The Slug Design of Multi-slug and Equi-fluidity Oil Displacement with Binary Flooding

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Abstract. This paper optimizes the design of the nature of each slug and the combination of slugs through theoretical calculations and laboratory experiments, which is the key to tremendously enhance the oil recovery with the oil-displacing method of multiple multi-slug combinations. When oil-displacing experiments with multiple multi-slug combinations are conducted on heterogeneous cores in the laboratory, it is necessary that each injected slug be designed rationally in their viscosity, volume, etc., with the view to guarantee the synchronous equi-fluidity mobility of each slug after water flooding. With the synergistic effect of a variety of oil-displacing agents, the remaining oil in each permeability layer can be dug, driven by overall piston.

Keywords: Slug Design, Multi-slug, Equi-fluidity, Binary Flooding.

1. Introduction

When developing the layer of heterogeneity with water flooding, it is unable to regulate particularly high permeability layer only with injecting water, which leads to the injection of a large number of invalid fluid and results in severely futile cycle and a waste of resources. When displacing oil with polymer, phenomena like flow difficulties or clogged pores will emerge in the migration process of polymer in the core pores if the molecular radius of gyration is close to the channel cross-section ratio, or large enough to severely affect the normal flow of fluid [1-2]. The author evaluates the possibility of the rejection of the binary system at the early stage through the injection experiment on different core permeability with binary system solutions of different molecular weights and different concentrations of polymers, laying the necessary foundation for the slug design of equi-fluidity.

2. Design of Slug Viscosity

If expulsion is seen as the piston-driving process, and to achieve the synchronous movement of juxtaposed slugs in different permeability layers in the subsequent course of water flooding, it is required that the flow rates of each slug are the same, to achieve which the slug viscosity should be designed properly based on the differences in the permeability of each layer. Considering that the slug viscosity should match the permeability, and fluidity is equal to the ratio of the layer's permeability where the slug exists and the slug viscosity, it is reasonable to design equal fluidity of each slug, to further facilitate the movement of constant velocity. When $k_l/\mu_l=k_m/\mu_m=k_s/\mu_s$, the synchronous movement of constant velocity of parallel slug in each permeability layer can be realized according to Darcy formula, without considering the volume of the injected slug [2].

According to the result of experiment on fluidity, in terms of the core of $3000\times10^{-3}\mu m^2$, the fluidity controlled by experimental viscosity ranges from 35 to 450. According to the law of the lower fluidity, the higher oil recovery with chemical flooding [3], it will be better to choose low fluidity. If the figure of fluidity is 35, 27 groups of slug combination can be drawn according to the formula above.

3. Design of Slug Volume

A. The Assumption of Slug Design Condition

After the viscosity design of each slug according to the principle of equal fluidity, considering the actual situation of slug injection, it is indispensable to have rational calculation of the volume for each injected slug, in order to fulfill the synchronous movement of each slug in the same velocity. And for the heterogeneous cores of positive rhythm containing three different permeability layers, the author makes design calculations of injection volume of slug in the experiment on oil displacement with multiple multi-slug combinations [4-5].

Table1 the design of slug

fluidity	The first slug	The second slug	The third slug
35	25millon,600mPa s 16millon,295mPa s 8millon,170mPa s	25millon,600mPa s 16millon,295mPa s 8millon,170mPa s	25millon,600mPa s 16millon,295mPa s 8millon,170mPa s

The basic data includes: The length of heterogeneous cores with positive rhythm is *L*. The sectional area of the three layers with different permeability is A. The permeability of high, medium and low permeability layer is K_1, K_2, K_3 respectively. The porosity of three layers is φ_1, φ_2, φ_3 respectively. The viscosity of slug injecting into the cores in turn are μ_1, μ_2, μ_3. The specific figures can be obtained from the viscosity design of slug above. The viscosity of original fluid in core before the injection of slug is μ_L. The viscosity of water in the subsequent water flooding is μ_w. To calculate easily, simplified model is designed, as shown in Fig.1.

