14	2500	177	29.6	75.7	

Microscopic experiments

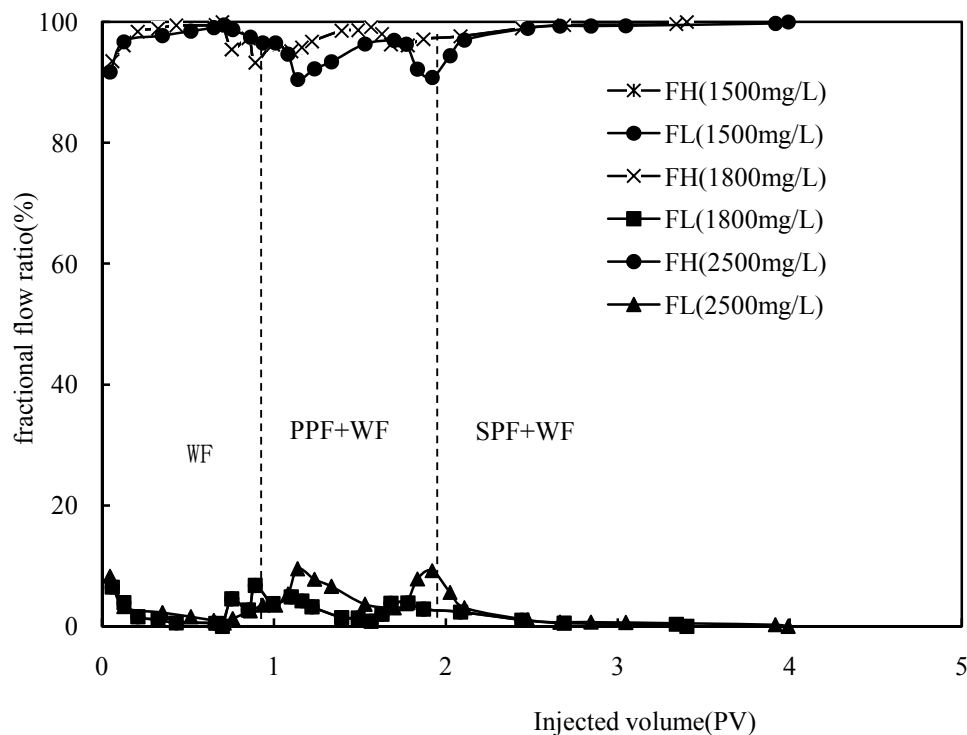
For the microscopic experiments, the process is similar to that of macroscopic experiments. The whole flooding course including startup of oil drop, residual oil distribution can be recorded with camera.

2. RESULTS AND DISCUSSION

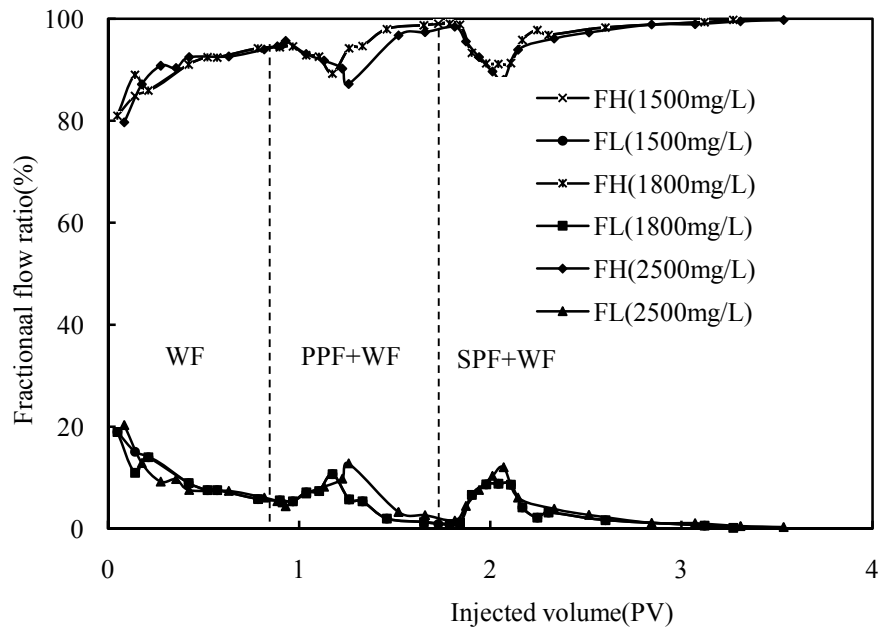
2.1 Water profile improvement

For the interstratal heterogeneous cores, there is an isolating layer, flow trough higher and lower permeable layers can be measured separately, thus fractional flow change before and after polymer flooding can be used to characterize the degree of improving water profile, so we adopt the percentage of separate layer FH and FL to show the flow change.

