A new method for division water injection layers based on difference of interlayer percolation resistance

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Abstract. Dynamic split model for injection fluid of water drive oil production was established based on theoretical calculation. It can be used to analyse the mutual interference between the layers in the arbitrary water cut stage and predict the occurrence and aggravation of the interference node. The results show that: Liquids preferentially pass through areas with low percolation resistance, so the difference of interlayer percolation resistance is the essence of interlayer contradiction; Percolation resistance is mainly determined by the difference of layers (Permeability and Thickness of layer) and dynamic water status. The greater the percolation resistance difference is, the worse the average degree of injection fluid is, and the lower the oil production efficiency is; A new method of water injection layer division was established to weaken the interlayer interference from the source. This method considered influence factors of permeability, thickness and water cut. And the new method is better than the old method of assigning water injection interval only by the limit of permeability differential. It can guide the high efficiency production of oil field.

1. Introduction

Multilayer sandstone reservoir is the main reservoir type of continental sedimentary basin in China. The typical characteristics of multilayer sandstone reservoir are that the number of layers is large, the permeability difference between layers is large, and usually the effective thickness of layers is positively correlated with the permeability\cite{1}. Generally, for the injection water development of heterogeneous reservoirs, layer segments with similar physical properties are grouped together. However, the interference between layer and layer in the process of commingling production leads to the poor recovery of the low permeability layer, and the overall oil flooding efficiency is low\cite{2}. Therefore, how to weaken the interference between layer and layer at the source is important to the efficient development of oilfield. At present, there are many studies on interlayer interference, but most of them only describe the influence of heterogeneity\cite{3-7}. There are two kinds of main factors: Static factors and dynamic factors. Here, the static difference is the difference of permeability and effective thickness of each small layer. The dynamic difference is represented by the change of water absorption of each layer in the process of displacement\cite{8-9}. Therefore, it is necessary to create a new method for synthetically dividing water injection layers.
2. Model establishment

2.1. Calculation model of percolation resistance in water displacement process

The Moving equation of plane one way flow with constant saturation surface[10]:

\[ X - X_0 = \int_0^t Q \frac{\partial f_y(S_y)}{\phi A_y} dt \]  \hspace{1cm} (1)

Total flow through the two-phase percolation zone of arbitrarily section for a plane one way flow

\[ Q = -A_y K \left( \frac{K_{rw}}{\mu_r} + \frac{K_{ro}}{\mu_o} \right) \frac{d\mu}{dx} \]  \hspace{1cm} (2)

Integral (2)

\[ \Delta P = -\int_{P_1}^{P_2} d_P = \frac{Q \mu_o}{A_y K} \int_{P_0}^{P_1} \frac{d_x}{\left( \mu_r K_{rw} + K_{ro} \right)} \]  \hspace{1cm} (3)

Water cut can be expressed as

\[ f_y = \frac{\mu_r K_{rw}}{\mu_r K_{rw} + K_{ro}} \]  \hspace{1cm} (4)

Here:

\[ \mu_r = \frac{\mu_o}{\mu_r} \]  \hspace{1cm} (5)

Then, (3) divided by Q can get \( R \)

\[ R = \frac{\mu_r}{A_y K} \int_{P_0}^{P_1} \frac{\int f_y(S_y)}{K_{rw}} d_x \]  \hspace{1cm} (6)

(1) can be represented as

\[ X_F - X_0 = \int_0^t Q \frac{\partial f_y(S_y)}{\phi A_y} dt \]  \hspace{1cm} (7)

With (1-1) divided by (7) and for differential

\[ d_x = \frac{X_F - X_0}{f_y(S_y)} d_x f_y(S_y) \]  \hspace{1cm} (8)

\( R \) can be acquires by (6) and (8)

\[ R = \frac{\mu_r}{A_y K} \int_{P_0}^{P_1} f_y(S_y) \frac{X_F - X_0}{f_y(S_y)} d_x f_y(S_y) \]  \hspace{1cm} (9)
Put (7) in (9) and we get the final expression of $R$

$$R = \int_0^\epsilon Q \frac{\mu_w}{K} \phi \frac{f_x(S_y)}{K_{rw}} d\epsilon_y$$

(10)

The main factors affecting the variation of percolation resistance include two major categories through formula (10). Innate static difference of reservoir (Permeability and effective thickness of small layer) and the dynamic difference of water cut in different layers.

2.2. Splitting model

In order to define the flow regularity of water flooding in multilayer commingled production, a dynamic split model of displacing fluid in water flooding process was established. This model can dynamically reflect the mutual interference between layers at any stage of water cut. And the model can predict the injection liquid how to division at any combination of layers. It is better than the method use average value or the empirical formula.

$$Q_j = \frac{Q}{1 + \sum_{i=1, i \neq j}^{n} \frac{R_j(S_y)}{R_{i}(S_y)}}$$

(11)

$R$ is the percolation resistance, MPa/ml/s.

$\Delta P$ is the displacement pressure difference, MPa.

$Q$ is the fluid quantity, ml/min.

