Injection profile inversion timing judgment model for polymer flooding and its theoretical validation

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Abstract. In the background of low oil price, polymer flooding plays a crucial role in offshore development of high-permeability and viscous oil reservoirs. However, during the whole flooding process, profile inversion occurred frequently and could lead to inefficient or low efficient circulation of polymer. Knowing the timing of profile inversion could implement the multi-plug mobility adjustment technology duly, it can effectively expand the sweep volume. At present, the mechanical control factors and influence laws of the profile inversion timing are still unclear, and the suitable mathematical model for judging the timing of profile inversion is also missing. Therefore, on basis of two-layer one dimensional flow model of heterogeneous reservoir, the flow rate distribution model and profile inversion timing judging model are established respectively. These two models are verified by fitting changing parameters of resistance factor using polymer core flooding data, and the influence rules of polymer profile inversion timing are also discussed in this paper. The results show that profile inversion timing is affected by parameters c and d on high permeable layer and parameter b on low permeable layer, which parameters b and d have negative correlation and parameter c has positive correlation with the timing. Based on the established profile inversion timing judgment model and combined with polymer core flooding relative flow ratio data, we can obtain the changing parameter of resistance factor which provide a new quantitative method to evaluate polymer system, predict flooding effect and judge implement time of multi-plug injection technology.

1. Introduction
With the profile control and displacement agent, especially polymer, develop continuously, polymer pilot tests or large-scale flooding projects were conducted in Argentina (El Tordillo oilfield), Germany (Bockstedt oilfield), Venezuela (Furrial oilfield) and other countries, besides China, the United States and Canada [1-3]. However, many oilfield liquid absorption profile tests show that the phenomenon of intake fluid profile inversion, namely the absorption amount of low permeability layer increases until achieve the maximum then starts to decrease (high permeability layer in contrast to low permeability...
layer), appears during the flooding process and results in polymer inefficient circulation in low permeability layers [4-6].

To mitigate the influence of profile inversion, multi-plug parallel energy gathering technology was introduced and implemented by injecting different properties and viscosity plugs in order to match different permeability layers [7-10]. Optimal injection timing of secondary slug is related to profile inversion timing. Therefore, many laboratory experiments have been carried out, aiming to clarify main control factors and influence laws of profile inversion timing [9-10]. The experimental results show that reservoir permeability grade, polymer relative molecular mass and injection timing have an influence on profile inversion during polymer flooding [9]. Profile inversion rate faster and the development level of low permeability layer is lower in heavy oil reservoir [10]. At present, the mechanical control factors and influence laws of the profile inversion timing are still unclear, and the suitable mathematical model for judging the timing of profile inversion is also missing.

To solve the above problems, one dimensional flow model and flow distribution model of two-layer heterogeneous reservoir are established. According to the correlation of resistance coefficient of high and low permeability layers, characteristic equation of profile inversion timing is deduced and three main mechanical control factors of profile inversion timing are confirmed. This paper also analyzes the influence laws of different main control factors on profile inversion timing through sensitivity analysis. Main mechanical control factors and influence laws of profile inversion timing can be applied to calculate polymer concentration, dosage and slug injection timing. The study results have practical application value for oilfield profile control and displacement technology.

2. Profile inversion mathematical model

2.1. Polymer flooding flow model

According to polymer flooding mathematical model and Darcy law, total seepage velocity of oil and water two-phase fluid during polymer flooding is

\[ q = -KWh \left[ \frac{k_{ro}(S_w)}{\mu_p(c_p)R(c_a)} + \frac{k_{ro}(S_w)}{\mu_o} \right] \nabla p \] (1)

where, \( q \) = fluid flow rate, cm³/s; \( k \) = absolute reservoir permeability, D; \( W \) = seepage section width, cm; \( h \) = seepage section thickness, cm; \( k_{ro}(S_w) \), \( k_{ro}(S_w) \) = relative permeability of water and oil phase respectively; \( S_w \) = Water saturation; \( p(Cp) \) = viscosity of polymer system, mPa·s; \( R(c_a) \) = resistance coefficient of polymer system; \( c_a \) = polymer adsorption amount, mg/g; \( \mu_o \) = viscosity of oil phase, mPa·s; \( \mu \) = pressure gradient, atm/cm.

