

Experimental Study on Influencing Factors of Resistance Coefficient and Residual Resistance Coefficient in Oilfield Z

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How to cite this paper: Wang, X.R., Ge, L.Z., Liu, D., Zhu, Q. and Zheng, B. (2019) Experimental Study on Influencing Factors of Resistance Coefficient and Residual Resistance Coefficient in Oilfield Z. *World Journal of Engineering and Technology*, 7, 270-281.

<https://doi.org/10.4236/wjet.2019.72018>

Received: January 25, 2019

Accepted: March 22, 2019

Published: March 25, 2019

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Abstract

In order to clarify the major influence factors of resistance coefficient and residual resistance coefficient, so as to provide the basis for optimizing the polymer flooding schemes in oilfield Z of Bohai Sea, artificial cores were made by simulated the characteristic parameters of real reservoir and the spacing of production-injection wells. The main parameters considered include reservoir permeability, polymer solution concentration and polymer injection rate. Core experiment of polymer flooding was taken by considering all the main parameters. The result showed that resistance coefficient and residual resistance coefficient decrease with the increase of core permeability. Resistance coefficient and residual resistance coefficient increase with the increase of concentration of polymer solution. The increment of displacement pressure in low permeability core is higher than in medium and high permeability core. The resistance coefficient increase with higher displacing velocity, and the increment in high permeability core is higher than in low permeability core. The displacement velocity has little effect on the residual resistance coefficient. The experimental results can effectively guide the formulation of polymer flooding scheme in offshore oilfields, and optimize the appropriate injection rate and concentration of polymer solution for different properties of reservoirs, thus ensuring the effectiveness of polymer flooding in offshore oilfields.

Keywords

Resistance Coefficient, Residual Resistance Coefficient, Polymer Flooding, Laboratory Experiment, Offshore Oilfield

1. Introduction

Compared with the onshore oilfields, offshore oilfields have characteristic with

higher development investment costs, shorter economic life and more difficulty for development. Therefore, in order to reduce development costs and improve economic benefits, offshore oilfield mostly chose natural water energy or water flooding methods to supplement formation energy. But with the increase of oilfield development age, the water cut of oilfield rises rapidly, which leads to a large decline in production and a lower economic benefit, especially for the water flooding oil field; injected water is liable to form channeling, oil production following declined seriously as a result. The degree of water cut increase can be restrained for some extent through profile control of injection wells and water plugging in production wells. However, the short valid period of general measures does not meet the strategic needs of offshore oilfield development. Chemical flooding can solve the problem of water flooding to a great extent [1]-[6], in which polymer flooding can significantly improve water-oil mobility ratio and expand sweep volume of displacement phase; it can effectively block the channeling channel in high permeability layer and reduce the ineffective displacement of injected water. Therefore, polymer flooding has become an important way to enhance oil recovery in offshore oilfield development.

Polymer flooding technology began in the United States in the 1960s, but mostly in small-scale field tests. From 1980s to 1990s, this tertiary enhance oil recovery technology started to be popularized in large oilfields such as Daqing and Shengli oilfields in China, and that had achieved optimistic application results; the oil recovery had been enhanced about 12% more in those oilfields. In the early 21st century, polymer flooding has been widely used in some countries in Eastern Europe, North America, South America and offshore oilfields in China [7] [8] [9]. With the development of research technology, the application scope of polymer flooding is increasing; the application limit is widening and the application cost is decreasing. Therefore, more and more offshore oilfields begin to choose polymer flooding as the key technology for maintaining stable production. For specific oilfields, the effect of polymer flooding is mainly reflected in two aspects: one hand is the ability to decrease the water and oil mobility ratio. That's defined as called resistance coefficient; one other hand is the ability to decrease the permeability of the reservoir. That's defined as residual resistance coefficient. Therefore, resistance coefficient and residual resistance coefficient are important indexes for evaluating polymer properties [10]-[15]. These two indexes are largely influenced by reservoir conditions and fluid properties, and the existing research on the factors affecting resistance coefficient and residual resistance coefficient is mainly carried out in the onshore oilfields, which with lower production rate and smaller injection-production spacing [16] [17] [18]. However, compared with onshore oil fields, offshore oilfields have the characteristics of fast production speed, large injection-production well spacing and strong reservoir heterogeneity. Hence, experience of onshore oilfields cannot be directly copied. In this paper, the reservoir parameters and fluid properties of oilfield Z were taken as examples; the experimental study on influencing factors of resistance coefficient and residual resistance coefficient was conducted, which

provides an important basis for the scheme design of polymer flooding in oilfield Z.