$\mu$ is the viscosity of the water, mPa·s.

$A$ is the sectional area, m2.

$\phi$ is the porosity.

$K$ is the permeability, 10-3μm2.

$f_x(S_y)$ is the water cut.

$K_{rw}$ is the water relative permeability.

$K_{ro}$ is the oil relative permeability.

$S_{or}$ is the residual oil saturation.

$X$ is the any point in the two-phase region, m.

$Q_j$ is the j-layer flow splitting, ml/min.

$R_{i}(S_y)$ is the percolation resistance at the current water cut of i-layer.

$\beta_j$ is the splitting coefficient of injection water in j layer;

$N$ is the total number of injection layers.

3. Schemes

Based on previous research results and practical production experience, the influence plan of different permeability differential and reservoir thickness on multilayer commingled production effect was designed. Theory research carried out to discuss the essence of interlayer interference and establishing a new method for fine classification of water injection layers.
Table 1. Schemes of composite layer with different permeability gradient difference.

| Scheme | Gradient difference | Permeability (mD) | Scheme | Gradient difference | Permeability (mD) |
|--------|---------------------|------------------|--------|---------------------|------------------|
| 1      | 2                   | 50, 100          | 5      | 8                   | 50, 400          |
| 2      | 3                   | 50, 150          | 6      | 10                  | 50, 500          |
| 3      | 4                   | 50, 200          | 7      | 2                   | 50, 100(Thickness×2) |
| 4      | 6                   | 50, 300          | 8      | 2                   | 50, (Thickness×2) |

4. Model solution

Formula (10) is used to calculate the corresponding percolation resistance in the water flooding process, and these curves of percolating resistance is used to calculate the dynamic splitting of injection fluid in parallel production of two composite layer. The calculation steps of percolation resistance in water flooding are as follows:

Step 1: The derivative of water cut and the water cut can be calculated through the data of oil and the water relative permeability, see formula (4). Here, phase permeability data of Daqing oilfield. See Figure 1.

Step 2: According to the formula (10), percolation resistance curve in the water flooding process can be obtained by the corresponding data.

Step 3: Calculating the splitting results of the mixed production by formula (11). Here, percolating resistance R of each layer changes dynamically with the change of water cut.

5. Application

5.1. Application of percolation resistance model

The graph of permeability - water cut - percolation resistance is established by the theoretical model of formula (10). See Figure 2, curves of percolation resistance can be divided into three stages when layer independent water flooding: rising A, falling B and stable C. Analysis the regularity of those percolation resistance changing with water cut, Stage A: The pore channels of oil are gradually
replaced by water, and the mutual interference between oil and water are increased. In this process, oil droplets continuously interrupt water droplets, and water droplets also continuously interrupt oil droplets. Jamin effect is serious, the additional flow resistance increases continuously. Stage B: Displacing phase at this moment has some volume in rock pore. When the space of water flow reaches a critical value, the flow ability is gradually stronger. Then, a small part of the water flow passage will be formed, and the flow channel network will be gradually expanded with more and more flow holes. This node is defined as a real breakthrough point, and the seepage resistance will rapidly decrease.

Stage C: The water phase was completely continuous but with occasional oil droplet distribution. The percolation resistance will drop to very low and the oil exchange efficiency will be very low in this stage. It is called an invalid cycle stage.

5.2. Application of splitting model

According to curves of percolation resistance in the process of water flooding, we can combine any two or more different permeability layers and by use of splitting model to predict the flooding dynamics of interlayers. We obtained the dynamic splitting result of injected fluid on design schemes during commingled production process. As shown in figure 3, the layer with low percolation resistance will always be selected as the priority runner for injection fluid. The layer with low percolation resistance has strong ability to absorb fluid. Therefore, the unbalance of percolation resistance is the root cause of injection fluid splitting and this reduces oil recovery efficiency. Here, percolation resistance difference is caused by static difference and dynamic difference between layers. Different static conditions between layers determine different initial percolation resistance of each layer and this result uneven distribution of injection fluid in the initial stage of commingling production. Then, the dynamic difference of water cut will further lead to the percolation resistance difference change between each small layer. With the distribution ratio of injected liquid in each layer will change continuously, and the contradiction between layers will gradually change or intensify. But the static difference induces the dynamic difference and determines the upper and lower limits. At the initial stage of commingling production, the splitting component of the injected fluid showed a slight decrease in the high permeability layer and a slight increase in the low permeability layer. In stage A, the percolation resistance of the high permeability layer is less than that of the low permeability layer, and its liquid absorption ratio is greater than that of the low permeability layer. The corresponding water content rise rate of the high permeability layer is faster than that of the low permeability layer. Therefore, the resistance rise rate of the high permeability layer is greater than that of the low permeability layer at this stage. As each layer water content increased to some value (B stage, water
cut about 40%), the percolation resistance in low permeability layer will be increase faster than the high permeability layer resistance or after the percolation resistance in high permeability layer has to peak, and then inject fluid split began to increase. With the percolation resistance in the high permeability layer decrease, water absorbing ability in high permeability layer will be more and more serious until low permeability layer almost absorbing ability. Stage C, water cut more than 95% the interference degree between layers reaches the peak until water cut reach 98% we called the injected water circulates inefficiently in the high permeability layer.