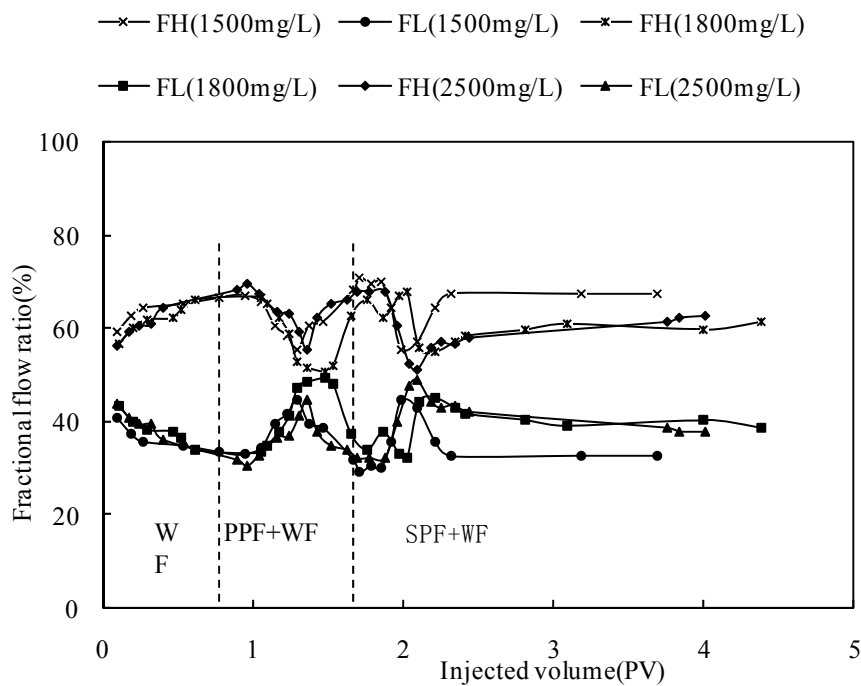
The designed experimental plan can be seen in column 1~9 of Table 2. The investigated concentrations of polymer are 2500mg/L, 1800mg/L and 1500mg/L, and the permeability ratios are 8, 5 and 2. The results are shown in Fig. 3 and Table3.



(a) Permeability ratio 8



(b) Permeability ratio 5



(c) Permeability ratio 2

Figure 3: Curves of high/low permeability zones diversion ratio of interlayer heterogeneous cores

Table 3: Diversion ratio variation before and after secondary polymer flooding

Permeability ratio	C_p (mg/L)	FH/FL before SPF (%)	Ratio of FH/FL before SPF	FH/FL after SPF (%)	Ratio of FH/FL after SPF	Reduction ratio of fractional flow through high permeability layer
8	2500	98.6/1.4	70.4	83.8/16.2	5.2	15.0
	1800	98.5/1.5	65.7	88.2/11.8	7.5	10.5
	1500	98.5/1.5	65.7	90.3/9.7	9.3	8.3
5	2500	89.6/10.4	8.6	73.1/26.9	2.7	18.4
	1800	90.7/9.3	9.8	78.5/21.5	3.7	13.5
	1500	88.9/11.1	8.0	79.8/20.2	4.0	10.2
2	2500	67.9/32.1	2.1	54.4/45.6	1.2	19.9
	1800	67.0/33.0	2.0	55.7/44.3	1.3	16.9
	1500	66.7/33.3	2.0	56.4/43.6	1.3	15.4

From Figure3, we can obviously see that, in the condition of permeability ratio of 8 and 5, large difference between high and low permeability layers during the water flooding exists, that is to say, sweep efficiency in low permeability layer is very poor because of serious heterogeneity. After the primary polymer flooding, although water profile is improved to some extent, during the subsequent water flooding, fractional flow through low permeability layer reduces again with high ratio of FH/FL. After secondary polymer flooding, just as shown in Table 3, fractional flow through high permeability layer reduces extremely, with reduction ratio of fractional flow through high permeability layer in the range of 8 to 20 in the condition of different permeability ratio and polymer concentration.

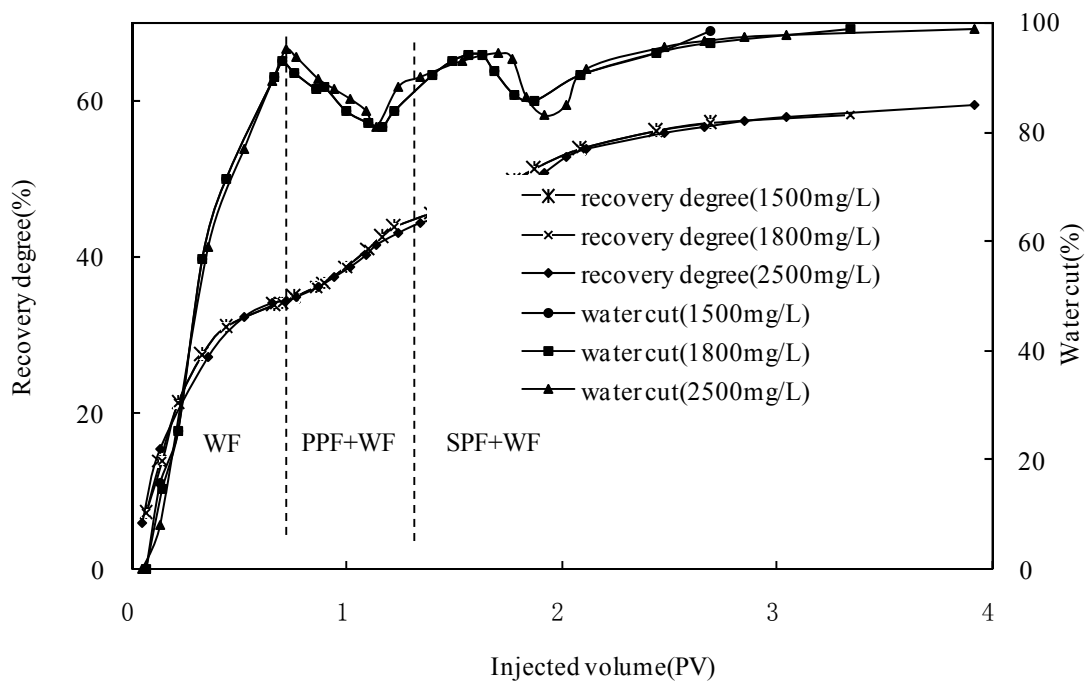
Even with permeability ratio of 8 and polymer concentration of 1800mg/L, fractional flow ratio increased from 1.5 to 11.8%. With polymer concentration increasing, fractional flow ratio further increases, so secondary polymer flooding can undoubtedly improve water profile to some extent.

