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Study on Displacement Mechanism of Residual Oil Film Deformation in Micro-Channels

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Abstract:

In order to further explore the displacement fluid elastic displacement mechanism of remaining oil, use the convection maxwell viscoelastic fluid constitutive equation is established in the microchannel flow equation. Based on the stress tensor theory, the normal and horizontal deviator stress difference acting on the residual oil film is calculated. The effects of different viscoelastic displacement fluids and oil film widths on the horizontal and normal deviator stress difference acting on the residual oil film are comparatively analyzed. The results show that the displacement fluid acting on the residual oil film will cause sudden change in the horizontal and normal deviator stress of the residual oil film. For polymer solution with greater viscoelasticity, there is greater normal and horizontal deviator stresses acting on the residual oil film, and the deformation of the residual oil film will be greater. The study lays the foundation for calculating the stress and deformation of residual oil under special boundary conditions. At the same time, also as the research provides theoretical basis for residual oil membrane rupture.

Keywords*: micro-channel; viscoelastic fluid; residual oil; Weisenberg number*

I. INTRODUCTION

In the early 1970s, China also took the lead in conducting polymer flooding experiments in Daqing Oilfield. As the main battlefield of global polymer flooding, Daqing Oilfield enjoys natural conditions for polymer flooding compared with other domestic oil fields. The practice of the Daqing oilfield show that the viscoelastic polymer solution, especially after water flooding of high concentration polymer solution, can further improve oil recovery. In order to explore the elasticity of polymer flooding mechanism. Xia H. et al. studied the effect of polymer solution viscoelasticity on displacement efficiency through displacement experiments, pointed out that elasticity can enhance displacement efficiency, and analyzed the factors influencing viscoelasticity of polymer solution, molar mass of polymer and mass concentration of polymer solution. Clarke A. et al.[1-2] research showed that the surfactant polymer is driven by pulling the residual oil into oil droplets and oil filaments, and pulling large oil droplets into small oil droplets and oil filaments. Smaller oil droplets are formed in different channels during seepage, which makes the oil more easily carried and transported by the displacement fluid. You Q. et al.[3] divided the microscopic residual oil into six types of shapes: intragranular, throat, pore surface film, intergranular adsorption, corner and cluster. It can be seen through quantitative analysis that: chemical flooding has obvious effect, the absolute oil saturation of the film-like and cluster-like residual oil on the pore surface decreases

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successively under water flooding, polymer flooding, and ASP flooding. Sun C. et al.[4] showed that reducing the difficulty in starting the residual oil and emulsifying the crude oil into small droplets are the main mechanisms for microemulsion to displace the residual oil. This study proved the feasibility of microemulsion flooding in low-permeability reservoirs, and scientifically explained the effect of microemulsion flooding, which helps to perfect the theory of tertiary oil recovery by microemulsion. Liu L. et al.[5] studied the changing state of the polymer when displacing oil droplets. Therefore, through the changes in the field diagrams of pressure, stress, and velocity, it can be more intuitively recognized that in the process of polymer flooding, the unique elasticity of the viscoelastic fluid increases the volume of residual oil swept by the displacement fluid during the collisional compression process, so that non-flowing oil flows first. Bahrami P. et al. [6] pointed out that polymer plays a role in reducing the mobility ratio of the displacing agent to crude oil, increasing the viscosity of the displacing agent, and increasing the displacement pressure. Under the action of the system, the displacement effect of residual oil difficult to be used after water flooding is significantly improved. Sharafi M. S. et al. pointed out that polymer solutions with higher concentrations or molecular weights will significantly increase its elasticity and cause significant deformation of the residual oil, which then facilitates the migration or peeling of the residual oil. In view of the current development difficulties of the Kekeya X_{52} high water-flooded volatile oil reservoir. Hellevang, H. et al.[7-8] applied CO_2 miscible displacement to the reservoir. At present, the reservoir pressure has reached the technical limit of miscible displacement, and miscible displacement can greatly improve oil reservoir recovery efficiency. Ceniceros H. D. et al. [9] concluded that with the increase of the relative angle between the oil droplets, the oil droplet spacing, the particle diameter ratio of oil droplet, and the concentration of the dispersed phase incompatible liquid, the coalescence rate of the oil droplets decreases. Izbassarov D. et al.[10] studied the deformation of droplets adhering to the solid wall due to water flooding under the action of equal pressure difference, finding that droplet deformation is affected by the droplet flow rate, volume, and viscosity ratio. The critical condition of droplet sliding and separation was captured by a high-precision camera. Chung C. et al.[11] studied the kinetic characteristics of droplets passing through restricted micro-channels through experiments and numerical calculations. The upper convective Maxwell constitutive equation was used to establish the flow equation of viscoelastic fluid in the micro-channel, and the flow field was calculated by numerical analysis method. The displacement mechanism was analyzed from the Angle of residual oil film stress, and the influence of different rheological oil flooding fluid on normal and horizontal deviating stress difference of residual oil film was compared. The study of residual oil film activation and the theoretical research of the stress and deformation of laid a foundation.

