A New Method for Quantitative Description of Dominant Channels in High Water-Cut Stage

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Abstract

The development of the dominant channel seriously affects the water-flooding effect of the oil field and leads to a decrease in the recovery. How to effectively describe the dominant channel is an urgent problem to further improve the recovery rate of water-flooding in high water cut oilfields. Therefore, the quantitative calculation of the dominant channel's parameters was carried out by using the seepage theory and mathematical models in this study. The reservoir that developed the dominant channel was regarded as the parallel of the normal reservoir and the dominant channel. The ineffective water injection was calculated from the ineffective circulating water model. According to the principle of equivalence, the ineffective water production of the oil well and the water production of the normal reservoir were calculated. Then the parameters of the dominant channel were quantitatively described by the volume analogy and the Carman-Kozeny formula. The interwell connectivity model was used to calculate the parameters of the dominant channel in the well group. The results showed a good agreement with the actual offshore oilfield situation, and the effectiveness of the method was verified.

Introduction

At present, most oil fields in China have entered a period of high water cut, and long-term water injection development has led to the development of dominant channels in the reservoir (Moreno 2013; Fattahpour et al. 2012; Mamghaderi and Pourafshary 2013). The development of dominant channels has led to a large amount of injected water being directly produced by oil production wells, leading to ineffective circulation, exacerbating inter-layer contradictions, resulting in uneven displacement and poor development effects (He et al. 2000; Feng et al. 2009; Lerlertpakdee et al. 2014). Therefore, how to effectively describe the dominant channels quantitatively is a problem to be solved urgently in order to further improve the water flood recovery factor in oilfields with high water cut. At present, the qualitative identification methods of dominant channels are relatively mature (Wang et al. 2013; Jin 2009; Yu et al. 2009; Han et al. 2006;Wang et al. 2003). It is still difficult to use reservoir engineering methods to quantitatively calculate dominant channels, but many researchers have tried. Zeng et al. (2002) proposed the reservoir engineering method of quantitative calculation of the superior channel earlier, but the calculation result has a larger error, but the volume analog formula proposed by him is widely used. Peng et al. (2007) used the fuzzy comprehensive evaluation method to quantitatively describe the advantage channel, but the essence is still qualitative judgment, and the specific parameters of the advantage channel cannot be given. Liu et al. (2012) conducted a quantitative study using phase-controlled stochastic modeling on the basis of fuzzy comprehensive evaluation. Li et al. (2011) and Chen et al. (2015) respectively used intelligent training algorithms to study the quantitative calculation of dominant channels, but the method requires a large amount of well-logging data and the scope of application is relatively small. Yang et al. (2013) and Liu et al. (2003) used the tube flow model to estimate the parameters of the dominant channel. Feng et al. (2011) and Chen et al. (2013) respectively

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proposed the method of quantitatively describing the dominant channel using excess water-fuzzy comprehensive evaluation method and excess water-well connection method, but the use of the volume analog formula proposed by Zeng is not standardized. Liu et al. (2017) proposed a quantitative method based on the theory of mass transfer and diffusion. Ding et al. (2013) and Wang et al. (2016) respectively carried out quantitative calculation studies of the dominant channel considering the high-speed non-Darcy case. In this paper, the seepage index was 0.5 (turbulent state), but it was derived using the laminar flow mode.Therefore, on the basis of previous researches, the seepage theory and mathematical methods are carried out to calculate the parameters of the dominant channel, and provided theoretical support for the quantitative identification and governance of the dominant channel.

Methodology

Quantitative Description of One Injection One Production Advantage Channel. In order to ensure the rationality of the calculation, the following assumptions are made: the reservoir is macroscopically homogeneous; after the formation of the dominant channel, the original reservoir as the dominant channel forms parallel connection with the normal reservoir, as shown in Figure 1; only residual oil is left in the dominant channel, only producing water, and still obeying Darcy's law; the normal reservoir produces oil and water.