From the above analysis, permeability ratio and polymer concentration both affect the profile improvement degree, by contract, the influence of the former is more obviously. For instance, with permeability ratio of 5, polymer concentration changes from 1500mg/L to 1800mg/L and 2500mg/L, ratio of FH/FL after SPF varies from 4.0 to 3.7 and 2.7, in the mean time, with polymer concentration of 1800mg/L, permeability ratio varies from 8 to 5 and 2, ratio of FH/FL after SPF varies from 7.5 to 3.7 and 1.3.

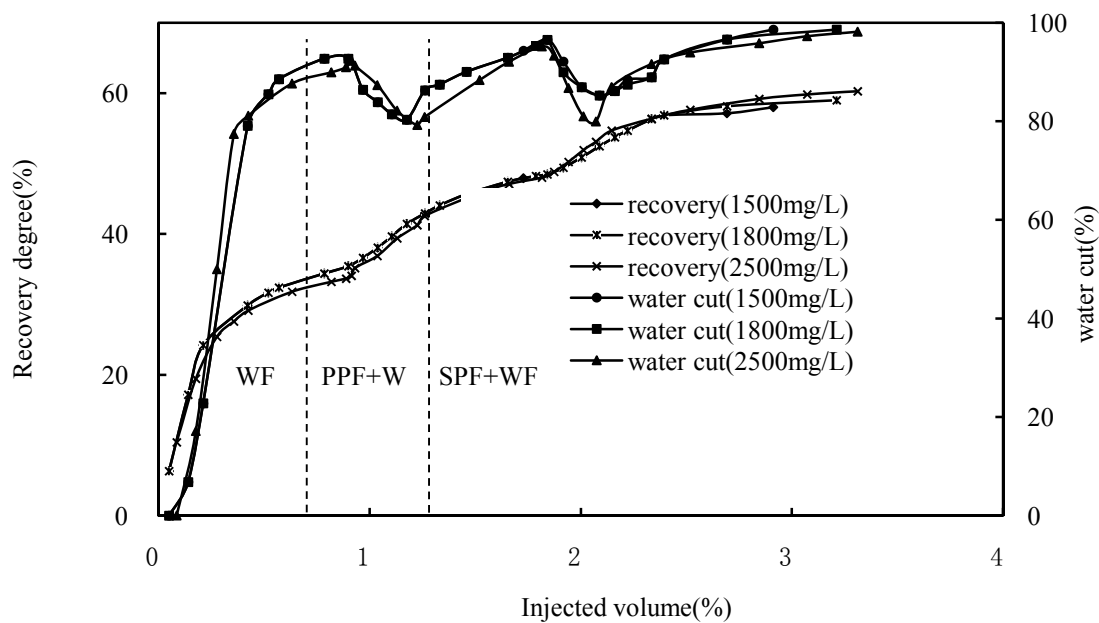
It must be noted that, even though secondary polymer flooding improved profile to some extent, after subsequent water flooding, fractional flow through low permeability layer reduces to less than 1%. It can be concluded that the profile improvement degree by polymer is limited for the seriously inhomogeneous. Therefore firstly it is essential to inject water shutoff agent with high intensity such as linked polymer or gel to control the water breakthrough and then inject polymer with reasonable concentration.