2. Introduction of Bohai Oilfield Z

Oilfield Z is located in the northern Liaodong Bay of the Bohai Sea in China, the mainly oil-containing formations is lower Dongying formation second member, its sedimentary microfacies is delta front. This reservoir with the physical properties of medium to high porosity and permeability, the average permeability is range from 650 mD to 2650 mD, and the average porosity is range from 25.5% to 31.2%. The heterogeneity of this oilfield is strong, and the permeability contrast is 3.8 to 4.2, its fluid belongs to medium viscosity crude oil, the average viscosity is range from 10.6 mPa·s to 26.3 mPa·s. Nature water energy development method was chosen in the early stage, due to the pressure of the reservoir dropped seriously, the development method changed into water flooding. However, the water cut of the oilfield raised rapidly because of the heterogeneity of the reservoir, the decline rate of oil production still large. After research of various methods to improve oil recovery, polymer flooding is determined as the main method to improve oil recovery.

3. Experiment Preparation

3.1. Experimental Materials and Devices

The polymer solution used in the experiment is polyacrylamide solution, the water used for displacement is made up in simulate with the water in field injection, and the experiment cores are artificial, which divided into three permeability levels: high, medium and low, so as to simulate the three main reservoir layers in oilfield Z, the basic data of cores is shown in **Table 1**. The experimental devices include thermostat, core holder, Teledyne Isco high-pressure and high-precision plunger pump, pressure sensor, etc. The experimental temperature simulates the reservoir temperature of Z oilfield at 63°C. The injection velocities are set at 0.35 mL/min and 0.50 mL/min respectively.

3.2. Experimental Fundamental and Scheme

According to the existed literature introduction [19], resistance coefficient is defined as the ratio of water mobility to polymer solution mobility, it is usually represented by R_f . It reflects the ability of polymer solution to control displacing phase mobility in porous media during polymer flooding.

$$R_f = \frac{\lambda_w}{\lambda_p} = \frac{(K_w/\mu_w)}{(K_p/\mu_p)} \quad (1)$$

In the formula, λ_w is the mobility of water; λ_p is the mobility of polymer solution; K_w is the relative permeability of water; K_p is the relative permeability of polymer solution; μ_w is the viscosity of water; μ_p is the viscosity of polymer solution flooding. According to Darcy porous flow formula, Formula (1) can be changed as follows:

Table 1. The basic data of experimental cores.

Core No.	Diameter (cm)	Length (cm)	Porosity (%)	Permeability (mD)
1-1	2.43	6.58	31.2	2480.3
1-2	2.49	6.89	25.5	976.6
1-3	2.52	6.63	31.0	658.2
2-1	2.48	7.29	29.6	2519.0
2-2	2.49	6.89	25.5	1189.1
2-3	2.48	7.28	28.6	728.8
3-1	2.43	6.47	31.2	2642.1
3-2	2.45	6.29	25.5	1333.2
3-3	2.51	6.64	29.0	675.6
4-1	2.46	6.83	30.3	2558.1
4-2	2.47	6.55	26.5	1353.9
4-3	2.42	7.19	29.8	663.1

$$R_f = \frac{Q_w \cdot \Delta P_p}{Q_p \cdot \Delta P_w} \quad (2)$$

In the formula, Q_w is the flow of water through cores; Q_p is the flow of polymer solution through cores; ΔP_w is the differential pressure of water flooding; ΔP_p is the differential pressure of polymer flooding.

Residual resistance coefficient is the ability of polymer solution to reduce permeability of porous media. It is the ratio of water relative permeability of porous media before and after polymer flooding. It is usually represented by R_k , it reflects the degree of permeability decline in porous media.

$$R_k = K_{wb} / K_{wa} \quad (3)$$

In the formula, K_{wb} is the water relative permeability before polymer flooding; K_{wa} is the water relative permeability after polymer flooding.