II. FLOW FIELD AND CALCULATION MODEL

Due to the complexity of the actual reservoir flow channels, the displacement fluid injected into the reservoir will flow to different flow channels. Hence, a simplified model is used here, as shown in Fig. 1.

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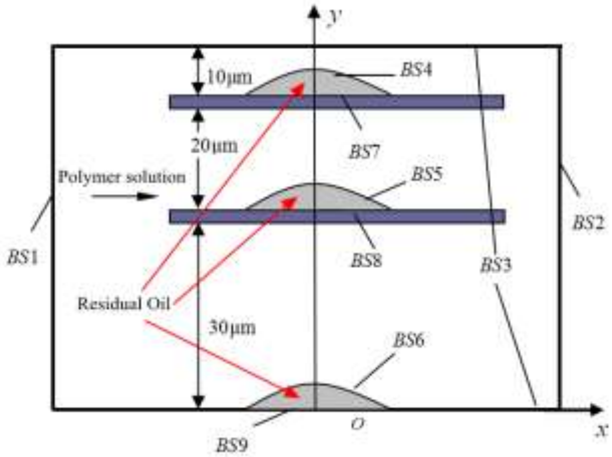

Fig.1 Parallel channel model

In order to calculate residual oil at a constant flow of different flow channel width under the stress and deformation, respectively take the different flow channel width to 10 microns, 20 microns and 30 microns, flow length is 100 microns. BS1 is the inlet of the flow channel, BS2 is the outlet of the flow channel. BS4, BS5, and BS6 are the surface of the residual oil. BS7, BS8, and BS9 are the contact interface between the residual oil and the rock. The remaining is wall surface, which is recorded as BS3. The corresponding computing grid is shown in Fig. 2.

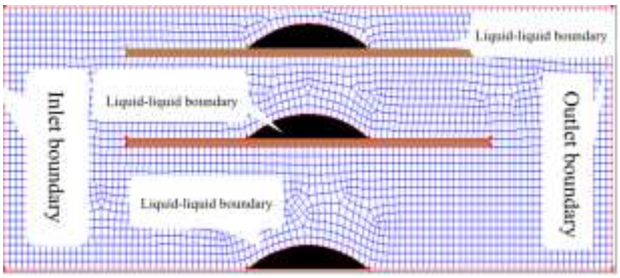

Fig2 Compute grid and boundary conditions

2.1 Boundary conditions of flow

1) Displacing fluid and rock of contact interface and the remaining oil and rock contact interface adopts wall slip conditions; BS3-zero wall velocity(v_n=v_s=0) along boundary 3; BS5-zero wall velocity(v_n= v_s=0) along boundary 5.

2) The inlet and outlet adopt equal flow, Q=6×10^{-10} $m^3 \cdot s^{-1}$;BS1-inflow along boundary 1; BS2-outflow along boundary 2.

3) In the static calculation of liquid-liquid interface, assumed that residual oil is fixed, and to meet the wall with no slip conditions; BS4-zero wall velocity (v_n=v_s=0) along boundary 4, BS5-zero wall velocity(v_n=v_s=0) along boundary 5, BS6-zero wall velocity(v_n=v_s=0) along boundary 6. When calculating deformation, it belongs to dynamic grid calculation. The liquid-liquid interface is set as: BS4-interface, BS5-interface, BS6-interface. The interfacial tension is all set to 10 $mN \cdot m^{-1}$, and the sliding effect of the liquid-liquid interface is considered. The Lagrangian method is used for the grid reconstruction. The

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Crank-Nicolson calculation is used for solution, and the maximum truncation error is 0.01.

2.2 Physical parameters

The zero-shear viscosity of the displacement fluid is 1200 mPas, with density 1.1×10^{3} $kg\cdot m^{-3}$. The viscosity of the residual oil is 20 mPas, with density 860 $kg\cdot m^{-3}$. The relaxation time is 0.67, 1.33 and 2, respectively, representing different elasticity, and the viscosity ratio is 0.1. The calculation process ignores the effect of gravity. Since Maxwell's constitutive equation is non-linear, the calculation process adopts the evolution of relaxation time. The tapering function is selected as $f(s)=s$, and the gradient parameters are selected as follows: the initial value of s is 0, the upper limit is 1, and the initial $\Delta s= 0.01$, the minimum value of Δs is 0.0001, and the maximum value is 0.25.

