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and
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Polymer solution analysis experiment

According to the practical demand of oilfield, instrumental analysis, physical simulation and reservoir engineering theory are applied for the experimental study on the influence of polymer concentration on the seepage characteristic of polymer solution, molecular coil dimension D_h and its distribution, oil displacement effect, besides, an analysis is made on the enhanced oil recovery mechanism by compound polymer flooding with broad relative molecular mass distribution. It turns out that for polymer with the same concentration, the resistance coefficient F_R and residual resistance coefficient F_{RR} decrease as core permeability increases; for the same core permeability, F_R and F_{RR} increase as polymer concentration increases. For polymer with broad relative molecular mass distribution compounded by 3 polymers (middle molecule, high molecule and ultrahigh molecule), with larger proportion of ultra-high-molecule polymer, the molecular coil dimension D_h in compound polymer increases. The physical simulation indicates that while the polymer solution viscosity is identical, the flooding effect of compound polymer is better than that of high molecular polymer, and with increase of proportion of ultra-high-molecule polymer in compound polymer, the growth of recovery efficiency also increases.

Keywords: High concentration polymer flooding; resistance coefficient; residual resistance coefficient; molecular coil dimension; compound polymer.

Preface

Polymer flooding has been widely given attention due to its great economic benefit and social benefit for production of oilfield, while the recovery rate of polymer flooding only increases by approximately 10%, and there is still about 50% of crude oil remained underground after polymer flooding. In order to tap the potential of underground oil remaining drastically, and maintain the production scale of the existing oilfield, it is urgent to adopt new technologies for further enhanced oil recovery after polymer flooding, of which high-concentration polymer flooding is a significant technology. Relative to the polymer solution with general concentration, in the high concentration polymer, the intermolecular entanglement becomes stronger, and the molecular coil gyration radius increases; thus, the oil-displacing agent has higher seepage resistance in porous medium during flowing, this greatly enlarges the swept volume, and substantially enhances the oil recovery factor. However, the injection pressure of polymer flooding system rises with the increase of polymer concentration and molecular mass, which restricts the injection concentration of polymer flooding to some extent, and influences the polymer flooding effect. If the higher injection pressure is settled and the polymer injection scheme is optimized based on the practical field, it will greatly improve the economic benefit of oilfield and significantly support the sustainable development of oilfield.

1. Influence of polymer concentration on oil flooding

1.1 EXPERIMENTAL MATERIALS

The polymer (HTPW-112) has a relative molecular mass of 2500×10^4, and effective content of 88%; quartz sand epoxy bonding artificial core has a geometric dimension of $\varphi\,2.5\times10$ (cm), and the gas log permeability Kg is respectively 100×10^{-3}, 500×10^{-3}, 1000×10^{-3}, 1500×10^{-3}, 2000×10^{-3} and $3000\times10^{-3}\mu m^2$. Hitachi S-3400N electron microscope is used to measure the aggregation state of polymer molecule in polymer solution, American LVDV-II+PRO type Brookfield viscometer measures the viscosity of polymer solution; American Bowing TX-500 type spinning drop interfacial tensiometer measures interfacial tension between polymer solution and crude oil. Core flooding experimental devices include constant-flux pump, pressure sensor, core holding unit, hand pump, intermediate container, etc., which should be placed in calorstat of 53ºC except for constant-flux pump and hand pump.

1.2 RESISTANCE COEFFICIENT AND RESIDUAL RESISTANCE COEFFICIENT

The effect of core permeability and polymer concentration on the resistance coefficient (F_R) and residual resistance coefficient (F_{RR}) of polymer solution is shown in Table 1.