Define \( X \) as total injection volume of polymer system and ignore the effect of concentration on viscosity, polymer adsorption amount is only related to total injection volume. Equation 1 can be represented as:

\[ q = -KWh \left[ \frac{k_{ro}(S_w)}{\mu_p R(x)} + \frac{k_{ro}(S_w)}{\mu_o} \right] \nabla p \] (2)

In order to deduce the above problem to a single phase model, equivalent viscosity is defined as:

\[ \frac{1}{\mu} = \frac{k_{ro}(S_w) \mu_o / \mu_p + k_{ro}(S_w) R(x)}{\mu_o} \] (3)
Where $\mu$ = equivalent viscosity of oil and water two-phase fluid, mPa*s.

Flow velocity of oil and water two-phase fluid can be simplified as follows:

$$q = -\frac{KWh}{\mu R(x)} \nabla p$$  \hspace{1cm} (4)

2.2. Flow distribution equation

For the high-low permeability two-layer reservoir model, according to equation 4, assume seepage section width is the same, flow ratio of the two layers is given by the following relationship:

$$q_1 = \frac{K_1h_1}{\mu_1 R_1(x)} \nabla p$$

$$q_2 = \frac{K_2h_2}{\mu_2 R_2(x)} \nabla p$$

$$q_1 = q_2$$

$$q_1' + q_2' = 1$$

Where $q_1$, $q_2$ = flow rate, cm³/s; $K_1$, $K_2$ = absolute permeability, D; $h_1$, $h_2$ = seepage section thickness, cm; $\mu_1$, $\mu_2$ = equivalent viscosity of oil and water two-phase fluid, mPa.s; $R_1(x)$, $R_2(x)$ = resistance coefficient of polymer system; $k_{rw1}(Sw1)$, $k_{ro1}(Sw2)$ = relative permeability of water and oil in high permeability layer respectively; $k_{rw2}(Sw1)$, $k_{ro2}(Sw2)$ = relative permeability of water and oil in low permeability layer respectively.

The influence of relative permeability is neglected, for relative permeability is generally much smaller than resistance coefficient. According to equation 5, flow distribution equation of high and low permeability layer is presented blow:

$$q_1' = \frac{K_1h_1 R_2(x)}{K_2h_2 R_1(x) + K_1h_1 R_2(x)}$$  \hspace{1cm} (6)

$$q_2' = \frac{K_2h_2 R_1(x)}{K_2h_2 R_1(x) + K_1h_1 R_2(x)}$$  \hspace{1cm} (7)

Where $q_1$, $q_2$ = relative flow. $q_1' + q_2' = 1$.

2.3. Profile inversion timing judgment model

According to the change of resistance coefficient obtained by polymer injection experiment, relationship between resistance coefficient of high and low permeability layer is obtained by regression [5], as shown in equation 8 and equation 9.

$$R_1(x) = c \ln x + d \hspace{1cm} c > 0$$  \hspace{1cm} (8)

$$R_2(x) = ae^{bx} \hspace{1cm} b > 0$$  \hspace{1cm} (9)

Where $c$, $d$ = changing parameter of resistance coefficient in high permeability layer; $a$, $b$ = changing parameter of resistance coefficient in low permeability layer.

Generally, in the early stage of injection, polymer system mainly enters in high permeability layer. Resistance coefficient $R_1(x)$ of high permeability layer rises faster than resistance coefficient $R_2(x)$ of...
low permeability layer, therefore flow rate of low permeability layer gradually rises. Flow rate ratio of high and low permeability layer decreases gradually. When injection volume $x$ exceeds inversion timing, flow rate of low permeability layer begins to decrease and ratio of flow rate starts to increase. Therefore, inversion timing is the extremum of flow ratio in high and low permeability layer. When ignoring influence of seepage and substituting equation 8, 9 into equation 5, the extremum of flow ratio of high and low permeability layer can be obtained by derivative two sides of equation 5. So profile inversion timing judgment model can be represented as:

$$b(c \ln x + d) - \frac{c}{x} = 0$$

As shown in equation 10, profile inversion timing is influence by parameter $c$, $d$ and $b$. According to equation 8 and 9, parameter $c$ and $b$ characterize the rise rate of resistance coefficient in high and low permeability layer respectively. Parameter $d$ characterizes resistance coefficient of high permeability layer when injection volume is 1.

3. Profile inversion model verification

3.1. Flooding experiment

(1) Experimental materials

The polymer is high-molecular polymer (Relative molecular mass is $1900 \times 10^4$) produced by Petro China Daqing Refining & Chemical Company, and its effective content is 88%. In this experiment, crude oil viscosity is 17mPa·s, total salinity of experimental water is 1678mg/L and experimental temperature is 57°C. Experimental core is artificial heterogeneous quartz sand epoxy cemented core, and its size is $4.5 \text{cm} \times 4.5 \text{cm} \times 30 \text{cm}$. The core consists of high and low permeability layer with thickness of 1.5cm and 3.0cm respectively, and permeability is $2250 \times 10^{-3} \mu \text{m}^2$ and $750 \times 10^{-3} \mu \text{m}^2$.

