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ANALYSIS OF THE ALTERNATING INJECTION POLYMER FLOODING WITH VARIABLE VISCOSITY IN HETEROGENEOUS RESERVOIR

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In this paper, the experiment of mercury intrusion and casting thin section indicated that there exists diversity of microscopic pore structure among reservoirs. The hydrodynamic of polymer on residual oil confirmed the stress and deformation calculation of residual oil droplets under the actions of the different fluids, and analyzes the alternating injection mechanism from two aspects of the elasticity and pressure gradient. The experiment for oil displacement in two parallel cores established the sweep and oil displacement efficiency of alternating injection process of polymer solutions. The experiment for oil displacement of cores which was covered with electrodes demonstrated the development extent and distribution of remaining oil. The results show that comparing with continuous injection process, the alternating injection process of polymer solutions can improve the phenomenon of fluid overload in the large pores and the fluid deficiency in the small pores, making the polymer of low concentration and low molecular weight enter into the low permeability layers with more residual oil displacement and stress, hence the swept volume can be expanded, and the oil displacement efficiency can be improved.

Keywords: Alternating Injection, Polymer, Heterogeneous Reservoir

1. Aims and Background

In recent years, polymer flooding has been widely used in various oil fields for controlling water and improving oil recovery, injection methods of polymer flooding has been researched and some of them were developed in China. The oil displacement efficiency of physical simulation show that the best injection process of polymer flooding is equal volume polymer slug, followed by increasing the size of the main polymer slug, the worst injection process of polymer flooding is the bulk slug [1]. Research reports have pointed out that oil recovery rate of the decreases relative molecular mass of polymer slug flooding is superior to those of increasing relative molecular mass of polymer slug flooding [2]. The researchers have summarized the practical experience of polymer flooding in Daqing oilfield that the recovery of polymer flooding by injecting high

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relative molecular mass polymer as pre-slug primarily is 1.5% higher the bulk slugs of medium molecular weight polymer [3]. The conventional theory suggests that polymer slugs only increase the oil recovery by expanding the swept volume. However, the high concentration polymer flooding experiments and field tests in Daqing oilfield show that high concentration polymer viscoelasticity can significantly improve the micro-displacement efficiency [4-7]. Here, the authors studied the pore structure differences of heterogeneous reservoirs, and pointed out that alternating injection process of polymer solutions is more suitable for heterogeneous reservoirs, which is superior to the general injection method from the perspective of viscoelasticity [8-10]. The experiment for oil displacement in two parallel cores established that the alternating injection process of polymer solutions have the effect on crude oil in low permeability layer [11-12]. The experiment for oil displacement of cores which is covered with electrodes was further proved the ability of improving washing oil efficiency and expanding swept volume of alternating injection through the distribution of remaining oil [13-16].

2. Experimental condition

2.1 Cores

Natural cores, with a size of Φ2.5×10 cm, were taken from the reservoir of the PI formation of Daqing oilfield. Part of the natural cores were used in conventional mercury injection and casting thin section experiments, the other cores are composed of two parallel models were used for oil displacement experiment. The permeability of natural cores was measured by water, the cores with permeability of 1.5 $\mu m^2$and 0.3 μm^2 were selected as the research object.

The plane heterogeneous cores are composed of quartz sand and epoxy resin, which are consistent with the pore structure, permeability and porosity of Daqing oilfield. The plane heterogeneous cores which are evenly covered with 25 electrodes have a length, width and height of 30×30×4.5 cm. They are composed of two regions; the permeability of an area is 1.5 $\mu m^2$and the permeability of B area is 0.3 μm^2. The plane heterogeneous cores are shown in Fig. 1.