III. ANALYSIS OF THE DEFORMATION CALCULATION RESULTS OF THE RESIDUAL OIL FILM

3.1 Calculation of normal deviator stress

FIG. 3 shows the curve of normal deviational stress of residual oil in microchannels with different widths as *We* changes. The results show that the normal deviational stress on the surface of residual oil film increases with the increase of We content in viscoelastic displacement fluid in microchannels of different widths. In a narrow channel, the upstream of the residual oil is compressed, the downstream is pulled. In a wide flow channel, the downstream tension trend of the residual oil weakens with the increase of *We*. When *We*=0.3, the remaining oil in the downstream is only pulled by a small part of the oil center, and the value is very small, and the rest is subject to greater pressure. This force distribution will make the small area near the center protrude from the residual oil matrix and become longer and thinner under the continuous action of the displacement fluid. After reaching the stress limit, it breaks and separates out small oil droplets. For the residual oil of the same size, the extreme normal deviator stress in a wide channel is nearly 6 times that of a narrow channel.

Into We = 0.3 after flooding oil, wide flow channel and method of residual oil in the narrow passage to the deviatoric stress and wide flow channel of the method to the deviatoric stress are quite different. The main reason is that the high concentration polymer has great viscoelasticity, which greatly increases the stress and deformation of the residual oil, while overlapping the polymer molecules in the solution, so that the molecular coils are too large to enter the middle and low permeability layer, especially the low permeability layer. High concentration polymer is more suitable for high permeable formation, therefore, this will have a larger residual oil of high permeable zone, the method to the deviatoric stress.

Into We = 0.1 after flooding oil, wide flow channel and the method of residual oil in the narrow port to the deviatoric stress and residual oil in wide port is normal deviatoric stress. The main reason is that the high concentration polymer has great viscoelasticity, which greatly increases the stress and deformation of the residual oil, while overlapping the polymer molecules in the solution, so that the molecular coils are

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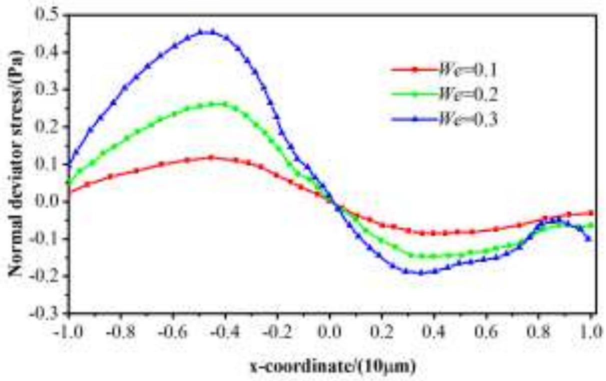
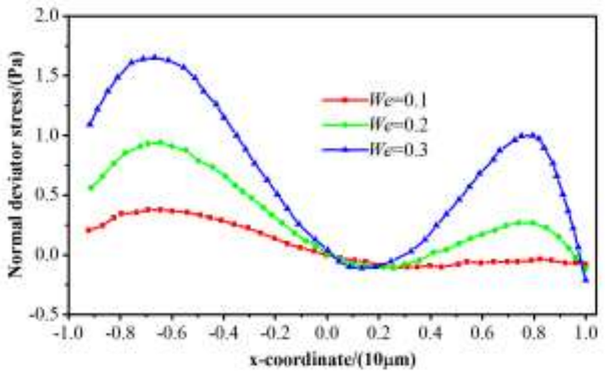
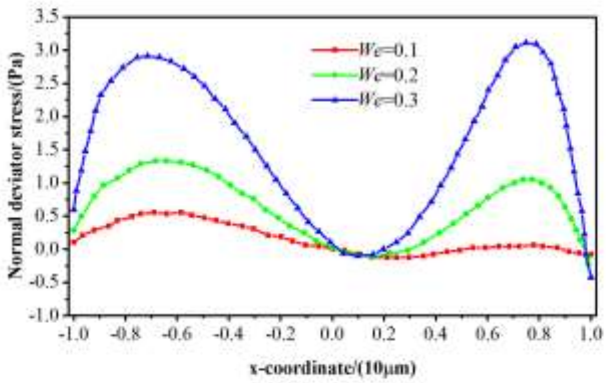
too large to enter the middle and low permeability layer, especially the low permeability layer. As a result, high concentration of polymer is more suitable for high permeable formation, which to a residual oil in a high permeable zone more normal deviatoric stress. Therefore, low concentration polymer solutions are suitable for medium width and narrow flow channels.