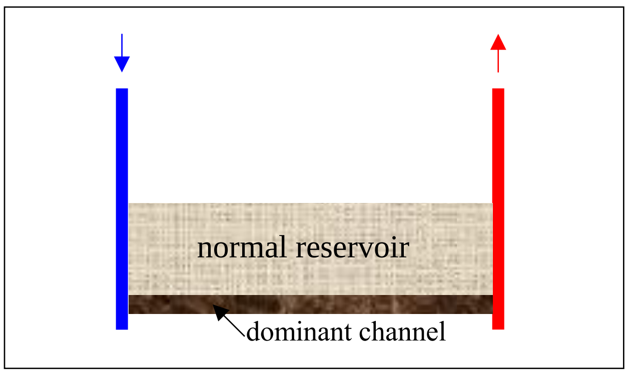

Figure 1--Diagram of dominant channel model.

In reference, the calculation method of invalid circulating water is proposed, but due to the large calculation error, it is seldom used. Based on the percolation theory, the author puts forward the calculation method of the invalid circulating water, that is, the water injected by the actual water injection volume is more than the theoretical water injection volume is the invalid circulating water, which is directly produced by the production well, and the calculation formula is shown in **Eq.1**.

$$Q_{\mathrm{wzx}} = Q_{\mathrm{wzs}} - Q_{\mathrm{wzl}} \quad (1)$$

$$Q_{\mathrm{wzl}} = \frac{2\pi K K_{\mathrm{rw}} h \Delta p}{\mu_{\mathrm{w}} \ln \frac{r_{\mathrm{i}}}{r_{\mathrm{w}}}} \frac{1}{B_{\mathrm{w}}} \quad (2)$$

where, Q_{wzx} is the invalid circulating water volume, cm^3/s; Q_{wzs} is the actual water injection volume, cm^3/s; Q_{wzl} is the theoretical water injection volume, cm^3/s; K_{rw} is the relative permeability of water phase, the general value within the control radius of water injection well is 1.0; K is the original permeability of reservoir, 10^{-3}μm^2; h is the effective thickness of reservoir, cm; Δp is the injection pressure difference, MPa; μ_{w} is the viscosity of injected water, mPa s; r_{i} is the control radius of water injection well, m; r_{w} is the radius of water injection well, m; B_{w} is the volume coefficient of water, f.

Since the invalid circulating water is directly produced by the production well, according to the principle of equivalence, the water quantity produced by the dominant channel of the production well is

$$Q_{\mathrm{wsd}} = Q_{\mathrm{wzx}} \quad (3)$$

where, Q_{wsd} is the water yield of the dominant channel, cm^3/s.

According to the volume analogy formula, the volume of the dominant channel can be determined as

$$\frac{V_{\mathrm{d}}}{V} = \frac{Q_{\mathrm{dl}}}{Q_{\mathrm{sl}}} \quad (4)$$

where, V_{d} is the volume of the dominant channel, cm^3; V is the pore volume of the injection production direction, cm^3; Q_{dl} is the theoretical water production when the dominant channel is the normal reservoir, cm^3/s; Q_{sl} is the theoretical water production of the production well when the dominant channel is not formed, cm^3/s.

In the application of **Eq. 4**, some papers mistakenly use the invalid circulating water volume as the dominant channel when it is the theoretical water production of normal reservoir, resulting in the increase of calculation error. Therefore, the author puts forward the following calculation methods.

After the formation of dominant channel, the water production of normal reservoir is as follows

$$Q_{\mathrm{wsc}} = Q_{\mathrm{wss}} - Q_{\mathrm{wsd}} \quad (5)$$

where, Q_{wsc} is the water production of normal reservoir after the formation of dominant channel, cm^3/s; Q_{wss} is the water production of production well, cm^3/s.

After the formation of the dominant channel, the oil production is part of the normal reservoir, so the water cut of the normal reservoir can be expressed as

$$f_{\mathrm{wc}} = \frac{Q_{\mathrm{wsc}}}{Q_{\mathrm{wsc}} + Q_{\mathrm{osc}}} \quad (6)$$

where f_{wc} is the water content of the normal reservoir, f; Q_{osc} is the oil production of the normal reservoir after the formation of the dominant channel, cm^3/s.