Apparent in Table 1, for polymer with the same concentration, F_R and F_{RR} decrease as core permeability

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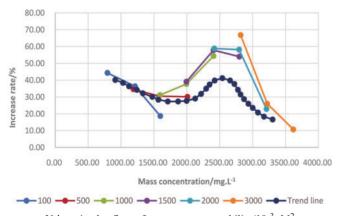
TABLE 1: EFFECT OF CORE PERMEABILITY AND POLYMER CONCENTRATION ON F_R AND F_{RR} OF POLYMER SOLUTION

	Permeability /$10^{-3}\mu m^2$	Polymer /mg·L⁻	Viscosity /mPa·s	Resistance coefficient		Residual resistance coefficient	
				F_R	Increase rate/%	F_{RR}	Increase rate/%
1	100	400	2.91	8.81	0	4.6	0
		800	6.91	15.81	44.31	8.42	45.21
		1200	17.02	25.02	36.8	12.8	34.4
		1600	35.61	30.81	18.81	18.2	29.71
2	500	800	6.92	9.0	0	5.4	0
		1200	17.11	13.82	34.8	8.3	34.91
		1600	35.53	20.0	31.0	13.0	36.22
		2000	66.02	28.81	30.6	20.2	35.6
3	1000	1200	17.02	11.0	0	6.4	0
		1600	35.81	16.0	31.31	9.6	33.31
		2000	66.24	26.0	38.52	15.93	39.61
		2400	122.24	57.52	54.82	33.5	52.52
4	1500	1600	35.64	12.8	0	7.0	0
		2000	66.12	21.1	39.3	11.9	41.21
		2400	122.01	51.12	58.71	27.4	56.61
		2800	168.82	111.9	54.31	58.1	52.8
5	2000	2000	66.03	18.0	0	8.1	0
		2400	122.5	43.0	58.1	21.5	62.3
		2800	170.12	103.0	58.32	51.5	58.3
		3200	228.0	135.0	23.71	68.9	25.32
6	3000	2400	122.12	31.02	0	15.2	0
		2800	168.91	94.81	67.3	46.91	67.63
		3200	228.3	128.4	26.22	64.21	26.9
		3600	281.02	144.8	11.33	70.91	9.42

increases; for the same core permeability, F_R and F_{RR} increase as polymer concentration increases. The further analysis shows that when the polymer mass concentration increases to 1600mg/L from 400, the growth of F_R and F_{RR} declines; while the concentration increases to 2800mg/L from 1600, the growth of F_R and F_{RR} rises; when the concentration exceeds 2500mg/L, the growth of F_R and F_{RR} declines again (Figs.1 and 2).

In conclusion, when the polymer mass concentration is about 2500mg/L, the growth of F_R and F_{RR} reaches the maximum, showing strong capacity of fluid diversion, which is recommended the polymer concentration limit of high-concentration polymer flooding for targeted oil reservoir.

Values in the fig. refer to core permeability/$10^{-3}\mu M^2$
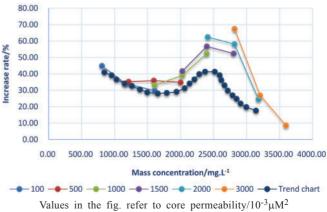Fig.1 Relationship between polymer concentration and resistance coefficient

Values in the fig. refer to core permeability/$10^{-3}\mu M^2$
Fig.2 Relationship between polymer concentration and residual resistance coefficient

TABLE 2: POLYMER MOLECULAR COIL DIMENSION D_h (POLYMER CONCENTRATION 100mg.L^{-1},55°C)

Polymer	Middle molecule	High molecule	Ultra high molecule	Fh1 (20:75:5)	Fh2 (15:75:10)	Fh3 (10:75:15)	Fh4 (5:75:20)
D_h/nm	182.51	192.91	196.32	105.41	119.11	170.42	213.51

TABLE 3: FLOODING TEST RESULT (POLYMER CONCENTRATION 1000mg.L^{-1})

Scheme no.	Name of main slug	Working viscosity/mPa.s	Oil saturation/%	Recovery efficiency/%		
				Water flooding	Chemical flooding	Enhance
1	High molecular polymer solution	42.11	71.49	38.85	46.99	8.14
2	Fh1 solution	39.81	71.32	39.97	48.01	8.05
3	Fh2 solution	42.41	71.32	40.12	49.43	9.29
4	Fh3 solution	46.62	71.62	40.03	50.44	10.41
5	Fh4 solution	48.61	71.52	40.01	50.93	10.93