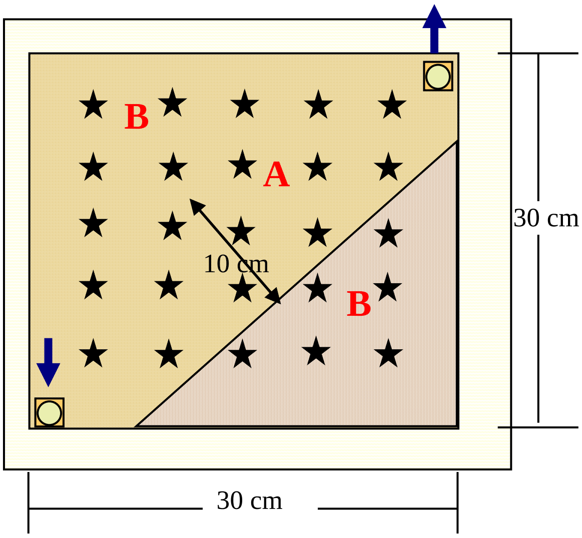


Fig.1 Plane heterogeneous

2.2 Experimental materials

The experimental materials used in this study include experimental water was taken from the Daqing oilfield and the ion composition of the water are shown in Table1. Experimental oil: with a viscosity of 9.8 mPa·s at 45 ℃, composed of dehydration crude of oil Daqing oilfield and kerosene oil. Partially hydrolyzed polyacrylamide (HPAM) with a solid content of 89.3% and molecular weight of 1.9×10^7.

Table 1

Ionic composition of water

Ion	Total	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca_2^+	Mg^{2+}	Na^++K^+	PH
Concentration (mg/L)	4697.6	75.0	2135.7	895.4	96.1	16.1	4.9	1474.5	8

2.3 Experimental procedures and equipment

Mercury intrusion: The mercury porosimetry with a working pressure of 0~120 MPa is made up of vacuum plant, pressurize system and capacitance measurement system of mercury change in volume. The principle of conventional mercury intrusion test is that the injection pressure is equivalent to the capillary pressure corresponding to the pore space and the corresponding capillary radius is equivalent to the pore throat radius of the core. With the increase of injection pressure, the capillary pressure curve and the mercury volume can be calculated.

Casting sheet: The pore space of the core is filled with the dyeing resin in a state of vacuum and the core was grinding into a thin sheet after the resin is consolidated. Finally, the pore and throat of nature cores were evaluated by BX51-P polarizing microscope which is produced by Olympus.

Viscoelasticity The viscosity and elasticity of polymer solution were measured by type RS150 rheometer which was produced by HAAKE company, German. The solution is added to the cone plate system when the water temperature is constant at 45℃ and the data is automatically controlled by the computer.

Oil displacement experiment of two parallel cores The experimental equipment mainly includes the displacement pump, the pressure collection system, the core holder, and the middle container. All equipment remained in the constant temperature of 45 ℃. The experimental apparatus were shown in Fig.2. The cores were saturated with crude oil. Then, the polymer solution in the intermediate container was injected into the model and the crude oil was discharged from the model under the push of the pump. The cores of the two groups with different permeability respectively represent the high and low permeability layers of heterogeneous reservoirs, the flow rate and recovery ratios are calculated by calculating the oil production and liquid production of these two cores.

