Assessment of polymer flooding effects on the recovery of heterogeneous thick reservoirs with dominant channel

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Received: 4 July 2019 / Accepted: 23 August 2019 / Published online: 27 August 2019
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Abstract

The formation of dominant channel has restricted the improvement in oil recovery in heterogeneous thick reservoirs greatly. How to effectively solve the problem has become a key issue in the development process. In this paper, firstly, the plugging effect of polymer flooding on the dominant channel is studied by visual microscopic-model displacement experiment. And then, we established a flow resistance model and simulated the effect of polymer flooding on improving dominant channel. The result shows that the present model matches the oilfield testing data greatly. And the higher the concentration, the more effective the plugging. When the polymer concentration is 2.0 g/L, the water content can reduce by 21.24% and the enhanced oil recovery can reach 13.69%. Besides, the efficiency of the reverse rhythm is higher than the positive rhythm under the same condition. This study has provided a quick and accurate assessment of the polymer flooding for the dominant channel in the heterogeneous thick reservoir.

Keywords Polymer flooding · Dominant channel · Thick reservoir · Heterogeneous

Introduction

The heterogeneous thick reservoir is one of the most important oil storage types in the world. Because of the strong heterogeneity structure, the formation pressure of the heterogeneous thick reservoirs declines rapidly under the natural energy, which will lead to low efficiency (Bane et al. 1994; Germanovich et al. 2012). Most oilfields are used to supplement the pressure loss by water flooding. The advantage of water flooding is that the formation pressure can be raised rapidly. But it is easy to form dominant channel after long-term strong injection, and the fluid tends to flow through high-permeability layer with low resistance, which would lead to circulating inefficiently, smaller reservoir swept volume. And then, the remaining oil in the thick braided river sand is dispersed and enriched (Bane et al. 1994; Zhang et al. 2008; Feng et al. 2013).

To control the resistances of all channels, we must plug the dominant channel. After a lot of experiments and theoretical studies, polymer plugging has become one of the most effective methods for enhanced oil recovery across the globe. Polymer flooding has been put into practice in the oilfield for about 40 years (Khodaverdian et al. 2010; Maya-Toro et al. 2012; Sheng et al. 2015; Sharafi and Jami-alahmadi 2016; Torrealba and Hoteit 2018). And now China is leading in the implementation of polymer flooding. The advantage of polymer flooding over water injection is that it can not only provide improved sweep efficiency by reducing the viscous fingering effects in the reservoir but also provide a preferable mobility ratio by increasing the viscosity of the displacing fluid, and then improving the recovery (Dupas et al. 2013; Deng et al. 2014; Riahi-zhad et al. 2017; Mahran et al. 2018). Some studies show that polymer flooding can reduce water content by 50% at most and increase flow resistance by 5–15% (Kamal et al. 2015).

To observe the flow state of fluids in porous media directly, the visual microscopic-model experiment comes into being and has better application in practical items. At present, we can study the development of water flooding and polymer flooding under different pore sizes, different oil types and different temperatures by the visual microscopic model (Xia et al. 2008; Wu et al. 2016).

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In this paper, firstly, a visual microscopic-model experiment was carried out to study the plugging effect of polymer flooding on the dominant channel. Secondly, a mathematical model to characterize the change rule of water content using flow resistance was established. And then, we verify the correctness of the present model through oilfield testing data. After that, we analysis the influence of polymer concentration and rhythm on the recovery of the reservoirs. This study has provided a quick and accurate assessment of the polymer flooding for the dominant channel in the heterogeneous thick reservoir.

Methodology

Study area

The study area in this paper is located in a certain block in the Southwest of Lamadian Oilfield, Daqing City, China. This area belongs to the high-permeability sandstone reservoir, and the main sedimentary facies is a meandering river, as shown in Fig. 1. The average permeability of the reservoir is $200 \times 10^{-3} \mu\text{m}^2$. And the reservoir buried depth is about 1270–1320 m. Even though the meandering river sand body is thick and distributed in succession, the heterogeneity in the layer is strong, and the interlayer in the sand body is discontinuous. After long-term strong exploitation, a high-water consumption zone formed, and the residual oil in thick braided river sand body showed dispersive enrichment.