The factors which affecting the resistance coefficient and residual resistance coefficient can be conferred through Formula (1) to Formula (3), the permeability of the core, the flow of the displacing phase and the viscosity of polymer solution, in addition, formation water salinity and reservoir temperature also have some influence on resistance coefficient and residual resistance coefficient, whereas, for destine oilfield, the change of water salinity and reservoir temperature is small, thus the viscosity of polymer solution, the core permeability and the velocity of polymer solution flooding are the main factor of this research. Among the factors, the viscosity of polymer solution is positively correlated with the concentration of polymer solution. Experimental schemes are shown in **Table 2**.

Table 2. Experimental schemes.

Core No.	Concentration of polymer solution (mg/L)	Velocity of flooding (mL/min)	Flooding method		
			Water flooding first time	Polymer flooding	Water flooding second time
1-1, 1-2, 1-3	800	0.35			
		0.50			
2-1, 2-2, 2-3	1000	0.35			
		0.50	Until Porous flow steady	Until polymer flooding 2.0 PV	Until Porous flow steady
3-1, 3-2, 3-3	1200	0.35			
		0.50			
4-1, 4-2, 4-3	1500	0.35			
		0.50			

3.3. Experimental Procedures

1) Vacuumize the core and saturated with water, the core is loaded into the core holder and the temperature is set to 63 C. Injection of water at a flow rate of 0.35 mL/min under confining pressure, measured pressure difference and flow rate during steady flow and calculating permeability;

2) Polymer flooding at a flow rate of 0.35 mL/min, measured pressure difference and flow rate during steady flow (injection 2.0 PV polymer solution);

3) Water flooding second time at a flow rate of 0.35 mL/min after polymer flooding, record pressure variation with time and the pressure difference at steady flow;

4) Replacement of core and polymer concentration, repeat steps 1) to 3);

5) Water flooding, polymer flooding and secondary water flooding at the speed of 0.50 mL/min under confining pressure, repeat steps 1) to 4);

6) The resistance coefficient and residual resistance coefficient are calculated and the variation law is summarized.

Experimental procedures are shown as **Figure 1**.

4. Experimental Results and Analysis

4.1. Effects of Core Permeability

Reservoir in oil field Z is highly heterogeneous, so it is necessary to study the influence of different permeability level on polymer properties. Resistance coefficients of different core permeability tests are shown in **Figure 2**, it indicates that resistance coefficients decrease with permeability increase. This is because the lower the permeability, the smaller the pore radius of the core, the higher the shear rate of polymer solution porous flow through the core, the higher the tensile stress, so the elastic effect of displacement phase is enhanced. At the same

time, the pore radius of low permeability core is small, which leads to larger specific surface area of core, so more polymer molecules were adsorbed. Moreover, the ratio of polymer molecular aggregates to core porous size increases, the mechanical trapping effect of core media on polymer molecules is enhanced, so the retention of polymer molecules in core porous is further aggravated. Therefore, in low permeability cores, the porous flow resistance of polymer solution is greater and the resistance coefficient is larger.

As can be seen from **Figure 3**, the variation trend of residual resistance coefficient with core permeability is consistent with that of resistance coefficient, residual resistance coefficient increases with the decrease of core permeability. This is because with the decrease of core permeability, the ratio of polymer molecules aggregates size to effective core porous size increases, and the resistance of polymer molecules through pore throat structure increases. At the same time, the ability of core porous media to capture polymer is enhanced, and the volume effect of polymer molecular hydrodynamics is enhanced. At the same time, the pore throat structure of low permeability cores is more compact, so the specific surface area is larger and more polymer molecules can be adsorbed. Therefore, the residual resistance coefficient increases with the core permeability decreases.

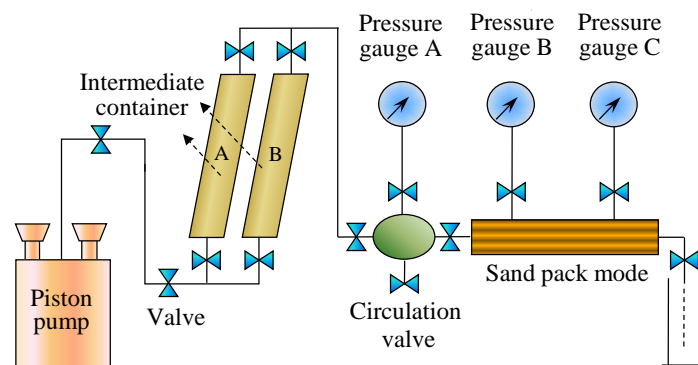


Figure 1. Experimental device and processes.