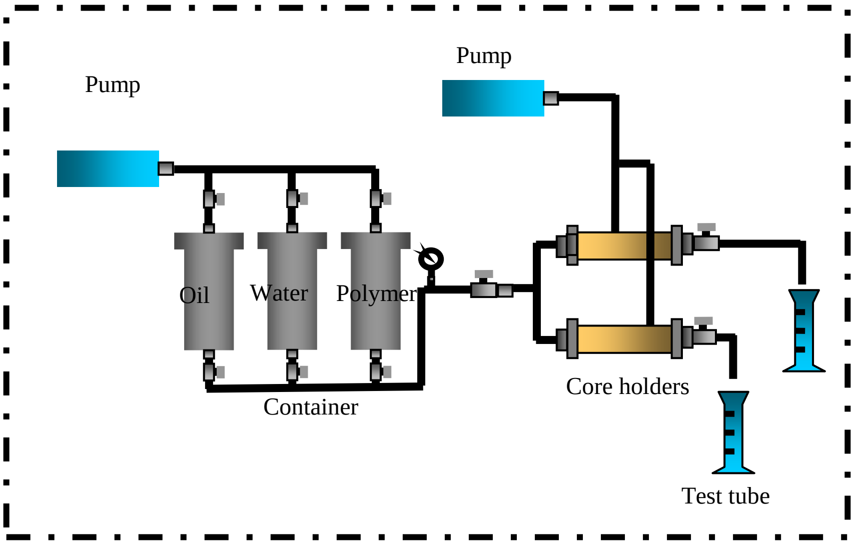


Fig. 2 Diagram of two parallel cores for oil displacement

Oil displacement experiment of plane heterogeneous core

The heterogeneous core was composed by the diagonal area with high permeability and the two wings region with low permeability. The plane of the core was filled with 25 electrodes, and the saturation of the core reflected by the theory of the relationship between Archie saturation and lithology. By detecting the resistivity of 25 electrodes, the oil saturation or water saturation of each test point can be calculated. Fig.3 shows the experiment- process diagram.

$$I = \frac{R_t}{R_o} \tag{1}$$

Type: R_t—Resistivity of rock filled with water, $\Omega \cdot m$;

R_o—Resistivity of rock filled with oil, $\Omega \cdot m$;

3. Results and Discussion

3.1 Differences of pore structure in heterogeneous reservoir.

Mercury intrusion

In this paper, natural cores with permeability 1.5 μm^2 and 0.3 μm^2 were selected for the experiment of mercury injection, pore structure parameters of these two cores are shown in Table 2.

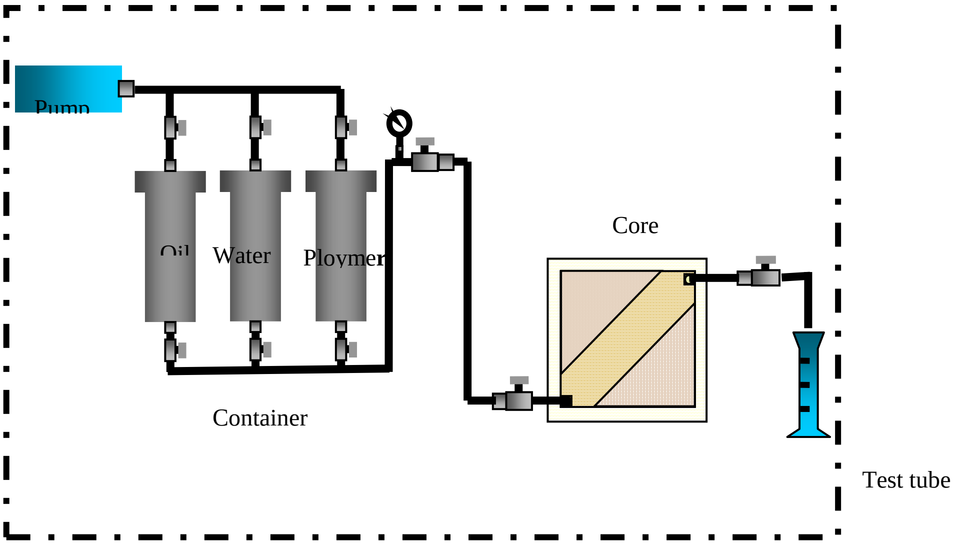


Fig. 3 Diagram of two parallel cores for oil displacement

Table 2

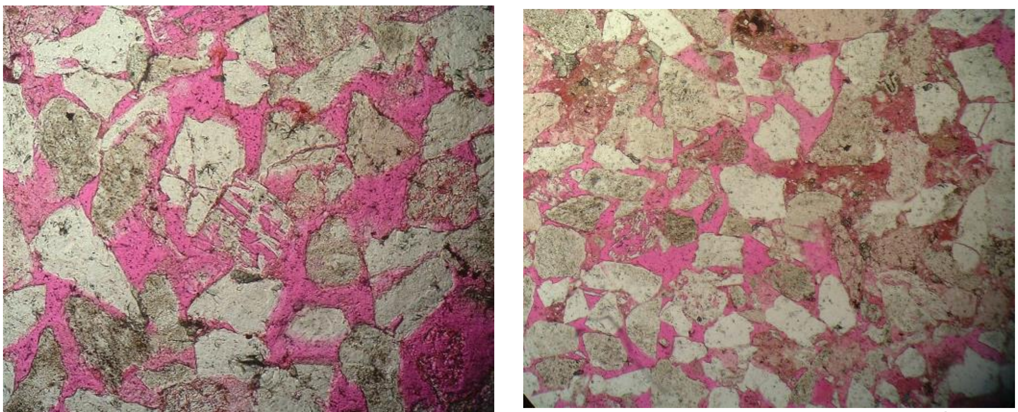
Porosity parameters of different permeability cores