(a) Normal deviational stress on residual oil film surface at different We numbers in narrow channel



(b) Normal deviational stress on residual oil film surface at different *We* numbers in medium width channel



(c) Normal deviational stress on residual oil film surface at different *We* numbers in wide channel

Fig.3 Normal deviational stress of residual oil in microchannels with different permeability

3.2 Calculation of horizontal stress difference

Horizontal thrust at different flooding oil displacement is the horizontal stress difference. The numerical value, the greater the deformation of residual oil, the more obvious. Can be seen from the figure

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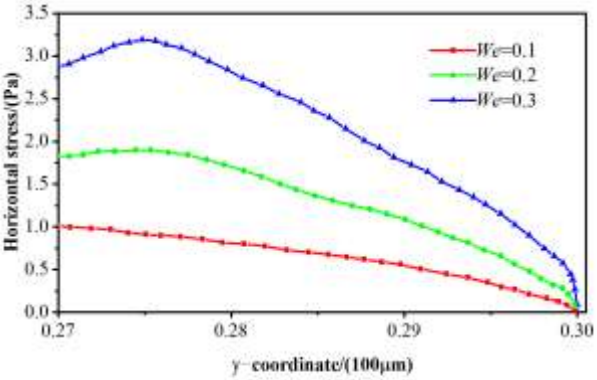
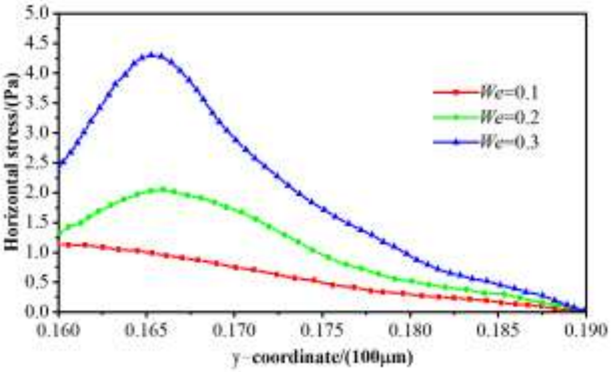
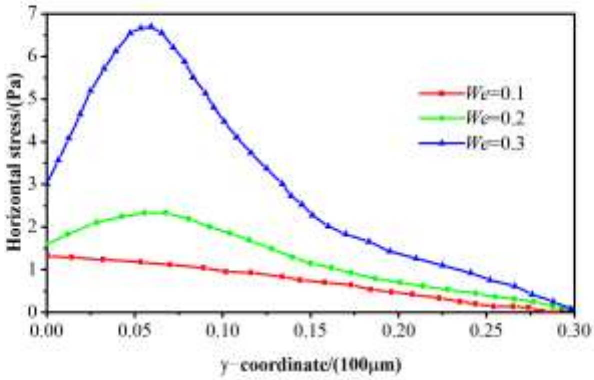
4, with the increase of We, viscoelastic fluid ACTS on the remaining oil on the surface of the horizontal stress difference increasing; The horizontal stress difference of residual oil in 30 μm flow channel is significantly higher than that in 20 μm and 10 μm flow channel. This applies to high concentration replacement fluids. However, the low concentration of polymer has little effect on the horizontal stress difference of residual oil in 20 μm and 10 μm channels. Therefore, level between maximum differential pressure and We change curve as shown in Fig. 5.



(a)10 microns flow under different *We* count in the residual oil on the surface of the horizontal stress difference



(b)20 microns flow under different *We* count in the residual oil on the surface of the horizontal stress difference



(c) 30 microns flow under different *We* count in the residual oil on the surface of the horizontal stress difference

Fig.4 Different permeability microchannel residual oil in the results of the horizontal stress difference