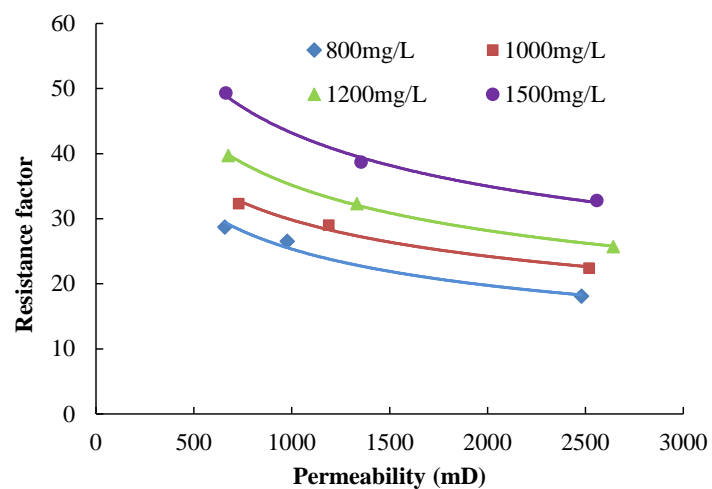


Figure 2. Effects of core permeability for resistance coefficient.

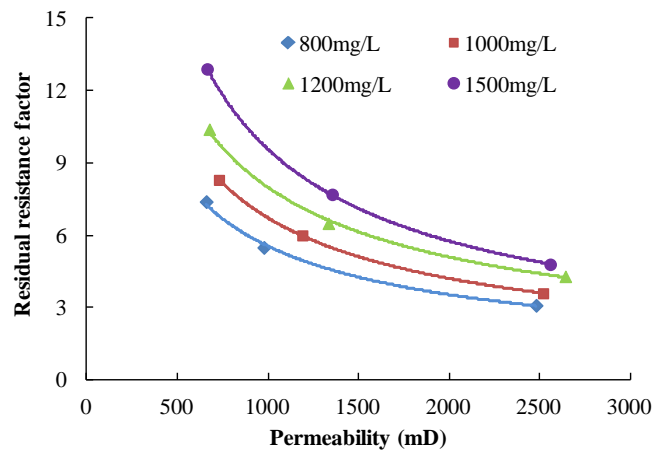


Figure 3. Effects of core permeability for residual resistance coefficient.

4.2. Effects of Polymer Solution Concentration

Figure 2 also illustrates the effect of polymer solution concentration on resistance coefficient, it can be seen that with the increase of polymer concentration, the resistance coefficient of cores with different permeability tends to increase. This is because with the increase of the concentration of polymer solution, the association between polymer molecules will be strengthened, and the size of the molecular aggregates will also increase. The amount of seepage adsorption, mechanical trapping and hydrodynamic trapping of polymer molecules in core porous structure will also increase. Therefore, the resistance of polymer solution flow through porous structure increases.

Figure 3 also illustrates the effect of polymer solution concentration on the residual resistance coefficient, the higher the polymer solution concentration, the greater the residual resistance coefficient. This is because with the increase of concentration, the swept volume of polymer solution increases, and polymer molecules enter more core porous volume, resulting in the increase of residual resistance coefficient. For low permeability cores, the degree of reducing effective permeability by high concentration polymer solution is more obvious, and the residual resistance coefficient is larger. In addition, as shown in **Figure 4**, with the increase of polymer solution concentration, the flooding pressure difference of the model increases, especially for low permeability cores. If the concentration of polymer solution reaches 1500 mg/L, the flooding pressure difference increases twice as much as that of 800 mg/L. For larger flooding pressure difference will cause high injection pressure exerted on injection wells in actual production, it is difficult to realize in offshore oilfields which with limited capacity of water injection equipment. At the same time, excessive injection pressure in production process can easily cause safety accidents. Therefore, low concentration polymer solution should be selected for low permeability cores, so that to avoid blocking the pore structure of seepage flow and reducing the injection pressure during injection of polymer solution, so as to effectively avoid safety risks of water injection equipment of offshore oil field.