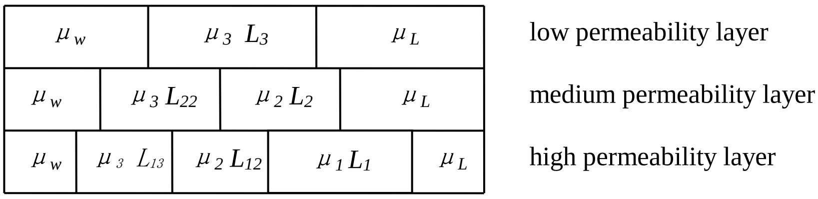

Fig.1 The idealized injection situation of slug in heterogeneous core

The injected length of three slugs with viscosity of μ_1, μ_2, μ_3 in the high, medium and low permeability layer are as shown above. As the cross-sectional area of each permeability layer is the same, the ratio of injected length for each slug in each layer is equal to the ratio of injected volume for each slug in each layer. Then it calculates the injected volume of slug according to the formula when the flow is unidirectional and steady, to achieve the same seepage velocity in each layer after the injection of slug, and to further realize the overall piston flooding. To make the moving velocity of slug in the three layers are v_1, v_2, v_3 after the injection of slug, and all equals *v*, there is:

$$v_1 = \frac{K_1 \Delta p}{\phi_1(\mu_3 L_{13} + \mu_2 L_{12} + \mu_1 L_1)}$$

$$v_2 = \frac{K_2 \Delta p}{\phi_2(\mu_3 L_{22} + \mu_2 L_2)}$$

$$v_3 = \frac{K_3 \Delta p}{\phi_3 \mu_3 L_3}$$

In these three formulas:

Δp-- differential pressure before and after slug, *MPa*;

v_1, v_2, v_3-- slug's flowing velocity in high, medium and low permeability layer, *m/s*

B. Determination of the injection length of each slug

The above analysis shows that after the injection of three slugs, there are three slugs in the high permeability layer, two slugs injected later in the medium permeability layer, and in low permeability layer, there is only the last third injected slug. By virtue of the simplified injection model (*Fig*. 1) and the injection length of slug in each layer gained from the reasonable assumption and calculation, the injection area of slug in each layer can be obtained. Then the total area of the three injected slug can be calculated after combining the slug of the same viscosity in each layer [6].

a. Determination of the injection length of each slug in the high permeability layer

By formula v_1, the seepage resistance of slug section in the high permeability layer can be obtained:

$$R_1 = \frac{\phi_1}{K_1}(\mu_3 L_{13} + \mu_2 L_{12} + \mu_1 L_1)$$

As we can see from Equation 4, the flow resistance of slug section in the high permeability layer contains the flow resistance made by the three sub-slugs. However, considering that theoretically slug 1 of viscosity μ1 plays a major role in the high permeability layer, and the subsequently injected slug 2 and slug 3 separately flow into the medium and low permeability layer, the flow resistance $\varphi_1\mu_1L_1 / K_1$ generated by slug 1 in the high permeability layer should be the main component of the overall flow resistance generated by the three slugs, and then comes the flow resistance $(\varphi_1\mu_2L_{12}/K_1)$ generated by slug 2, and the minimum flow resistance is the one generated by slug 3, which is $\varphi_1\mu_3L_{13} / K_1$. Idealizing the situation in high permeability layer in Fig 2, and considering the critical state of slug 1 broken by slug 2, Figure 2 can be gained.