2.2 Oil displacement result

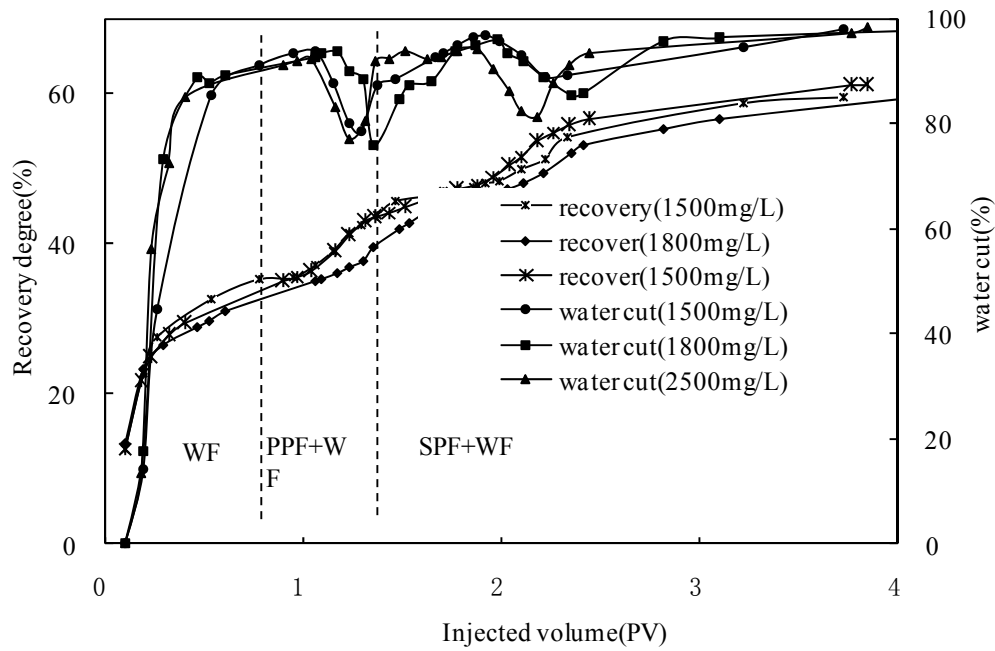
With different permeability ratio and polymer concentration, oil displacement results in interstratal heterogeneous cores can be seen in Fig. 4. (a)~(c) demonstrates the dynamic flooding characteristic including the changes in water cut and recovery degree with injected volume (PV), and (d) shows the recoveries of secondary polymer flooding in different conditions.



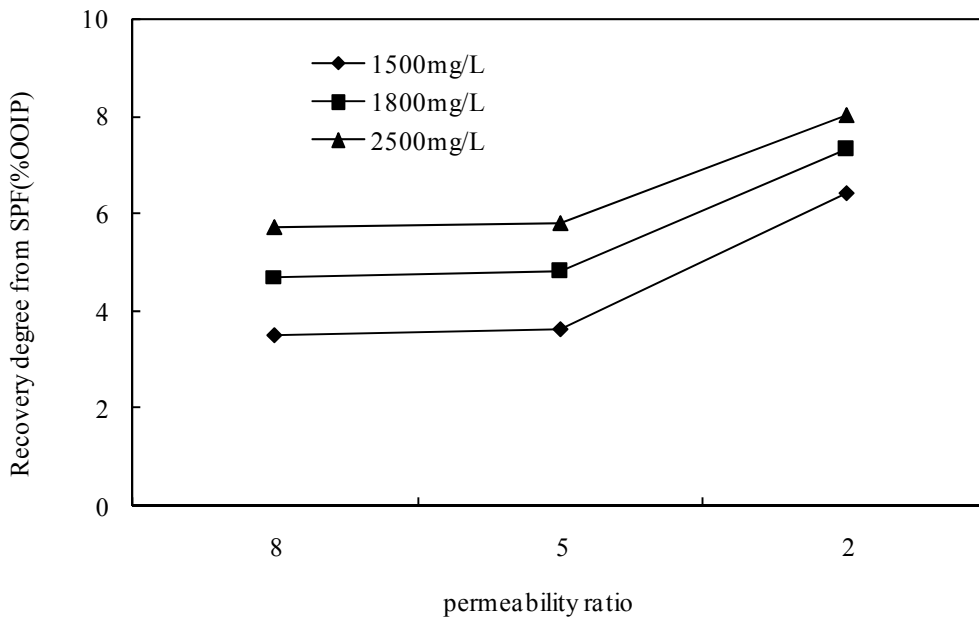
(a) Permeability ratio 8



(b) Permeability ratio 5



(c) Permeability ratio 2



(d) Enhanced oil recovery during SPF

Figure 4: Curves of RD and WC of different stage in the condition of different heterogeneity and polymer concentration

From the above results, the permeability ratio has great effect on the recovery including all stages of water flooding, primary polymer flooding and secondary polymer flooding. With permeability ratio of 8, 5 to 2, recoveries during water flooding are 40.6%, 41.9% and 42.0%, which demonstrates that with decreasing of permeability ratio, recovery from water flooding increases. Enhanced oil recoveries from primary polymer flooding are 11.4%, 12.8% and 12.9%, that is to say, in the condition of permeability ratio of 2, improved oil recovery is relatively low, because of lower remaining oil saturation and larger water washing range. After secondary polymer, the enhanced oil recovery ranges in 3.5%~7.2%, which proved that secondary polymer flooding is feasible for further improving recovery. In addition, it must be noted that, when the heterogenous degree is strong enough such as with 5 or 8 of permeability ratio, the effect can not be ensured.

On the other hand, the enhanced oil recovery depends on polymer concentration. With higher polymer concentration, enhanced oil recovery increases obviously. For example, as the concentration increase from 1500mg/L to 2500mg/L, enhanced oil recovery increases from 3.6% to 5.8% with permeability ratio of 5.

2.3 Secondary polymer flooding concentration optimization

With intrastratal heterogenous cores and 1300mg/L, 1500mg/L, 1800mg/L, 2200mg/L and 2500mg/L, polymer concentration are optimized. The result is shown in Fig.5.