Permeability (μm^2)	Average pore radius (μm)	Median pore radius (μm)	Mean radius (μm)	Mercury saturation (%)	Structure coefficient
1.5	10.5	15.2	9.4	89.6	1.1
0.3	3.6	2.8	3.0	82.7	1.9

As it is shown in Table 2, with the increase of permeability, the average pore radius of cores increases and the resistance of oil and gas migration decreases. The average pore radius of the core with permeability 1.5 μm^2 was 10.5 μm and the maximum mercury saturation was 89.6%, which indicated that the core belongs to the typical reservoir with high porosity and permeability. The core structure coefficient of 1.1 indicates that the porosity of the pores is the smallest and the connectivity of the pore throat was unimpeded. The average pore radius of the core with permeability 0.3 μm^{2}was 3.6 μm confirmed that the core belongs to the typical reservoir with medium porosity and permeability. The distribution of the pore throat of this permeability core was concentrated, the connectivity of the throat was poor, and the curving degree was serious. This results in the increase of oil and water migration resistance.

Casting sheet

Fig. 4 shows the skeleton and pores of different permeability cores. After the binary image processing, the proportion of rock skeleton and pore can be determined according to grey value. The porosity of core can be obtained by the ratio of saturated water volume to core volume. Therefore, the other pore structure parameters of rock samples were quantitatively described by fitting the rock porosity to the results.



a. Core with permeability of 1500×10^{-3}μm^2 b. Core with permeability of 300×10^{-3}μm^2

Fig. 4 Casting thin of cores with different permeability

The porosity, average pore radius, and specific surface pore structure parameters of the samples were analyzed by the quantitative description, as shown in Table 3.

Table 3

Casting thin parameters of cores with different permeability

Permeability (μm^2)	Diameter (mm)	Filling	Compaction effect	Connectivity
1.5	0.15-0.25	Volcanic rocks	Weak	Well
0.3	0.05-0.11	Iron calcite	Strong	Awfully

As it can be seen in Table 4, the lithic composition in the core with permeability of 1.5 μm^2 was dominated by volcanic rocks, and argillaceous matrix was distributed in siltstone. The pores were mainly micro porosity and formed small intergranular pores. The compaction of the formation was weak, and the intergranular pores develop a small number of particles, so the connectivity between the pores is strong. A large number of ostracods were distributed in the core of 0.3 μm^2 and the formation compaction was stronger, so the inter-pore connectivity was worse.

In conclusion, with the increase of permeability, the cuttings material filling in the rock decreases, the compaction effect is weakened, the intergranular pore development degree increases, the connectivity between the pores becomes better and the migration ability of the fluid in the rock sample have been enhanced.

3.2 Properties of alternating injection polymer solution

Definition The polymer flooding with constant concentration was called continue ous injection. Under the condition that the amount of the polymer dry powder and the volume of the polymer solution were all the same with the continuous injection, composition of high concentration polymer as pre-slug and low concentration polymer as a post slug were called alternating injection. Examples are shown in Table 4, the volume of polymer solution is expressed by multiple pore volume (PV).

Table 4

Comparison of experimental program

Injection mode	Program	Dry powder dosage
Continuous	0.6 PV 1500 mg/L	1500 mg/L*PV
Alternating	0.3 PV 2000 mg/L+0.3 PV 1000 mg/L	1500 mg/L*PV

Viscoelasticity The source solution with concentration of 5000mg/L under the condition of 45 ℃ for more than 12 hours, then the source solution was diluted into the concentration of 1000 mg/L, 1500 mg/L, 2000 mg/L. Viscosity and Wessenberg (We) values are shown in Table 5.