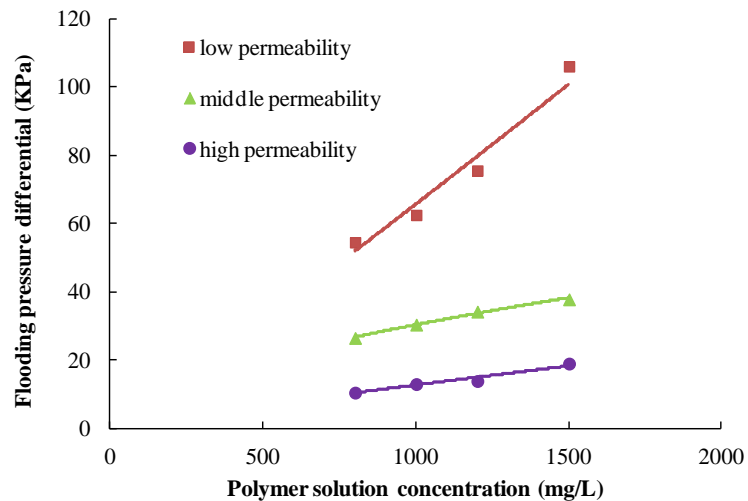


Figure 4. Relationship between polymer concentration and flooding pressure difference.

4.3. Effects of Flooding Velocity

All experimental cores were flooding at injection velocity of 0.35 mL/min and 0.50 mL/min at different polymer solution concentrations respectively. The effect of flooding velocity on resistance coefficient is shown in **Figure 5**. It can be seen that under the same polymer solution concentration, the higher flooding velocity is, the greater resistance coefficient is. This is because at lower flooding velocity, polymer molecules do not stretch in the porous media and the porous flow belongs to pure shear flow [20]. Whereas when the flooding rate is high, the tensile rate of polymer molecules increases in the porous media, and the flow in porous media is dominated by tensile flow. The viscoelasticity of polymer solution is enhanced, which leads to the increase of effective viscosity and consequently the increase of porous flow resistance. **Figure 5(a)** indicates that when polymer concentration is low, the degree of increase of flooding velocity to core resistance coefficient of all level permeability cores is basically the same. **Figure 5(b)**, **Figure 5(c)** and **Figure 5(d)** show that with the increase of polymer concentration and flooding velocity, the increase of resistance coefficient of high permeability core is higher than that of low permeability core, especially when the polymer concentration is 1500 mg/L, the increase degree of resistance coefficient of high permeability core is more obvious than that of low permeability core, this is because the viscoelastic characteristics of high concentration polymer solution are more obvious at higher flooding velocity, so the effective viscosity increases more greatly and the resistance coefficient can be higher.

The effect of displacement velocity on residual resistance coefficient is shown in **Figure 6**. The experimental results show that for different polymer solution concentration, the higher displacement velocity is, the larger residual resistance coefficient is. This is because when the flooding rate is low, the macromolecule in the polymer is still in a curly shape and cannot enter the pore smaller than its size, thus weakening the adsorption and mechanical trapping. When the displacement rate is high, the polymer molecules are stretched and deformed, and