(2) Experimental apparatus

Flooding experimental apparatus consists of stratospheric pump, pressure sensor, sandpack, hand pump and intermediate container. Except for stratospheric pump and hand pump, the other parts are placed in the 57°C thermostat.

3.2. Comparison of model calculation result

Polymer flooding begins after water flooding 0.6PV at rate of 0.2mL/min. According to flow distribution equation of polymer flooding, changing parameters of resistance coefficient in high and low permeability layer are obtained by fitting relative flow curve (figure 1), as shown in table 1. According to profile inversion timing judgment model, calculated profile inversion timing is 0.8PV. Calculated profile inversion timing is close to experimental result, and the trend of relative flow curves in high and low permeability layer are consistent, which partially validates rationality and practicability of profile inversion timing model.

| Table 1. Changing parameters of resistance coefficient in high and low permeability layer. |
|---|---|---|---|
| Parameter | $a$ | $b$ | $c$ | $d$ |
| Value | 0.1 | 5.5 | 55.0 | 30.8 |
4. Theoretical law analysis of profile inversion timing

4.1. Changing parameter of resistance coefficient in low permeability layer

(1) Parameter $a$

Adopting Changing parameter of resistance coefficient data in Table 1. Formation coefficient is 15. When parameter $a$ is given as 1, 1.5 and 3 respectively, relative flow curves show in Figure 2. When parameter $a$ increases monotonously, the maximum relative flow of low permeability layer decreases, but profile inversion timing is still 0.17PV. According to equation 9, when parameter $a$ increases, the maximum relative flow of low permeability layer decreases, because resistance coefficient increases. Profile inversion timing remain unchanged, as profile inversion timing is not related to parameter $a$, analyses through equation 10.

Figure 1. Experimental value and calculated value of relative flow.

Figure 2. Sensitivity of parameter $a$ to relative flow.
Figure 3. Sensitivity of parameter b to relative flow

(2) Parameter b
Using Changing parameter of resistance coefficient data in Table 1. Formation coefficient is 15. Assume parameter b is 2.5, 5 and 10, relative flow curve is shown in Figure 3. When parameter b increases monotonously, the maximum relative flow of low permeability layer decreases, and the profile inversion timing also decreases monotonously, its value is 0.25PV, 0.17PV and 0.12PV respectively. According to equation 9, when parameter b increases, the maximum relative flow of low permeability layer decreases, because resistance coefficient rises faster. So profile inversion timing also advanced.

4.2. Change parameter of resistance coefficient in high permeability layer
(1) Parameter c
Using the changing parameter of resistance coefficient data in Table 1. Formation coefficient is 15. Setting parameter c is 8, 12 and 16 respectively, relative flow curve is shown in Figure 4. When parameter c increases monotonously, the maximum relative flow of high permeability layer increases. Profile inversion timing also increases monotonously, its value is 0.06PV, 0.11PV and 0.17PV respectively. According to equation 8, when parameter c increases, the maximum relative flow of high permeability layer increases, because resistance coefficient decreases (0–1PV). So profile inversion timing will be delayed.

Figure 4. Sensitivity of parameter c to relative flow
Adopting changing parameter of resistance coefficient data in Table 1. Formation coefficient is 15. When parameter \(d\) is 48, 60 and 72 respectively, relative flow curve is shown in Figure 5. When parameter \(d\) increases monotonously, the maximum relative flow of high permeability layer decreases. Profile inversion timing also will decrease monotonously, its value is 0.17PV, 0.12PV and 0.09PV respectively. According to equation 8, when parameter \(d\) increases, the maximum relative flow of high permeability layer decreases, because resistance coefficient increases. So profile inversion timing also advanced.

5. Conclusion
In this paper, a flow distribution model and a profile inversion timing judgment model have been established, and the validity also been verified with experiment results. This paper also analyzes the influence law of different main control factors on profile inversion timing. So main conclusions are as follows.

(1) According to flow distribution model, relative flow of high and low permeability layer is influenced by formation coefficient ratio, relative seepage capacity and ratio of oil viscosity to polymer viscosity. It is also influenced by the change of resistance coefficient.

(2) According to profile inversion timing judgment model, profile inversion timing is influenced by parameters \(c\) and \(d\) on high permeability layer and parameter \(b\) on low permeability layer, which parameters \(c\) and \(d\) have negative correlation and parameter \(c\) has positive correlation to the timing.

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