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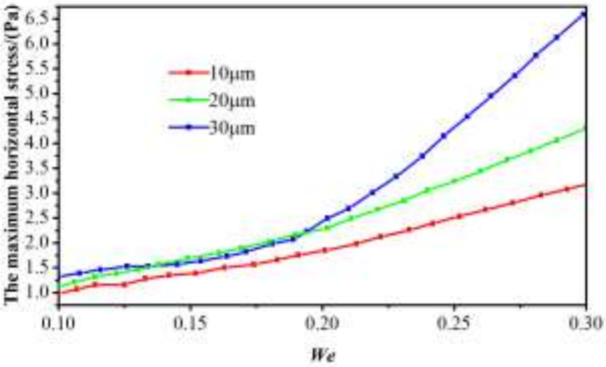
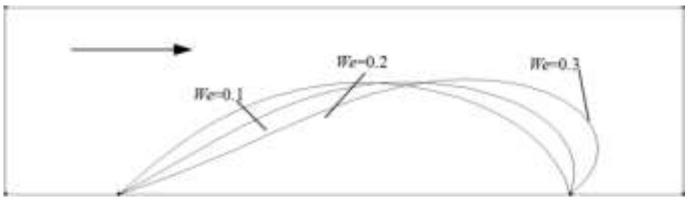


Fig.5 Different width *We* curve of maximum horizontal stress

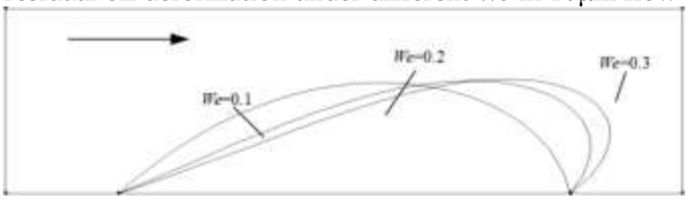
As can be seen from the Fig.5, the maximum horizontal stress difference as We increased. Compared with the flow channels of 10 μm and 20 μm, the maximum value of the horizontal stress difference increases almost linearly, while for the flow channel of 30 μm, the maximum value of the horizontal stress difference exhibits parabolic increase. That is to say, the greater the elasticity of the displacement fluid, the greater the *We*, and the greater the force on the 30 μm wide flow channel.

3.3 Analysis of the deformation results of the residual oil film

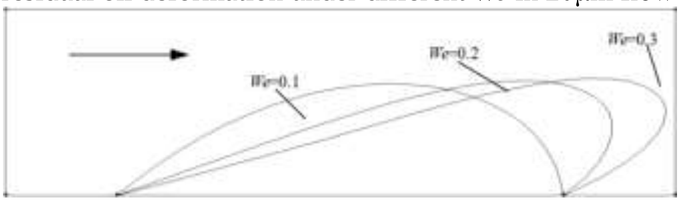
It can be seen from Fig. 6 that when high-concentration displacement fluid is injected, the deformation of residual oil in the 30 μm flow channel is more obvious than that in 20 μm and 10 μm flow channels; when low-concentration displacement fluid is injected, under small elasticity, the deformation of residual oil in 30 μm, 20 μm and 10 μm flow channels is not much different.



(a) The residual oil deformation under different *We* in 10μm flow channel



(b) The residual oil deformation under different *We* in 20μm flow channel



(c) The residual oil deformation under different *We* in 30μm flow channel

Fig.6 Residual oil deformation in microchannels with different permeability

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For the remaining oil in the parallel channel, the normal deviational stress of viscoelastic fluid on the remaining oil increases with the increase of *We* in the micro-channel with different permeability. When the oil droplets size close, high permeability of microchannel method to the deviatoric stress is about 6 times of low permeability micro channel. The horizontal stress difference of viscoelastic fluid increases with the increase of We. The horizontal stress difference of high concentration displacement fluid on high permeability oil is obviously higher than that of low permeability oil. In the medium and low permeability microchannels, there is little difference in the horizontal stress of low concentration polymer on crude oil.

The larger the displacement fluid elasticity is, the larger the normal deviant stress is, the larger the horizontal stress difference is, and the larger the residual oil deformation is, which is beneficial to the migration or rupture of the residual oil film. Therefore, the elasticity of displacement fluid is the main reason for polymer flooding fluid to improve displacement efficiency and thus enhance oil recovery.

IV. DISCUSSION ON THE START-UP CONDITIONS OF RESIDUALl OIL

4.1 Wetting hysteresis of residual oil

When the residual oil in the absence of external disturbance stationary surface, the rock has no wetting hysteresis shape is the initial shape. Displacing fluid by calculation of the size of the residual oil of various forces, further deformation to estimate the residual oil, summed up the impact factors of residual oil deformation and forces.

If gravity is ignored, the oil droplet in spherical shape is a spherical crown on the surface of the lipophilic rock, while the shape on the hydrophilic rock surface is a hemisphere. The change in the oil droplet volume will only cause a change in the radius of the spherical surface, without changing the contact angle. That is, a series of droplets of different volumes present a series of geometrically similar shapes on the rock surface of the same nature.