2. Influence of polymer relative molecular mass on oil flooding

2.1 EXPERIMENTAL MATERIALS

Polymer is the partly hydrolyzed polyacrylamide (HPAM) produced by Daqing Refining & Chemical Company. It includes 3 polymers with relative molecular mass of 1400×10^4 (called "middle molecule"), 1900×10^4 (called "high molecule") and 2500×10^4 (called "ultrahigh molecule") respectively, hydrolyzing degree of 25.4%, 25.8% and 26.5% respectively, and solid content of 88%. 4 compound polymers (expressed with middle molecule, high molecule and ultra high molecule) mixed by the above 3 polymers according to different proportion are also included, and are indicated as Fh1(20:75:5), Fh2(15:75:10), Fh3(10:75:15) and Fh4(5:75:20) respectively.

Experimental core is the columnar quartz sand epoxy bonded 2D longitudinal three-layer heterogeneous core, including high, middle and low permeable zones; the gas log permeability is respectively $900 \times 10^{-3} \mu m^2$, $300 \times 10^{-3} \mu m^2$ and $100 \times 10^{-3} \mu m^2$. The geometric dimension of core (height×width×length) is 4.5cm×4.5cm×30cm, and major instruments are BI-200SM type multi-angle dynamic/static light scattering instrument (Brookhaven Instruments Corporation), DV-II type Brookfield viscomeer (Brookfield) and core flooding experimental device.

2.2 EXPERIMENTAL METHODS

2.2.1 Determination of molecular coil dimension

BI-200SM type multi-angle dynamic/static light scattering instrument is adopted for test, the scattering angle is 90 and the test temperature is 55°C during determination. Measured data are shown in Table 2.

2.2.2 Flooding experiment

Core flooding experimental devices, applied to test the oil flooding result, include constant-flux pump, pressure sensor, core holding unit, hand pump, intermediate container, etc., which should be placed in calorstat of 53°C except for constant-flux pump and hand pump.

The specific flooding steps are:

1. Vacuumize the model, saturate formation water and measure pore volume of model under room temperature;

2. Saturate simulated oil for model and calculate the oil saturation under 55°C;

3. Flood to the designated moisture content and measure the water displacement recovery under 55°C;

4. Inject oil displacement agent, further flood to 98% of moisture content and calculate the recovery ratio under 55°C; the injection speed is 0.3mL/min.

2.3 EXPERIMENTAL DATA ANALYSIS

Polymer molecular coil dimension D_h of 7 polymer solutions is shown in Table 3, and D_h distribution is shown in Fig.3.

As can be seen from Table 2, molecular coil dimension of 3 common polymers (middle molecule, high molecule and ultrahigh molecule) increases with the increase of relative molecular mass; as the proportion of high relative molecular mass increases, molecular coil dimension D_h of 4 compound polymers increases, and the number of long chain and longer chain segments of polymer molecule increases. With the
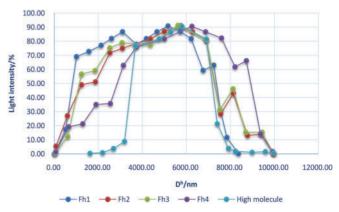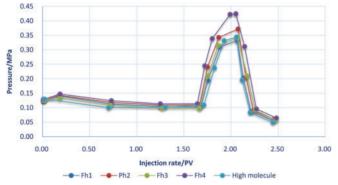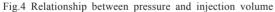

Fig.3 Polymer D_h distribution curve (polymer concentration 100mg.L^{-1}, 55°C)

increase of the number of long chain segments for polymer molecule, the internal rotation of molecular single bond becomes more complicated, salvation rate is larger, and the random coil dimension also becomes larger. A further study shows that in compound polymer, molecular coil dimension of Fh4 is greater than the maximum molecular coil dimension in 3 common polymers, while the molecular coil dimension of Fh1, Fh2 and Fh3 is smaller than the minimum molecular coil dimension in 3 common polymers.