As it is shown in Table 5, with the increase of the polymer concentration, the force between the polymer molecules increases, and the viscosity of the solution is enlarging gradually. This is because the higher the polymer concentration, the larger the number of polymer molecules in solution. This means that the probability of collision between molecules increases with the decrease of the distance among polymer molecules. The We number which was represented the elasticity of the polymer solution has the same rule.

Table 5

Viscosity and We measurements

Concentration (mg/L)	1000	1500	2000
Viscosity (mPa·s)	37.3	61.6	80.6
We	0.05	0.09	0.19

3.3 Oil displacement alternating injection polymer solution

The difference properties of heterogeneous reservoirs are the main reason for the formation of residual oil. In general, the oil field is usually injected with a single polymer concentration slug as the way to increase the production of remaining oil. The polymer with low injection concentration has good compatibility with the reservoir, and it mainly flows along the high permeability layer, so it cannot enlarge the volume of the sweep. Injection of high concentration polymer into the high permeability layer improve layer seepage resistance, fluid flow and more low permeability layer is not sufficient, but because of the compatibility of low permeability layer and high viscosity polymer system is poor, will inevitably lead to the phenomenon of rotary section. The higher concentration of polymer injected into the high permeability layer increases the resistance of the permeation within the layer, and the polymer begins to flow to the low permeability layer. A mismatch between the low permeability layer and the high concentration of polymer system will cause the profile of the rotation phenomenon.

Recovery and diversion rate of two parallel cores

In the case of the same amount of polymer powder, the recovery efficiency of continuous injection polymer flooding and alternating injection polymer flooding is shown in Table 6 and Fig. 5.

As it can be seen in Table 6, the water flooding recovery of these two groups of parallel experiments are basically the same, the water flooding recovery increases with the increase of core permeability and the remaining oil is mainly concentrated in the low permeability layer.

Table 6

Recovery experimental date

Experimental program	Core	Permeability (μm²)	Water flooding recovery (%)	Polymer flooding recovery (%)	Growth recovery (%)
Continuous injection 0.6PV1500mg/L	1	1.5	45.6	13.9	59.5
	2	0.3	29.9	14.2	44.1
	Total	/	38.3	14.1	52.4
Alternating injection 0.3PV2000mg/L+0.3PV1000mg/L	3	1.5	45.5	14.3	59.8
	4	0.3	29.6	19.2	48.8
	Total	/	38.1	16.5	55.6

After water flooding, the recovery can be greatly improved by polymer injection; especially the enrichment of remaining oil in the low permeability core can be effectively passive. Because of the matching relationship between low concentration system and low permeability layer, recovery of crude oil in low permeability layer is larger by the way of alternating injection polymer flooding. Compared with the continuous injection polymer flooding, not only the recovery of high permeability layer is not affected, but the recovery rate of low permeability layer has a 4 % increase. Proportion of the liquid flow produced by each permeable layer was calculated separately. The flow rate can effectively prove the effect of alternative injection method on the expansion of low permeability layer. The variation rule of the diversion rate with the injected pore volume is shown in Fig. 5.