Considering the influence of gravity, the radius of curvature of the bottom of the millimeter-level oil droplet is larger than that of the top, and the oil droplet is pear-shaped, but the top and bottom of the micron-level oil droplet has similar radius of curvature, and the oil droplet is spherical. Therefore, the shape of the tiny oil droplets will not be affected by gravity.

Driven by the displacement fluid, the change in the contact angle of the residual oil is reflected as wetting hysteresis, as shown in Fig. 7.

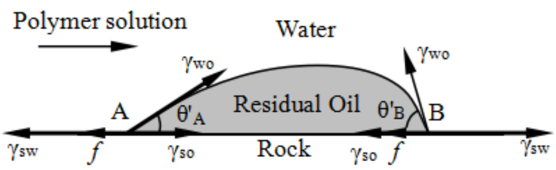

Fig.7 Wetting hysteresis

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The displacement fluid flowing to the right moves the residual oil to the right, and generates a force that prevents the residual oil from moving to the right at the oil-solid-water three-phase contact point. The force is expressed by the force f on the contact line per unit length, and its unit is $N \cdot m^{-1}$. The horizontal force balance equations for contact points A and B are shown below:

$$\begin{aligned} \gamma_{wo}\cos\theta_A + \gamma_{so} - \gamma_{sw} - f = 0 \\ \gamma_{wo}\cos\theta_B + \gamma_{so} + f - \gamma_{sw} = 0 \end{aligned} \tag{1}$$

After sorting, there is

$$\cos\theta_A = \frac{\gamma_{sw} - \gamma_{so}}{\gamma_{wo}} + \frac{f}{\gamma_{wo}} = \cos\theta + \frac{f}{\gamma_{wo}} \tag{2}$$

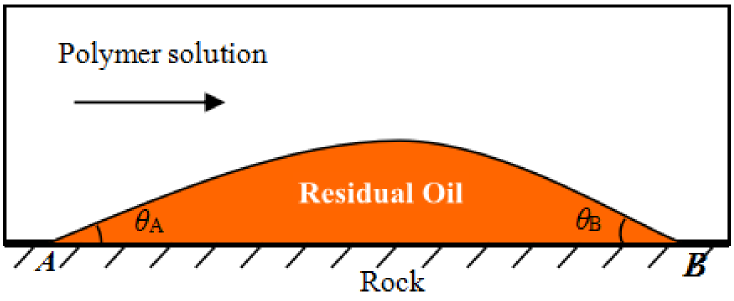
$$\cos\theta_B = \frac{\gamma_{sw} - \gamma_{so}}{\gamma_{wo}} - \frac{f}{\gamma_{wo}} = \cos\theta - \frac{f}{\gamma_{wo}} \tag{3}$$

Where θ denots the wetting angle at rest. Obviously, $\theta_A < \theta < \theta_B$. Here, θ_A is the receding angle, and θ_B is the advancing angle. Under the action of the displacement fluid, the residual oil undergoes wetting hysteresis, with the advancing angle increased and the receding angle decreased.

4.2 Start-up of residual oil

The start-up of residual oil can be analyzed from the following two situations:

Residual oil "sliding" is residual oil in the displacement along the surface of rock under the action of fluid movement, as shown in Fig. 8:



(a) Residual oil when the displacement fluid flow rate is 0

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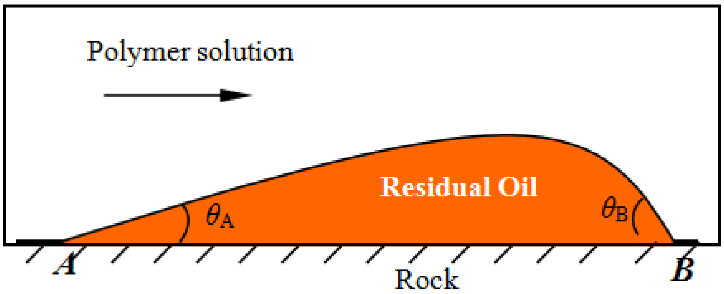

(b) Residual oil after the displacement fluid flow rate reaches a certain value

Fig.8The wetting angle of residual oil

Under the action of the displacement fluid, the wetting angle of the residual oil changes from θ shown in Figure 8(a) to θ_A and θ_B shown in (b). When θ_A is less than a certain critical angle θ_1, the boundary point A of the residual oil will shrink to the interior of the residual oil (point A will slide forward). That is, when the receding angle is lower than the critical value θ_1, the boundary point A will slide forward. When θ_B is greater than a certain critical angle θ_2, the residual oil boundary point B will extend to the exterior of the residual oil (point B slides forward). That is, when the advancing angle is greater than the critical value θ_2, boundary point B will slide forward. Therefore, when the displacement fluid speed reaches a certain value, the residual oil will slide forward along the rock surface if $\theta_A<\theta_1$ and $\theta_B>\theta_2$.