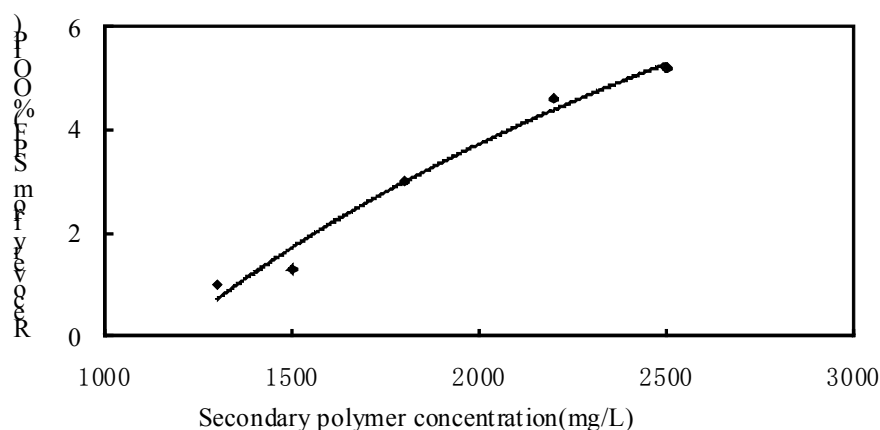
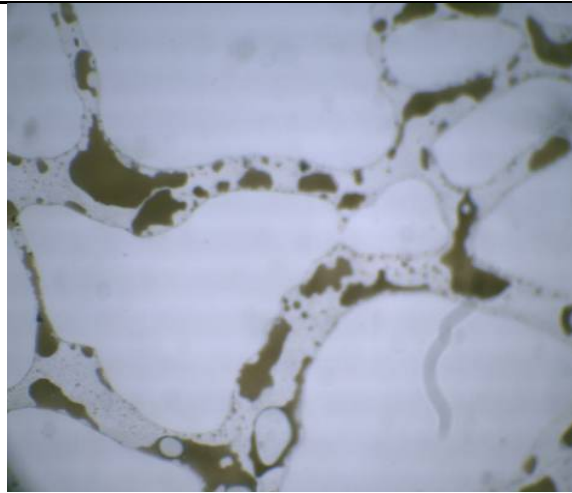


Figure 5: Curve of optimizing polymer concentration during secondary polymer flooding

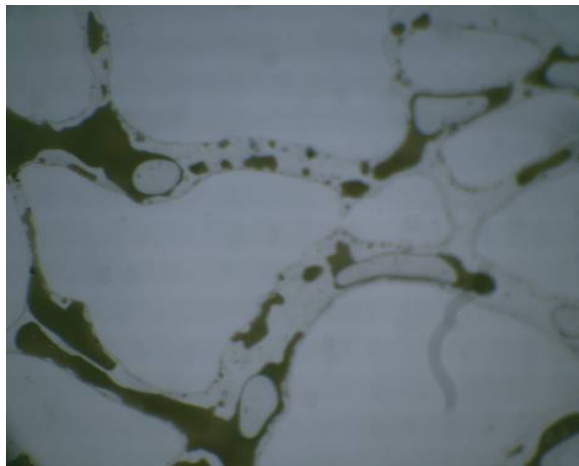
It can be observed that recovery from SPF increased with polymer concentration increasing. When polymer concentration reaches above 2200mg/L, the recovery rises slowly, from which we can obtain the optimum concentration with enhanced recovery of 4.6%OOIP in the certain experimental condition.

2.4 Microscopic displacement mechanism

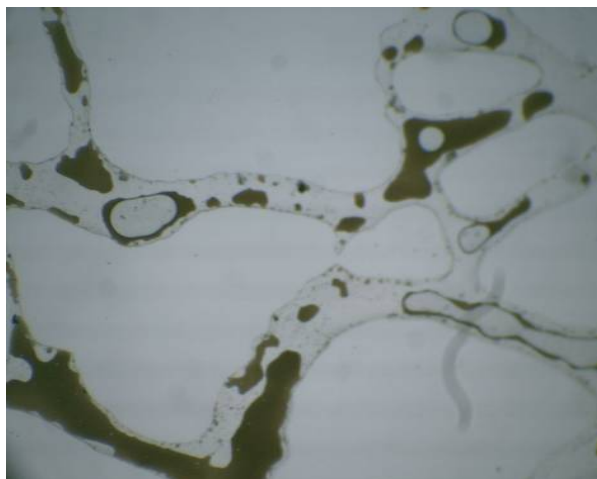
From different observing point, the startup of oil drop in microscopic pore and distribution of residual oil are shown in Fig.6.