According to the relative permeability curve, the relative permeability of some water phases of normal reservoir is calculated, and then the theoretical water production of oil well without forming dominant channel is calculated, as shown in **Eq. 7**.

$$Q_{\mathrm{wsl}} = \frac{2\pi K K_{\mathrm{rw}} h \Delta p}{\mu_{\mathrm{w}} \ln \frac{r_{\mathrm{i}}}{r_{\mathrm{w}}}} \frac{1}{B_{\mathrm{w}}} \quad (7)$$

where Q_{wsl} is the theoretical water production, cm^3/s.

Then the theoretical water production when the dominant channel is a normal reservoir is calculated, as shown in **Eq.8**.

$$Q_{dl} = Q_{\mathrm{wsl}} - Q_{\mathrm{wsc}} \quad (8)$$

Then, the volume of the dominant channel can be calculated by substituting Eq. 4.

Considering the dominant channel as one-dimensional flow, the permeability of the dominant channel is calculated according to the volume of the dominant channel and the deformation formula of linear flow.

$$K_{\mathrm{d}} = \frac{Q_{\mathrm{wsd}} \mu_{\mathrm{w}} l^2}{a V_{\mathrm{d}} \Delta p} \quad (9)$$

Where K_{d} is the permeability of the dominant channel, $10^{-3} \mu m^2$; l is the well spacing, m; a is the conversion coefficient, *f*.

Using Carman Kozeny formula to calculate the roar radius of the dominant channel.

$$r_{\mathrm{d}} = \sqrt{\frac{8 K_{\mathrm{d}} \delta^2}{\phi}} \quad (10)$$

where, r_{d} is the dominant channel radius, μm; δ is the tortuosity, with the value of 1.5-5.5; ϕ is the porosity, *f*.

Quantitative Description of Dominant Channels in the Well Cluster

There are many production wells in the water injection well group, and the production wells may be affected by many water injection wells. Therefore, the key to describe the dominant channel in the well group is the production split in each direction of injection and production. In this paper, the split production calculation is based on the inter well connectivity model, which overcomes the shortcomings of traditional split methods that rely too much on subjective judgment.

The inter well connectivity model (Chen et al. 2018; Yousef et al. 2006; Chen 2020) is a dynamic inversion method developed in recent years. It can use injection production data to quantitatively calculate the dynamic connectivity between wells in a reservoir. It overcomes the shortcomings of the traditional method (Deng et al. 2003; Liao and Wang 2002; Feng et al. 2014) such as complex operation, production impact, and expensive cost, so it is widely used in oilfield production. In reference, a new connectivity calculation model with clear physical meaning is proposed, and its calculation formula is shown in **Eq. 11**.

$$q_{\mathrm{L}}^{j}(t)=q_{\mathrm{L0}}^{j}(t)+\sum_{i=1}^{N_j} f_{ij}q_i(t)\ , \qquad (11)$$

where, j is the serial number of production well; $q_L^j(t)$ is the daily underground liquid production of production well j, m^3/d; $q_{L0}^j(t)$ is the daily liquid production contributed by non water injection of production well j, m^3/d; i is the serial number of water injection well; N_j is the number of water injection wells corresponding to production well j; f_{ij} is the connection coefficient between water injection well i and production well j; $q_i(t)$ is the daily water injection volume of water injection well i, m^3/d.

The injection production connection coefficient is the proportion coefficient of the injected water flow from the injection well to the production well to the total water injection of the injection well, which can be used to split the ineffective circulating water. The dominant channel is not developed in all injection production directions of the well group, so it is stipulated here that the average value of injection production connectivity coefficient fij greater than that of all injection production connectivity coefficients in the well group is regarded as the dominant channel. Therefore, the connection coefficient of injection and production in the direction of developing dominant channel is normalized again, and the invalid circulating water is divided into various directions.