This seems contradictory to the non-slip wall surface mentioned in the previous fluid mechanics. In fact, the non-slip wall surface in fluid mechanics means there is no wall slippage in the macroscopic large-scale flow process, and the problem is simplified, which has little effect on the result and conforms to the macro-scale large-scale flow. However, for some micro-flow and micro-scale flow in this paper, interfacial tension needs to be considered during the flow process, and there will also be natural wetting hysteresis, so wall slippage may occur. Due to the limitation of current testing methods, the critical receding angle and critical advancing angle of residual oil cannot be measured yet. In addition, it can also be seen from the calculation of the normal deviator stress and the horizontal stress difference in this paper that, if we use displacement fluid for flooding, the viscoelastic properties of the displacement fluid can increase the stress of the displacement fluid acting on the residual oil surface. At the same time, it also affects the force distribution on the residual oil surface. The maximum stress point is no longer the three-phase contact point, but close to the middle part of the upstream and downstream of the residual oil. Such stress distribution makes sliding almost impossible after wetting hysteresis of the residual oil. However, due to the change of the stress extreme point, stress concentration occurs at a certain position of the residual oil and then breaks, so that the separation of small oil droplets is very likely to occur. This is the second start-up condition.

The "separation" of residual oil means that the residual oil breaks and separates under the action of the displacement fluid, forms new small oil droplets before transport by the displacement fluid, as shown in Fig. 9.

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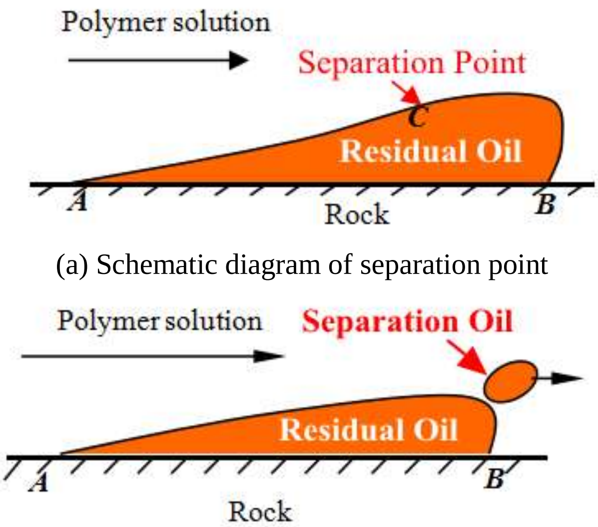

(a) Schematic diagram of separation point

(b) Separation of residual oil

Fig.9 The separation of residual oil

Under the action of displacement fluid, residual oil will occur deformation, as shown in Fig. 9 (a). At this point, you can calculate the residual oil of each point on the surface of force, also can calculate the residual oil distribution of each point on the surface of capillary number *Ca*. When the capillary number *Ca* at a point C on the oil droplet surface exceeds a certain critical value *Ca*, the residual oil will rupture from the point C and separate out free oil droplets as shown in Fig. 9(b), with the free oil droplets carried away by the displacement fluid.

At present, the research on the stability of residual oil in oil reservoirs is in the initial stage. The biggest difficulty is that the existing technical means cannot determine the critical capillary number *Ca*, which can only be calculated based on the critical capillary number *Ca*=4.0 in the stability analysis of droplets in physical chemistry. It is believed that future visualized micro-displacement experiments will solve this problem.

4.3 Calculation of the capillary number in residual oil

Residual oil meter capillary number is mentioned here each point on the surface of the tangential force and interface Zhang Lizhi ratio, it is a dimensionless number, can be expressed as the calculation formula:

$$Ca = \frac{\mu v}{\gamma} \tag{4}$$

Where *Ca* denots the capillary number (a dimensionless number), μ denots the viscosity of displacement fluid (Pa·s), v denots the characteristic velocity of the displacement fluid ($m \cdot s^{-1}$), γ denots the interfacial tension ($N \cdot m^{-1}$).