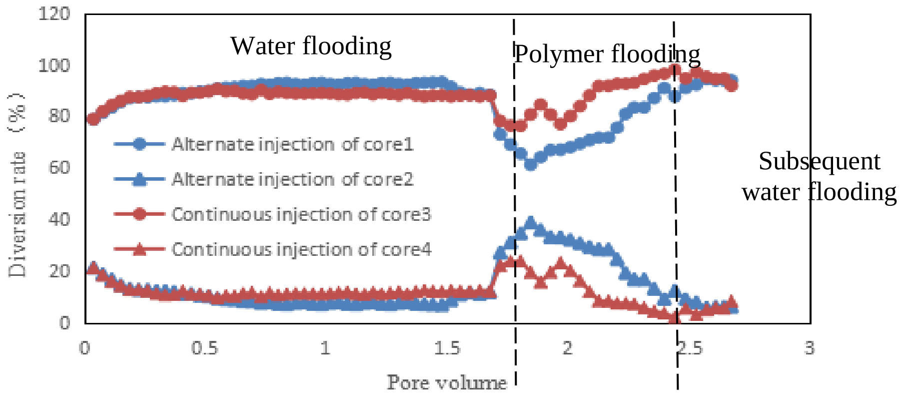
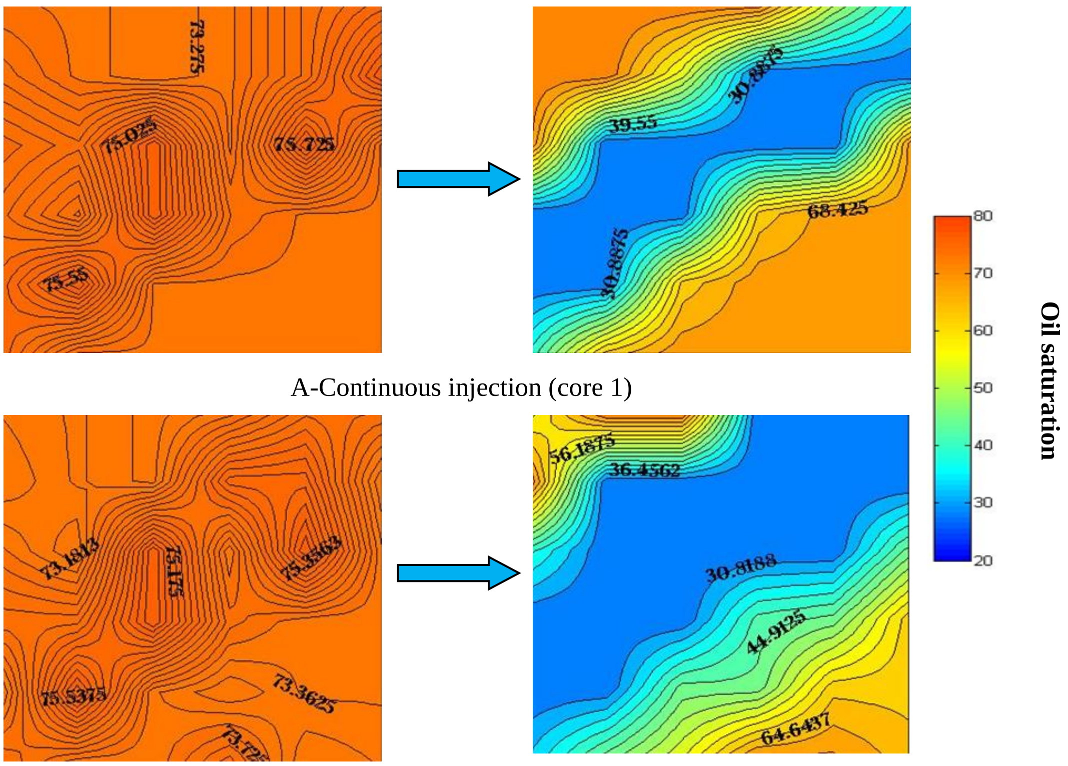


Fig. 5. Relationship between diversion rate and pore volume

Because of the sealing ability of polymer, the flow rate of the high permeability layer decreased rapidly, and the flow rate of medium and low permeability layers increased. Due to the poor adaptability of the high concentration polymer system and the low permeability layer, the continuous injection polymer flooding can only flow along the high permeability reservoir. It is reflected that the injection rate rapidly reaching the end of shunt gently, subsequent water is flooding along the high permeability layer first breakthrough in polymer flooding, flow rate increases gradually reaching to the water flooding stage. For the alternating injection polymer flooding, high concentration polymer flooding stage water content are reaching gently. With the injection of low concentration polymer system, shunt rate fluctuation declines which verified that the low concentration system turn into low permeability reservoir.

Recovery of plane heterogeneous core In order to further reveal that the alternating injection polymer flooding can increase the swept volume of heterogeneous reservoir, the distribution law of remaining oil is studied by using the plane heterogeneity model. According to the standard curve between the resistance value and the water saturation, the distribution of the oil saturation is indirectly determined by measuring the change of the resistance value of the test point. The remaining oil saturation map is shown in Fig. 6.