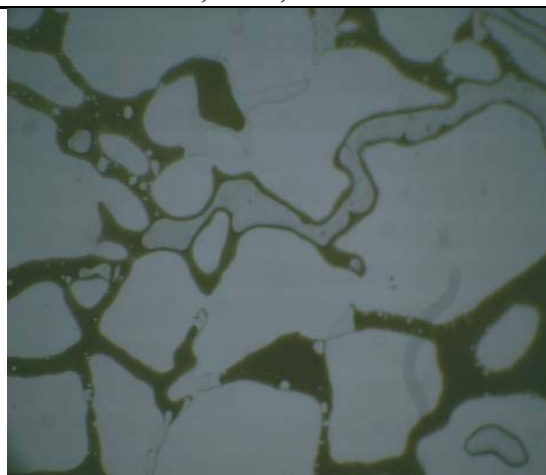
Water flooding (WF)



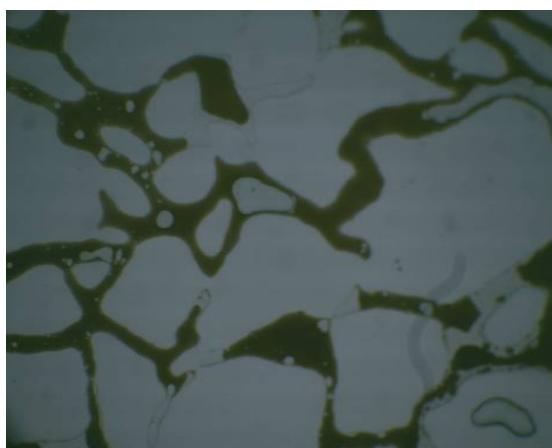
Primary polymer flooding (PPF)



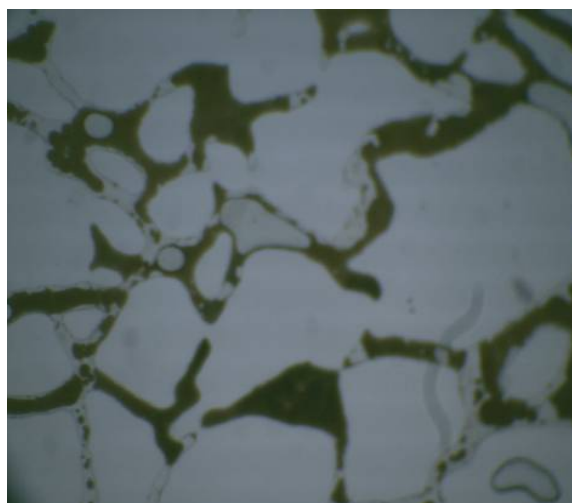
Secondary polymer flooding (SPF)
(a) Point H (with highest permeability)



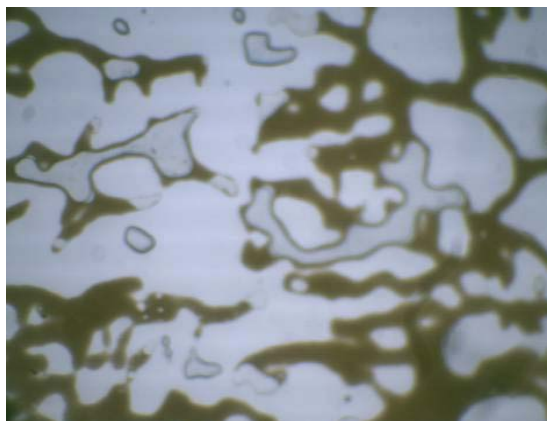
Water flooding (WF)



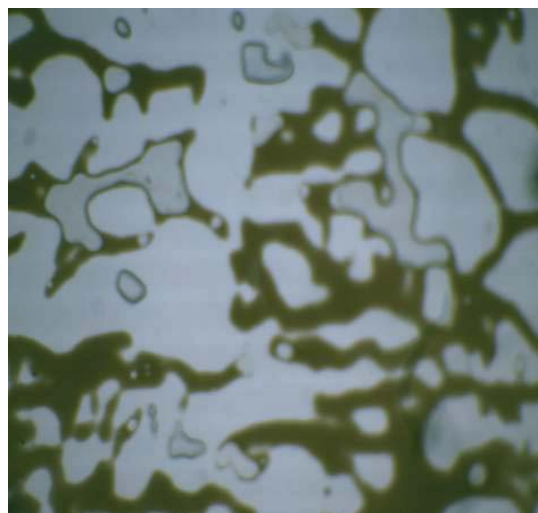
Primary polymer flooding (PPF)



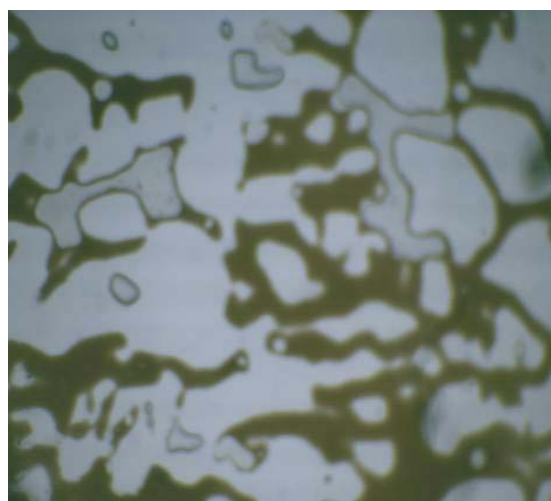
Secondary polymer flooding (SPF)
(b) Point M (with medium permeability)