Figure 3. Variation of injection fluid splitting with water cut.

6. New methods of layer combination

6.1. Reasons for injection splitting
It is shows in figure 3. The splitting of the injected liquid will be serious with the permeability gradient difference of the combined layer increase when initial water content is equal. Even in the early stage of commingling production, the water absorption of the high permeability layer accounts for more than 95% of the total injection volume. It can also be observed that, the splitting of the injected liquid will be serious with the water cut increase and the splitting of the injected water will tend to be stable when the water cut reach to 98%. Now, oil displacement efficiency is extremely low. Therefore, it is very important to set a reasonable limit of effective commingling production permeability gradient difference. But results the splitting of the injected liquid shown, the limit value of effective commingling production permeability gradient difference is also related to some factor of layers effective thickness and fluidity ratio. Because the fluidity ratio of a reservoir is constant, this paper focuses on the analysis of effective thickness and permeability gradient difference between small layers.

It is shows in figure 4. With the increase of the thickness of the high permeability layer, the limit value of effective commingling production permeability gradient difference is decreases. At this point, the interference between layers becomes increasingly serious, and even if the thickness of the high permeability layer is large enough, although the level difference of the combined production layers is very small, the low permeability layer is difficult to use. On the contrary, with the increase of low permeability layer thickness, the interlayer interference is weakened. Therefore, a scientific and accurate method is needed for the fine combination of water injection layers rather than use the only index of commingling production permeability gradient difference.
6.2. Evaluation coefficient of injection splitting

A splitting coefficient of injection water is proposed as the evaluation index for commingling layers. The expression is

$$\beta_i = \frac{Q_i - Q/N}{Q/N}$$  \hspace{1cm} (12)

The splitting coefficient of injection water is to describe the degree: the splitting quantity of the injected water in the high permeability layer deviates from the average quantity.

Calculating split coefficient of each scheme through the formula (12). It is shows in figure 5, figure 6 respectively, the splitting coefficient is a comprehensive index including those effect factors. On the whole, the splitting coefficient decreases before water cut 40% and then increases with the increase of water cut. 98% of the injected water will circulate in the high permeability layer regardless of permeability gradient difference, thickness and other factors when the water cut increases to 95%.

It is also shown in figure 5 the larger the permeability gradient difference is, the larger the initial splitting coefficient will be. In figure 6, the larger the low permeability layer thickness is, the smaller the initial splitting coefficient will be, and the larger the high permeability layer thickness is, the larger the initial splitting coefficient will be.

Figure 5. Variation of injection fluid splitting with water cut.
6.3. Effective limit of commingling production

The relationship between oil recovery and the splitting coefficient of injection water is established by investigating the results of the oil recovery of existing layers combination in Daqing oilfield. Then, the initial limit of splitting coefficient of reasonable injection layers combination is given by the relationship between them.

It is shows in figure 7: (1) the low-permeability layer contained in the composite layer can be used efficiently which can reach 45% when the initial value of splitting coefficient of injection water is less than 0.3. Here, oil recovery of composite layers is more than 40% and that of low permeability layer is more than 35%. (2) Oil recovery of composite layers is about 40% and that of low permeability layer is between 35% and 40% when the initial value of splitting coefficient of injection water is between 0.3 and 0.5. (3) Oil recovery of composite layers is between 35% and 40% and that of low permeability layer is less than 35% when the initial value of splitting coefficient of injection water is between 0.5 and 0.7. (4) Oil recovery of composite layers is less than 30% and that of low permeability layer is less than 20% when the initial value of splitting coefficient of injection water is more than 0.7. Obviously the inflection point is 0.7. We should set 0.7 as the value of optimization limit of splitting coefficient. It is reasonable layers combination when splitting coefficient is less than 0.7.
7. Conclusions
The method of layers combination this paper established can describe the inter-layer interference of composite layers in any water cut stage.

A splitting coefficient of injection water is proposed as the evaluation index for composite layers, it can be used to effectively predict whether the water injection composite layer is reasonable. It is also proved to reasonable layers combination when splitting coefficient is less than 0.7. The splitting quantity of the injected water in each layer is relatively stable and the interference degree is small in the early stage of water flooding. When the water cut reaches about 40%, more injection fluid continues to split to the high permeability layer, and the inter-layer interference starts to intensify. And the overall liquid production capacity of the composite layer changes from initial inhibition to promotion, the oil exchange efficiency gradually decreases. When the moisture content is 95%, the interference degree between layers reaches the peak, and almost all the injected water circulates in the high permeability layer inactively.

The essence of layers interference is the imbalanced percolation resistance, and the factors causing the uneven percolation resistance include: permeability gradient difference, effective thickness difference, mobility ratio and water cut condition, etc. Layers combination of water injection zone must be taken into account permeability gradient difference, layer thickness and later dynamic change of water cut.

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