Fig. 1 The phase diagram of the study block

Experiment

Because of the formation of the dominant channel, the overall water cut of the reservoir rises rapidly to 97.6%, the water injection efficiency is low, and the swept volume is small, which resulted in the comprehensive recovery percent of only 36.5%. At present, the most effective method to solve the invalid circulation of the dominant channel is injecting polymer slug, which can enlarge the swept volume of water injection and then enhance oil recovery.

We studied the effect of polymer flooding on improving the dominant channel through the visual microscopic-model displacement experiment. The experimental steps are as follows:

1. Designing and fabricating the visualized microscopic-model with physical properties similar to that of the study area.
2. Selecting suitable polymers according to the permeability and pore size.
3. Saturating the visualized microscopic model with oil.
4. Water flooding until the water content reaches 90%.
5. Injecting polymer solution and then water flooding again.

In this paper, we selected a kind of weak gel with high and stable viscosity, PAMS/phenolic gel, as the polymer solution. The results are shown in Fig. 2.

In the experiment, we carried out the blank test of water flooding to compare with polymer flooding, and the standard of primary water injection is that the water content reaches 90%. The results are shown in Table 1, and the ultimate EOR (enhanced oil recovery) of polymer flooding is 13.14%.

Mathematical model

Under the visual microscopic-model displacement experiment, we use mathematical methods to explain the effect of polymer flooding. The physical model is shown in Fig. 3; we inject the polymer as the slug after the formation of the dominant channel. And then, the residual oil area will be displaced.

Darcy's law shows that the rate of flow changes with the permeability change. And the true and effective permeability of the reservoir will change with the erosion of the porous media by flooding, which can decrease the flow resistance, and then the dominant channel will be formed. The flow resistance of each zone can be obtained by hydropower similarity principle, as shown below (Song et al. 2009; Wei et al. 2017).

Dominant channel:

$$R_d = \frac{1}{2\pi h k_{d,1} f_{d,1}} \ln \frac{r_{d,1}}{r_w} + \frac{1}{2\pi h k_{d,2} f_{d,2}} \ln \frac{r_{d,2}}{r_{d,1}} + \frac{1}{2\pi h k_{d,3} f_{d,3}} \ln \frac{r_e}{r_{d,2}} \quad (1)$$

Fig. 2 Changes of residual oil before and after polymer flooding **Table 1** Remaining oil saturation and enhanced oil recovery in different modes

Displacement mode	Remaining oil saturation (%)		Increase rate (%)	Enhanced oil recovery (%)
	Primary water injection	Dual water injection		
Water flooding	50.26	43.1	7.16	–
Polymer flooding	50.26	29.96	20.3	13.14

Fig. 3 Schematic diagram of polymer flooding model

Residual oil area:

$$R_r = \frac{1}{2\pi h k_{r,1} f_{r,1}} \ln \frac{r_{r,1}}{r_w} + \frac{1}{2\pi h k_{r,2} f_{r,2}} \ln \frac{r_e}{r_{r,1}} \quad (2)$$

And then, we can obtain the total resistance.

$$R_t = \frac{1}{\frac{1}{R_d} + \frac{2}{R_r}} = \frac{2R_d + R_r}{R_d R_r} \quad (3)$$

where f is the slug fluidity, and $f_{d,1} = f_{d,3} = \frac{k_{rod}}{\mu_o} + \frac{k_{rwd}}{\mu_w}$, $f_{d,2} = \frac{k_{rpd}}{\mu_p} + \frac{k_{rwd}}{\mu_w}$, $f_{r,1} = f_{r,1} = \frac{k_{ror}}{\mu_o} + \frac{k_{rwr}}{\mu_w}$, R_d and R_r are the resistance of dominant channel and residual oil area, respectively, R_t is the total resistance of the model, h is the thickness of the sand body, k_i is permeability of layer i , r_e is the well spacing, and r_w is the radius of the wellbore.

According to the hydropower similarity principle, the productivity of the model also can be expressed as follows.

$$Q_t = \frac{\bar{P}}{R_t} \quad (4)$$

And the water production of each zone is shown as follows:

Dominant channel:

$$Q_{wd} = \frac{\bar{P}}{\frac{\mu_w}{2\pi k_{wd} h} \ln \frac{r_e}{r_w}} \quad (5)$$

Residual oil area:

$$Q_{wr} = \frac{\bar{P}}{\frac{\mu_w}{2\pi k_{wr} h} \ln \frac{r_e}{r_w}} \quad (6)$$

The total water production is $Q_{tw} = Q_{dw} + Q_{rw}$.