A-Continuous injection (core 1)

B-Alternating injection (core 2)

Fig. 6 Distribution of remaining oil after polymer flooding

As it is shown in Fig. 6, because of the existence of plane heterogeneity, the original oil saturation distribution is not uniform, the original oil saturation of the high permeability zone is high than the value of the low permeability zone. With the increase of the permeability, the original oil saturation is increased.

As for continuous injection polymer flooding, the results of oil saturation distribution show that the continuous polymer flooding can affect the high permeability area and oil displacement effect is ideal. The residual oil saturation of the mainstream line is reach to 30% ， the residual oil exists in the pores in this part of the area and the flowable fluid is substantially all of the aqueous phase. The crude oil at the two wings of the model was not displaced and remained at the original oil saturation，this part of the region is called the "dead oil zone". Remaining oil is present in the transition zone between the main channel and the dead oil zone.

With respect to alternating injection polymer flooding, the oil saturation content of high permeability layer is very low, the formation of water channel wide along the main line direction. The remaining oil saturation near wellbore reach to residual oil saturation, the two wings of crude oil is highly affected by polymer flooding and the oil zone is essentially non-existent.

4. Mechanism analysis

The horizontal stress and normal stress of residual oil droplets were calculated by software named POLYFLOW which is one of ANSYS company's products. Firstly, the geometric model of oil drops is established by using GAMBIT module in software. Then the model is meshed, defined marginal conditions and defined region types. Finally, the visualization results of numerical simulations are displayed by CFD-Post.

A two-dimensional parallel pore model was established for the analysis of oil drop stress as shown in Fig.7, the radius of the two groups of channels were the average pore radius of nature core measured by mercury intrusion.

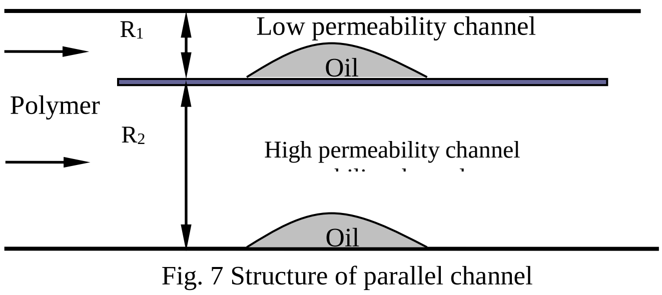
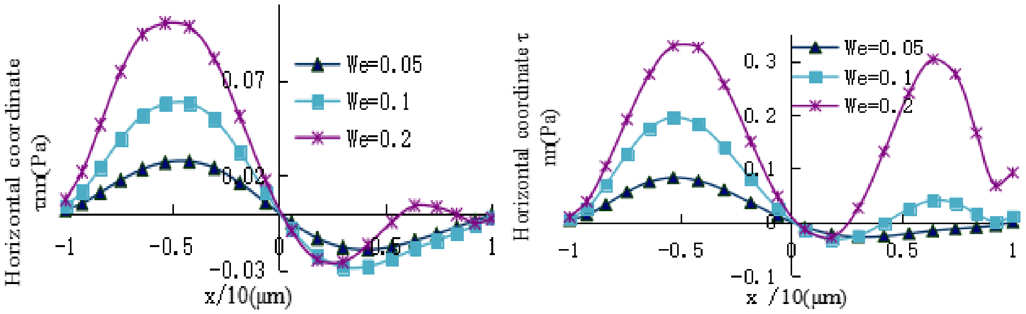