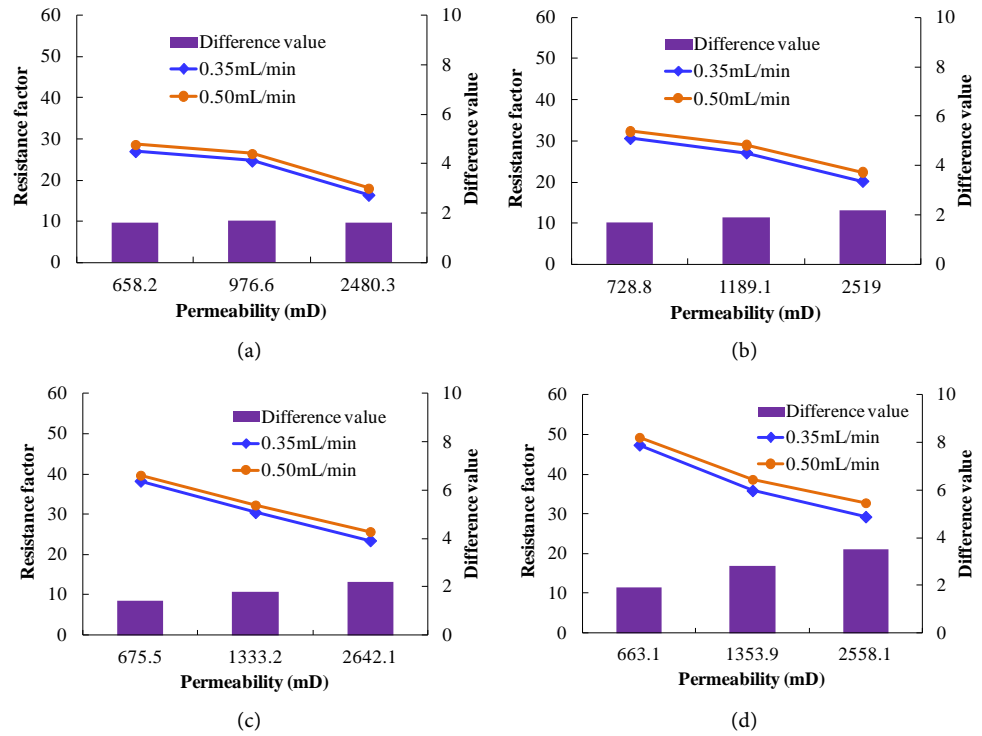


Figure 5. Resistance coefficients under different flooding velocity. (a) Polymer concentration 800 mg/L. (b) Polymer concentration 1000 mg/L. (c) Polymer concentration 1200 mg/L. (d) Polymer concentration 1500 mg/L

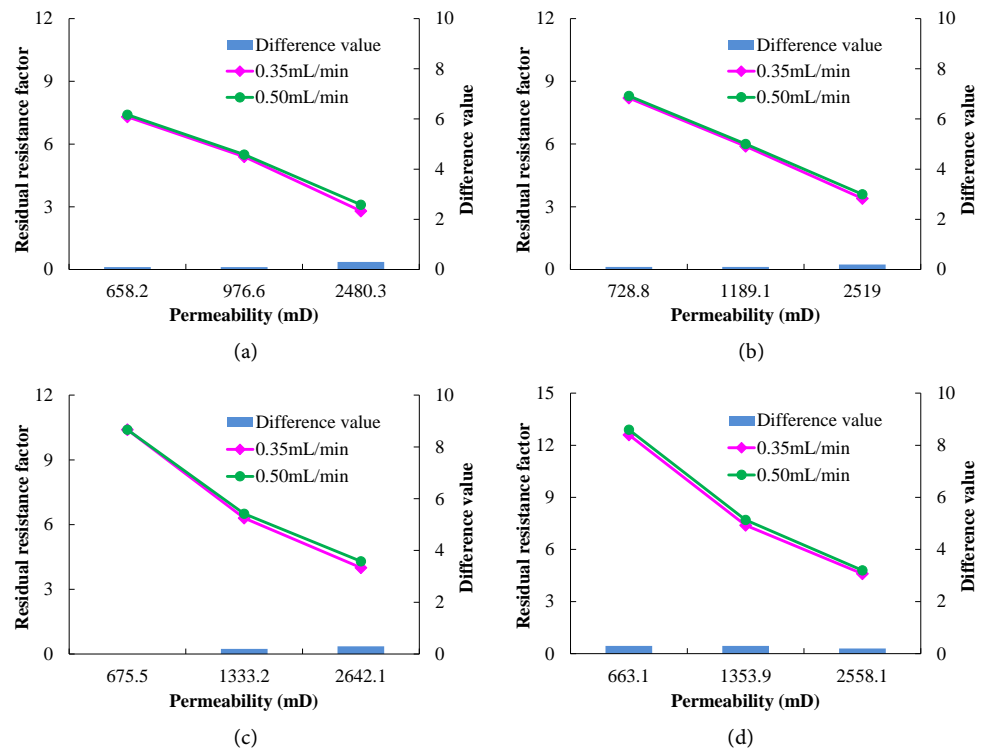


Figure 6. Residue resistance coefficients under different flooding velocity. (a) Polymer concentration 800 mg/L. (b) Polymer concentration 1000 mg/L. (c) Polymer concentration 1200 mg/L. (d) Polymer concentration 1500 mg/L.