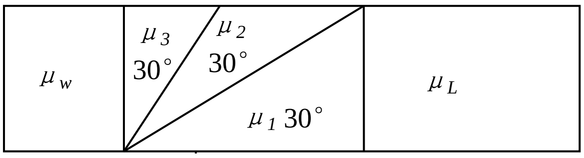

Fig.2 Ideal critical state of slug distribution in the high permeability layer

In Fig.2, the portion of the slug is the three slugs injected in order from right to left, respectively with a viscosity of μ_1, μ_2, μ_3. Because this is a theoretically general design of the injection proportion of each slug in the high layer, the angles formed by the slugs in the figure can be set as *30* °in order to facilitate the calculation. Thus, it can be calculated that in the critical state, the ratio of injection volume for the slug 1, 2, 3 in the high permeability layer is 3:2:1, which leads to the ratio L_1: L_{12}: L_{13} = 3:2:1 if reflected in the Figure. In practice, the injection proportion of slug 2 should be appropriately reduced, to ensure that slug 1 will not be broken through. Therefore, it can be supposed that: L_1: L_{12}: L_{13} = 9:3:1.

Since the design of viscosity is based on the principle of equal fluidity, the case of $K_1 > K_2 > K_3$ can result in $\mu 1 > \mu 2 > \mu 3$. Also, because L_1: L_{12}: L_{13} = 9:3:1, it can be guaranteed that the flow resistance generated by slug 1 in the high permeability layer is the largest, which means that in the high layer, slug 1 plays the major role of displacing, meeting the original design requirements. Therefore, from $v_1 = v$, it can be obtained:

$$L_{13} = \frac{K_1 \Delta p}{v\phi_1(\mu_3 + 3\mu_2 + 9\mu_1)}$$

$L_{12}=3L_{13}$, $L_1=9L_{13}$

Similarly, it can obtain the injection length of each slug in the medium permeability layer:

$$L_{22} = \frac{K_2 \Delta p}{\phi_2 v(\mu_3 + 3\mu_2)}$$

$L_2=3L_{22}$

The injection length of each slug in the low permeability layer is:

$$L_3 = \frac{K_3 \Delta p}{\phi_3 v \mu_3}$$

4. **Determination of the injection volume of each slug**

After determining the injection depth of three slugs in each permeability layer, then the injection volume of the three slugs can be calculated. Here we assume the injection volume of slug 1, 2, 3 are V_1, V_2, V_3, then:

$$V_1 = A\phi_1 L_1 = \frac{9A(K_1\Delta p)}{v(\mu_3 + 3\mu_2 + 9\mu_1)}$$

$$V_2 = A(\phi_1 L_{12} + \phi_2 L_2) = 3A\left[\frac{K_1\Delta p}{v(\mu_3 + 3\mu_2 + 9\mu_1)} + \frac{K_2\Delta p}{v(\mu_3 + 3\mu_2)}\right]$$

$$V_3 = A(\phi_1 L_{13} + \phi_2 L_{22} + \phi_3 L_3) = A\left[\frac{K_1\Delta p}{v(\mu_3 + 3\mu_2 + 9\mu_1)} + \frac{K_2\Delta p}{v(\mu_3 + 3\mu_2)} + \frac{K_3\Delta p}{v(\mu_3)}\right]$$

The injection volume V_1 of slug 1 is mainly the injection volume in the high permeability layer, the injection volume V_2 of slug 2 has two parts of injection volume which are in the high permeability layer and medium permeability layer, while the injection volume V_3 of slug 3 includes three parts of injection volume, namely injection volume in the high, medium, low permeability layers [7].

5. Conclusion

Through the design and analysis in the paper, it can be confirmed that the flow capacity of binary system in porous media has a relationship with polymer molecular weight and viscosity of binary system. The lower the viscosity is, the greater the influence produced by molecule weight on fluidity control is. The smaller molecular weight is, the decreasing figure of fluidity is larger as the viscosity increases, and namely the fluidity becomes more sensitive to the permeability. Under the same viscosity, the higher the molecular weight is, the lower the fluidity is. Thus, a system of the equi-fluidity slug combination of the different viscosity, molecular weights and fluidity can be designed, then realizing the equi-fluidity oil-displacement under the condition of binary flooding.

Acknowledgments

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