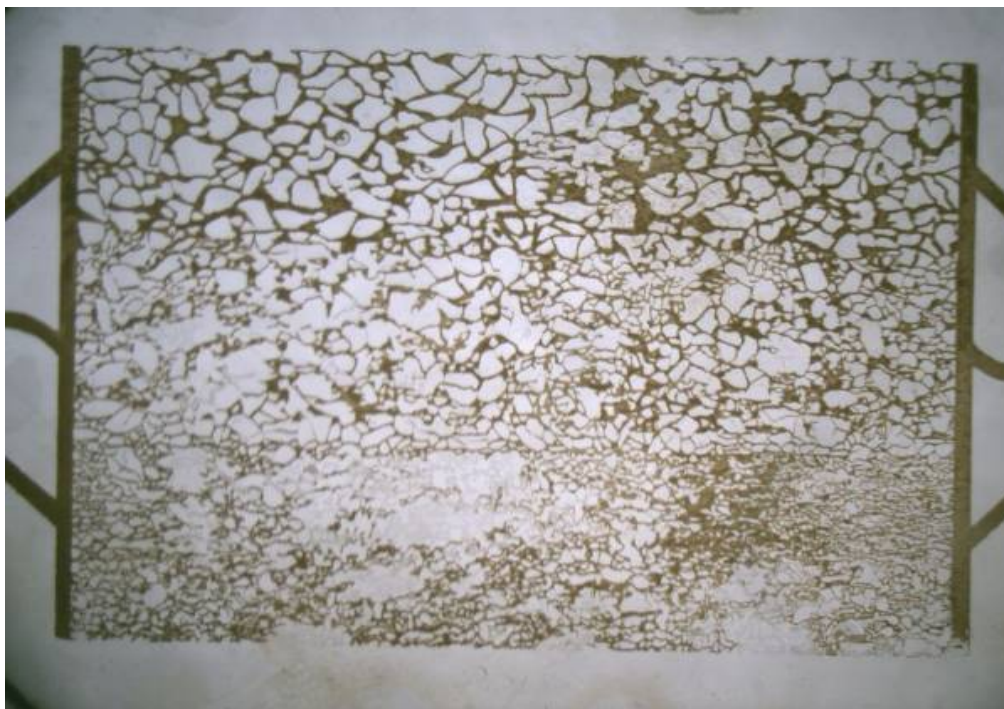
Water flooding (WF)



Primary polymer flooding (PPF)



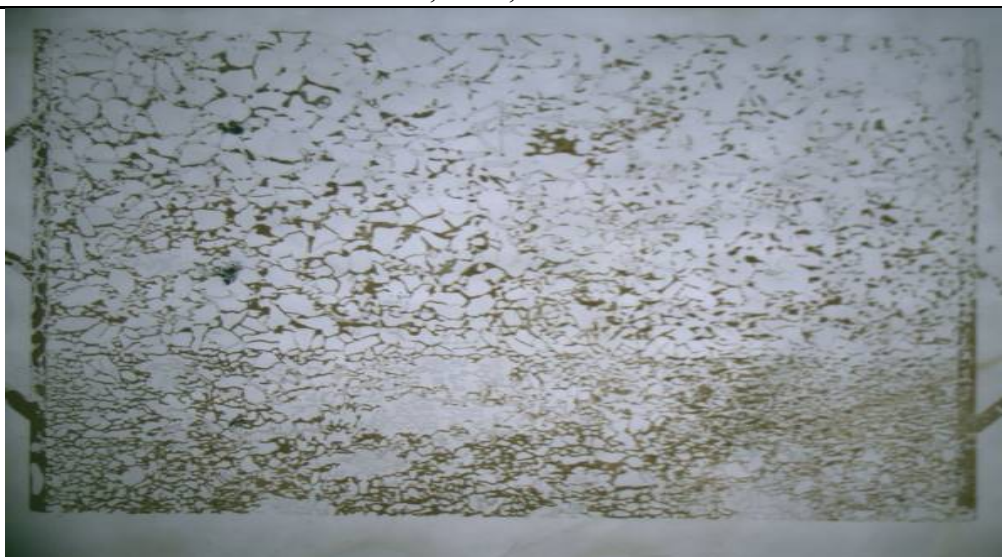
Secondary polymer flooding (SPF)
(c) Point L (with lowest permeability)



Saturated oil



WF



PPF



SPF

(d) Distribution of residual oil

Figure 6: Start-up of oil drop in microscopic pore and distribution of residual oil with SPF

From Fig.6 (a), point H locates in highest permeability layer, so the flowing resistance relatively small, and accordingly oil are effectively started and accelerated. For the moderately permeable layer (point M), a part of larger pore with good connectivity can be swept. For the layer with lowest permeability, in the outlet no oil could be observed. Thence, during water flooding, most of water flows through the layer with high permeability, and the water cut rises rapidly. From the Fig.6 (b), in the process of primary polymer flooding, because of high viscosity of polymer solution, oil in pores and throats located in most and moderately permeable layer can be further started, and it can be observed that column residual oil can be driven out with high sweeping efficiency. To further control water profile and improve recovery, secondary polymer flooding is conducted. Remaining oil in low permeability layer can be partly started relative to primary polymer flooding, so oil saturation in medium and low

permeability layers decreases. It must be noted that after SPF yet residual oil saturation is relatively high especially in low permeability, so it is essential to discover new technology to further improve oil recovery.

3. FIELD APPLICATION

3.1 Basic Parameters

Henan Xia'ermen oilfield is located at medium-high spot of Xia'ermen fracture structural belt east of Biyang sunken. The basic parameters of oil group H2II and H2III are listed in Table 4.