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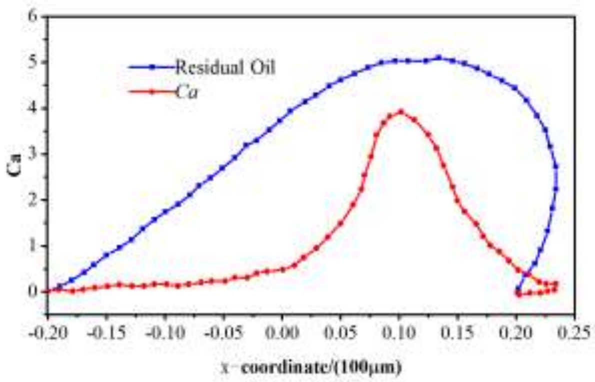
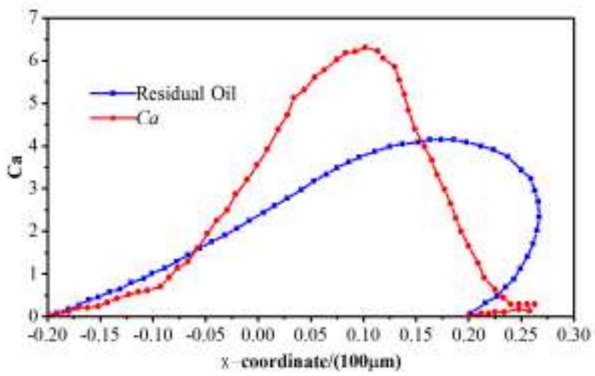
A greater capillary number means that the tangential force is large and the interfacial tension is small, and the oil film is easily broken and separated under the action of big tangential force. On the contrary, a small capillary number indicates that the tangential force is small and the interfacial tension is large, and the oil film tends to maintain the original shape under the action of interfacial tension. Fig. 10 shows the variation curve of the capillary number at each point of the residual oil surface after deformation of residual oil on the lipophilic rock surface when *We*=0.1, 0.2 and 0.4.

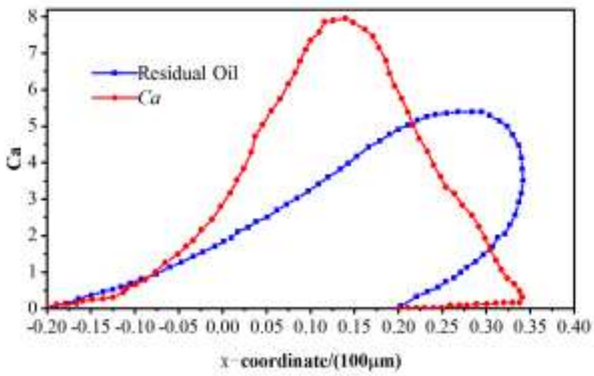
It can be seen from Fig. 10 that as the Weisenberg number (*We*) increases, the capillary number (*Ca*) on the residual oil surface also increases. It can be inferred that when the value of *Ca* at a certain point on the residual oil surface exceeds the critical value *Ca*, the oil film ruptures here, separating out small oil droplets.



(a) Curve of residual oil deformation versus capillary number at *We*=0.1



(b)Curve of residual oil deformation versus capillary number at *We*=0.2



(c) Curve of residual oil deformation versus capillary number at *We*=0.4

Fig.10 Water-wet rock surface deformation and capillary number of the residual oil

V. CONCLUSION

Maxwell constitutive equation is used to establish the flow equation of viscoelastic fluid in microchannels. Numerical calculation of residual stress field around the oil film and the level of effect on residual oil film and normal partial differential stress. The analysis of the flexibility of viscoelastic displacement oil's influence on the oil film bearing, further prove theoretically that the viscoelastic displacement oil can improve the microcosmic oil displacement efficiency.

The flow equation composed of continuity equation, motion equation and constitutive equation is a nonlinear equation with complex boundary conditions, so it is solved by numerical calculation. The results show that the viscoelasticity of polymer solution on residual oil film force and deformation have a significant impact. When high-concentration displacement fluid is injected, high permeability residual oil has more obvious deformation than medium and low permeability residual oil. When low-concentration displacement fluid is injected, residual oil with low, medium and high permeability presents similar deformation. The strength of the viscoelasticity of polymer solution, the greater the impact on residual oil film, the more obvious asymmetry, oil film is easy to deformation, which is broken, and finally isolated small droplets from the substrate.

The start-up of residual oil involves two situations: sliding of residual oil and separation of residual oil. There is no specific value for the critical advancing angle and receding angle in the residual oil start-up. In addition, the viscoelastic displacement oil is changed on remaining oil distribution of forces, the extreme value point is no longer a three-phase point of contact forces. Therefore, there is small possibility in sliding of the residual oil. Because of this, in the second case, the rupture and separation of residual oil is very likely to occur. When the residual oil surface reaches the stress limit at a certain position, it will break and separate out free oil droplets.

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