Then, the water content can be expressed as follows:

$$f_w = \frac{Q_{tw}}{Q_t} = \frac{2\mu_w (k_{wr} + k_{wd}) (R_d + R_r)}{2\pi R_d R_r k_{wr} k_{wd} h \ln \frac{r_e}{r_w}} \quad (7)$$

Numerical simulation

In order to further study the effect of polymer flooding on reservoir modification with the dominant channel, the streamline and saturation distribution of the injection–production unit before and after polymer flooding was studied by numerical simulation.

Figure 4 is the streamline and saturation distribution of the injection–production unit before and after polymer flooding. From Fig. 4a, we can know that most of the fluids flow through the dominant channel, which forms an invalid cycle. Under the same simulation conditions, and Fig. 4b shows that the swept area of water flooding is enlarged due to the

Fig. 4 Streamline and saturation distribution of the injection–production unit before and after polymer flooding

formation of polymer slug, which can improve the displacement efficiency.

Based on the numerical simulation, the recovery efficiency of water injection followed by polymer injection is calculated, and the result is shown in Fig. 5. From Fig. 5, we can obtain that the overall recovery efficiency will increase by about 12% after polymer injection, which means that the injection of polymer reduces the invalid cycle efficiency greatly.

Results and discussion

Model validation

Figure 6 displays the comparison of oilfield testing data and the presented model. With the same parameters of the oilfield, we calculated and compared the variation law of the water

Fig. 5 Relationship between recovery efficiency and injection volume

Fig. 6 Comparison of oilfield testing data and the presented model

content using the present model. The comparison shows that the present model considering flow resistance has good agreement with the oilfield testing data. From the result, we can obtain that water breakthrough occurred about 8500 days after production. Then, the water content increased rapidly. The basic parameters of the oilfield are shown in Table 2.

Influence of polymer concentration on reservoir water content

Figure 7 is the relationship between water content and polymer concentration under different polymer concentrations. The result shows that the higher the polymer concentration, the more obvious the decrease in water content, and the more effective the plugging. As shown in Table 2, under the three concentration conditions, the water content reduces rates, 10.13%, 15.87%, and 21.24%, and the corresponding EOR is 9.27%, 11.36% and 13.69%, respectively. Taking into account the costs and benefits of production, the polymer concentration is generally controlled within 3 g/L.

Influence of rhythm on reservoir water content

The rhythm is the main form of reservoir heterogeneity, which has a great effect on displacement efficiency. Figure 8 is the relationship between water content and injection volume under polymer flooding with different rhythms. The result shows that the development effect of the reverse rhythm reservoir is better than that of the positive rhythm reservoir under the same injection volume.

Fig. 7 Water content with different polymer concentrations

Fig. 8 Water content with a different rhythm

Conclusion

In this paper, a visual microscopic-model experiment was carried out to study the recovery of polymer flooding on the dominant channel. The result shows that the ultimate EOR of polymer flooding can reach 13.14%. And then, we established a mathematical model to characterize the change rule of water content using flow resistance. After that, the effect of polymer flooding on fluid flow and saturation was studied by numerical simulation. And we obtained that the overall recovery efficiency increased by about 12% after polymer flooding.

The result shows that the present model considering flow resistance has good agreement with the oilfield testing data. Besides, the higher the polymer concentration, the more obvious the decrease in water content, and the more effective the plugging. When the polymer concentration is 2.0 g/L, the

Table 2 The basic parameters of the reservoir

Parameters	Porosity	Permeability (mD)	Initial oil saturation (%)	Salinity (mg/L)	Original formation pressure (MPa)	Oil viscosity (mPa s)
Value	0.26	200	67	7150	11.27	10.3

water content can reduce by 21.24% and the enhanced oil recovery is 13.69%. Besides, the displacement efficiency of the reverse rhythm is higher than that of the positive rhythm under the same injection volume.

This study has provided a quick and accurate assessment of the polymer flooding for the dominant channel in the heterogeneous thick reservoir.

Acknowledgements We gratefully acknowledge the National Science and Technology Major Project under Grant 2016ZX05010-003 for financial support.

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