Table 4: Basic parameters of oil group H2II and H2III

Parameters		H2 II	H2III
Oil bearing area(km ²)		1.32	2.5
Reserves in place (×10 ⁴ t)		259	444
Average effective pay thickness (m)		14.2	16.8
porosity (%)		23.7	23.88
permeability (μm ²)		2.33	2.105
Initial oil saturation (%)		70	70
depth (m)		928~1050	1095
temperature (°C)		50	52.8
Original Pressure(MPa)		9.8	10.44
Saturation pressure(MPa)		8.0	7.84
Formation water	typre	NaHCO ₃	NaHCO ₃
	TDS(mg/L)	2127	2065
	C ^l (mg/L)	128	88
Physical properties of crude oil in HTHP	Original GOR (m ³ /t)	27.2	26
	Volume factor	1.077	1.083
	Underground viscosity(mPa.s)	72.6	58.3
	Density(g/cm ³)	0.877	0.866
	Compressibility(×10 ⁻⁶ MPa ⁻¹)	6.8	7.14
Ground properties of crude oil	Specific density	0.9297	0.9191
	Ground viscosity(mPa.s)	121	84
	Freezing point(°C)	29	27
	Wax content (%)	17.63	17.59
	Sulfur content (%)	0.22	0.17
	Resin and asphaltene content (%)	27.45	24.53

3.2 Development stages

The different development stages are listed in Table 5.

Table 5: Different development stages

		Water cut ascending rate (%)	Stage recovery (%)	stage injecting-producing ratio
H2II	Initial stage (1978.9~1981.12)	4.0	6.7	1:1.87
	Steady stage (1982.1~1988.12)	3.6	10.0	1:3.9
	Well pattern infill (1989.1~1996.7)	----	7.3	1:1.1
	Primary Polymer flooding stage (1996.8~2000.3)	----	8.29	----
	Subsequent water flooding (2000.4~2006.7)	----	5.06	----
	Before SPF (average)	93.16(water cut)	37.35	1:1.09
	SPF(2006.7-)			
H2III	Before SPF (similar to H2II)	90.36	35.5	1:1.14

3.3 Result Analysis of SPF

Comparing to PPF, SPF is more effective to increase injecting pressure (see Table6), which is favorable for starting low-medium permeability layer and improving profile.

Table 6: Comparison of injecting index between PPF and SPF of oil groups H2 II and H2III

	Stage	Number of polymer injectors	C_p (mg/l)	Plug (PV)	Injecting rate (PV/a)	Pressure before (MPa)	Maximum pressure (MPa)	Increased pressure (MPa)
H2 II	PPF	7	1000	0.43	0.10	2.4	5.6	3.2
	SPF	10	1800+2200	0.31	0.13	3.9	9.4	5.5
H2III	PPF	11	1000	0.42	0.12	4.4	10.0	5.6
	SPF	20	1800	0.33	0.14	4.7	11.1	6.4

Up to 2008.12, for H2II, quality of injected polymer powder is 1922t, the ratio of responding producer (RPR) is 88.23%, the oil production increases from 61.9t/d to 106.5t/d, the comprehensive water cut decreases from 92.7% to 83.6%, incremental increased oil production is 2.19×10^4 t. For H2II, quality of injected polymer powder (Q_p) is 3038t, the ratio of responding producer is 63.1%, the oil production increases (IOP) from 127.7t/d to 168.6t/d, the comprehensive water cut decreases (DWC)

from 91.8% to 90%, incremental increased oil production(IIOP) is 3.52×10^4 t, the production results of group H2II and H2III can be seen from Table7.

Table 7: Production results of group H2II and H2III

	C_p (mg/l)	Plug(PV)	Q_p (t)	IOP(t/d)	DWC (%)	RPR (%)	IIOP ($\times 10^4$ t)	IOR (%)
H2II	1800+2200	0.31	1922	44.6	9.1	88.23	2.19	1.32
H2III	1800	0.33	3292	40.9	1.8	63.1	3.52	1.35

From the above Table7, we can see that the secondary polymer concentration for H2II is adjusted to 2200mg/L, the optimum concentration from experiments, which is one of the reasons that the IOP, DWC, RPR of group H2II is higher than that of H2III. The above field results are the further proofs of the feasibility of secondary polymer flooding; also the optimum polymer concentration from experiments is verified from the field data.

4. CONCLUSIONS

In this paper, laboratory experiments were conducted to investigate feasibility of secondary polymer flooding. With microscopic visible glass physical models, further start-up of oil drops with secondary polymer can be observed distinctly. In the mean time, macroscopic heterogeneous core tests were carried out. The results shows that 3%~7% of further enhanced recovery and 20% decreased water cut can be obtained, and water profile can be improved to some extent after secondary polymer flooding. Thence, it is proved that secondary polymer injection after primary polymer can indeed further improve recovery and the technology of secondary flooding is feasible. Moreover, laboratory optimum concentration of 2200mg/L is determined and the field results prove its feasibility. On the basis of laboratory results, from 2007 to 2008, filed trial with above optimum parameters were implemented. Up to 2008.12, water cut decreased from 92% to 83%, and cumulative increased crude oil of 5.71×10^4 t. The success of secondary polymer flooding technology provides reference for the development of oil fields after primary polymer flooding in China and other regions in the whole world.

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