some of them enter into the pore which cannot be entered at low velocity, which leads to the increase of the retention of polymer solution in the core and the increase of the residual resistance coefficient. **Figure 6(a)**, **Figure 6(b)**, **Figure 6(c)** and **Figure 6(d)** show that for different polymer solution concentration, flooding velocity increases the residual resistance coefficient of different permeability levels cores are basically the same, it is proved that the residual resistance coefficient is less affected by the concentration of polymer solution.

5. Result of Field Application

According to the above research results, it provides an important basis for determining polymer flooding scheme in oilfield Z. The I, II and III oil formations in lower Dongying formation second member is the major oil bearing system in oilfield Z, the permeability of I and II oil formations is higher, in the lower part of Dongying Formation, the main oil group in Z oilfield. Therefore, the polymer solution with a high concentration of 1500 mg/L is used to obtain a higher resistance coefficient. The permeability of III oil formations is lower; therefore, the polymer solution with a low concentration of 1200 mg/L is used to avoid the problems of reservoir plugged and excessive injection pressure for injection wells. The velocity of polymer flooding is as fast as possible, however, the faster the injection speed, the higher the injection pressure, so the maximum injection capacity of offshore injection equipment should be considered, there's need to prevent production safety problems caused by too high injection pressure, combined with the characteristics of offshore platform engineering equipment and actual reservoir demand, the flooding velocity of polymer solution in oilfield Z is determined to be 0.05 PV/a. Polymer flooding was took into practice since 2007 in oilfield Z, the effect of reducing water cut and increasing oil production had been achieved. As shown in **Figure 7**, according to Oil recovery forecast template that defined by Tong Xianzhang, by comparing the fitness of oil recovery production curve in water flooding stage and polymer flooding stage, it is predicted that the oil recovery will increase by 8.5% after polymer flooding.

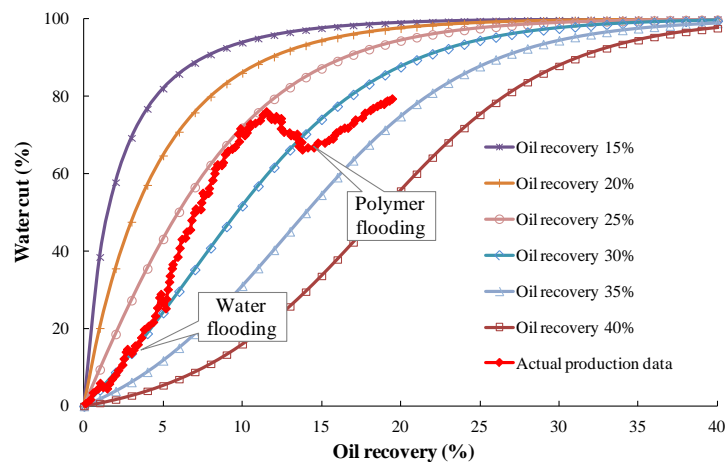


Figure 7. Oil recovery forecast template that defined by Tong Xianzhang.

6. Conclusions

1) Considering the actual reservoir characteristic parameters, laboratory flooding experiments were carried out according to similarity principle, and the main influencing factors of resistance coefficient and residual resistance coefficient in oilfield Z were studied.

2) Resistance coefficient and residual resistance coefficient decrease with the increase of reservoir permeability. With the increase of polymer concentration, the resistance coefficient and residual resistance coefficient increase, especially in the low permeability formation, so it is not appropriate to choose too large injection concentration in the low permeability formation.

3) The viscoelasticity of polymer solution increases with the increase of flooding velocity, which leads to higher resistance coefficient, but has less influence on residual resistance coefficient.

4) The conclusion is applied to the study of polymer flooding scheme in oilfield Z, which provides an important basis for the determination of injection concentration and flooding velocity of polymer solution that also achieves obvious effect to better oilfield production performance.

Acknowledgements

This project is supported by National Science and Technology Major Project foundation of China in the 13th Five Year Plan. Fund No. 2016ZX05058-001-007.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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