Visible in Fig.1, D_h distribution of compound polymer is broader than that of single polymer, and the compound polymer FP4 with ratio of "5:75:20" shows the broadest distribution. For polymer with broad relative molecular mass distribution compounded by 3 polymers, its distribution crest shifts right gradually as the proportion of high relative molecular mass increases. A further study shows that D_h distribution of compound polymer with broad relative molecular mass distribution is not as concentrated as that of polymer with narrow relative molecular mass distribution, but has larger fluctuation of curve. The molecule segments of 3 polymers (middle molecule, high molecule and ultra high molecule) vary greatly in length, flexibility, rigidity and curl degree, the contact, interpenetration and entanglement between each other are uneven, there is great difference in acting force between molecular chains, chains, macromolecules, the curl degree of polymer molecular chain differs greatly, and the hydraulic volume of random coil has

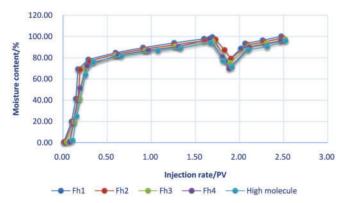Fig.4 Relationship between pressure and injection volume

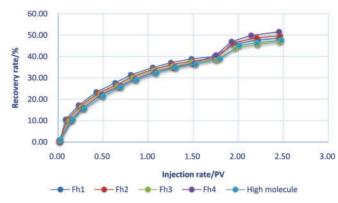Fig.5 Relationship between moisture content and injection volume

Fig.6 Relationship between recovery efficiency and injection volume

big difference, therefore, the distribution curve of compound polymer molecular coil dimension fluctuates greatly.

2.4 ANALYSIS ON OIL DISPLACEMENT EFFICIENCY

Physical simulation flooding test scheme and result are shown in Table 3, and the relationship between injection pressure, moisture content, recovery efficiency and injection volume is shown in Figs.4, 5 and 6.

Experimental core is three-tier heterogeneous core, and the permeability is respectively $900 \times 10^{-3} \mu m^2$, $300 \times 10^{-3} \mu m^2$ and $100 \times 10^{-3} \mu m^2$.

As can be observed from Table 3, Figs.4, 5 and 6, under almost same viscosity, the chemical flooding pressure of compound polymer (Fh2) is high, the moisture content declines rapidly, the enhanced oil recovery of its chemical flooding is generally higher than that of single "high molecular" polymer flooding; with larger proportion of ultra-high-molecule polymer in compound polymer, its chemical flooding pressure is higher, the moister content declines faster, and the enhanced oil recovery is higher. Compound polymer has a broader relative molecular mass distribution, the radius of gyration of molecule is unequal in size, and the hydrodynamic radius is different when it flows in pore paths of oil layer. Large-size molecule makes for plugging of high permeable zones, and the increase of suction differential pressure at middle and low permeable zones; small-size molecules can enter smaller pores in oil layer and reduce the inaccessible pore volume. As a result, by adopting compound polymer flooding, polymers with different relative molecular masses can pass through the pore throat of corresponding size, and the swept volume is effectively expanded, thus the low permeable zone can be employed in an effective way.

3. Conclusion

For polymer with the same concentration, F_R and F_{RR} decrease as core permeability increases; for the same core permeability, F_R and F_{RR} increase as polymer concentration increases. When the polymer mass concentration increases to 1600mg/L from 400, the growth of F_R and F_{RR} declines; while the concentration increases to 2500mg/L from 1600, the growth of F_R and FRR rises; when the concentration exceeds

2500mg/L, the growth of F_R and F_{RR} declines again.

For polymer with broad relative molecular mass distribution compounded by 3 polymers (middle molecule, high molecule and ultra high molecule), with larger proportion of ultra-high-molecule polymer, the molecular coil dimension D_h in compound polymer increases depending on the viscosity, and also becomes broader compared to high molecular polymer. The physical simulation indicates that while the polymer solution viscosity is identical, the flooding effect of compound polymer is better than that of high molecular polymer, and with increase of proportion of ultra-high-molecule polymer in compound polymer, the growth of recovery efficiency also increases.

Acknowledgements

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