Fig. 7 Structure of parallel channel

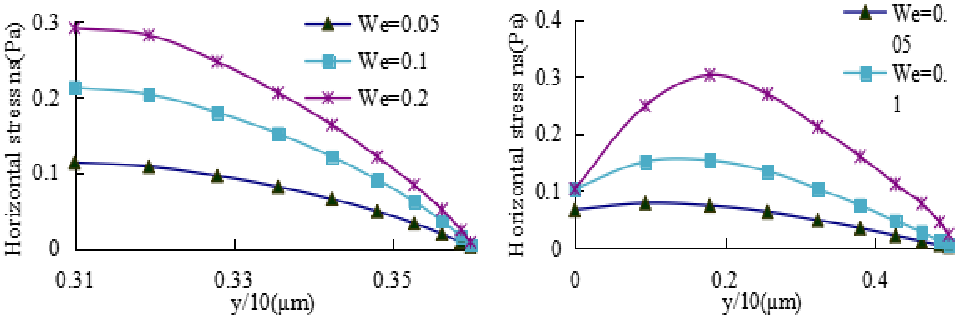
In order to analyze the force on oil drops when different viscoelastic fluid flow through oil drops, the normal stress and horizontal stress on the residual oil droplets was calculated when viscoelastic fluids were displaced in the parallel channel. The radiuses of the parallel channels were the pore radius of the two cores measured by the compression test. The We of aqueous solutions of different concentrations of polymer were 0.05, 0.1 and 0.2, respectively. The calculation results of normal stress and horizontal stress of the residual oil droplets under the pressure gradient of 0.02 MPa/m are shown in Fig.8. The pressure in the direction of fluid motion is defined as a positive value and the other direction is defined as a negative value.



a-High permeability pore b-Low permeability pore

Fig. 8 Normal stress on residual oil droplets

The normal stress of residual oil droplets in high permeability and low permeability channels were shown in Fig.8. It can be seen from the figure that the elasticity of the polymer solution increases the normal stress of the residual oil droplets, which further proves that the elasticity of the polymer solution has a positive effect on the residual oil droplets. The horizontal stress acting on the residual oil drops increases with increases of the elasticity of polymer solution.



a-High permeability pore b-Low permeability pore

Fig. 9 Horizontal stress on residual oil droplets

This theory has certain guiding significance for polymer preparation and field selection. For the polymer solutions with the same elasticity, the horizontal stress in the high permeability channel is greater than the value in the low permeability channel. As it is shown in Fig. 9, the horizontal stress of the residual oil droplets in high permeability channel and the low permeability channels increases with the increasing of the elasticity of the polymer, which proves that the elasticity of the polymer solution can effectively improve the horizontal stress difference acting on the residual oil droplets With the increase of the distance between oil droplets and rock, the horizontal stress of the residual oil droplets in the low permeability channel decreases. However, the horizontal stress of the residual oil droplets in the high permeability channel reaches the maximum near the middle of the oil film, which is more favorable to the deformation of the oil film.

The principle of alternate injection is to use different viscoelastic polymer solutions to drive the oil droplets, so that the oil droplets are deformed by different horizontal stresses and vertical stresses. Compared with the continuous injection, alternate injection method can improve the phenomenon of absorption of large pores and insufficient absorption of small holes, so that more low concentration of polymer solution can be entered into the low permeability layer and more residual oil can be force and deformation, so as to achieve the purpose of expanding the size of the wave.

According to the calculation of the normal stress, it can be seen that the difference of the normal stress of the oil droplets in high permeability and low permeability channels decreases as the polymer concentration decreases. This is because the molecules in high concentration polymer solution are overlapping leads to the molecular size is large, it is difficult to enter the low permeability layer and mainly enriched in high permeability layer. The low concentrated polymer solution can easily enter the low permeability layer, so that the residual oil in the low permeability channel is increased by extrusion deformation. It can be seen that the high concentration polymer is suitable for the high permeability channel and the low concentration polymer is suitable for the low permeability channel, this is the principle of alternating injection.

5. Conclusions

Compared with the continuous injection polymer flooding, the recovery of alternating injection polymer flooding has a 4% increase in the heterogeneous core. For the alternating injection polymer flooding, high concentration polymer flooding stage water content are reaching gently. With the injection of low concentration polymer system, shunt rate fluctuation declines which verified that the low concentration system turn into low permeability reservoir. As for alternating injection polymer flooding, the oil saturation content of high permeability layer is very low, the formation of water channel wide along the main line direction.

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