$$f_{\mathrm{g}ij}=\frac{f_{ij}}{\sum_{j=1}^{N_i} f_{ij}}\ , \qquad (12)$$

$$(q_{\mathrm{wsd}})_{ij}=(q_{\mathrm{wzx}})_{ij}=f_{\mathrm{g}ij}(Q_{\mathrm{wzx}})_i\ , \qquad (13)$$

where N_i is the number of oil production wells corresponding to water injection well i; $(q_{\mathrm{wsd}})_{ij}$ is the water production of the dominant channel between water injection well i and oil production well j, cm^3/s; $(q_{\mathrm{wzx}})_{ij}$ is invalid circulating water volume between water injection well i and oil production well j , cm^3/s; f_{gij} is the normalized connection coefficient between water injection well i and oil production well j, f; $(Q_{\mathrm{wzx}})_i$ is the total invalid circulating water in water injection well i, cm^3/s.

In addition, according to the injection-production connection coefficient, the amount of water injection to the oil production well can be calculated, and the water production of the same oil production well in all directions can be split according to this water injection quantity.

$$(q_{\mathrm{wss}})_{ij}=\frac{f_{ij}i_i}{\sum_{i=1}^{i=n_j} f_{ij}i_i}(Q_{\mathrm{wss}})_j\ , \qquad (14)$$

where $(q_{\mathrm{wss}})_{ij}$ is the actual water production in the direction of water injection well i and oil production well j, cm^3/s; n_j is the number of water injection wells related to oil production well j; $(Q_{\mathrm{wss}})_j$ is the actual production of oil production well j , cm^3/s.

After obtaining the invalid circulating water volume and the actual water production volume in all directions, the calculation is carried out according to the method of quantitative description of the one-in-one-dominant advantage channel.

Application

An offshore oil field is located in the Lower Liaohe Depression of the Liaodong Bay and the middle section of the Liaoxi Low Uplift, and is a lacustrine delta deposit. The average permeability of the oil field is $1100\times10^{-3}\mu m^2$, and the porosity is 0.30, which is a typical medium-high porosity reservoir. It has been more than 20 years since it was put into development. At present, the recovery degree is 29.6%, and the comprehensive water cut is 80.2%. It is in a high water cut stage. It is of great significance to carry out the identification of superior channels and quantitative description to guide the remaining oil potential.

Take a block as an example for calculation. The production wells in this block have fast water seepage rate, rapid increase in water content, poor water flooding development effect, and obvious development of dominant channels. Using the production data of this block, the dominant channels in each well group were identified and quantitatively described, as shown in **Table 1**. The test results show that there are well-developed channels between wells H3 and H4, H6 and H5, H6 and H7, H9 and H8, which is very consistent with the on-site understanding. In addition, the H6 well group carried out tracer test and calculated the permeability of the dominant channel using tracer data inversion. The calculation results are basically consistent with the method in this paper, and the reliability of the method is verified again. Through quantitative calculation, it can be seen that the permeability of the dominant channel in this block is basically above $4000\times10^{-3}\mu m^2$, and the average radius of the dominant channel is above 35 μm. Reagents with larger particle size of the plugging agent should be used to adjust the water drive structure.

Table 1--Preponderant Channel Recognition and Description Results of Blocks.

Injection well	Production well	Connectivity	Recognition result	Invalid circulating water volume m^3/d	Permeability of dominant channels $10^{-3}\mu m^2$	Mean radius of the dominant channel μm	Tracer explained permeability $10^{-3}\mu m^2$
H3	H4	0.60	√	62	4856	39.83	
	H7	0.35	×				
H6	H4	0.18	×				
	H5	0.29	√	38	3965	35.99	4233
	H7	0.36	√	47	5661	43.00	5916
	H8	0.17	×				
H9	H7	0.21	×				
	H8	0.40	√	46	5329	41.72	
	H10	0.20	×				
	H11	0.18	×				

Aiming at the three well groups developed in the dominant channel, the appropriate displacement control agent is selected according to the pore radius of the dominant channel of the well group for profile control. After the profile control and flooding, each well group has significant oil increasing effect. The whole block increases oil daily by about 60 m^3, and the water cut decreases by up to 10% (**Figure 2**).

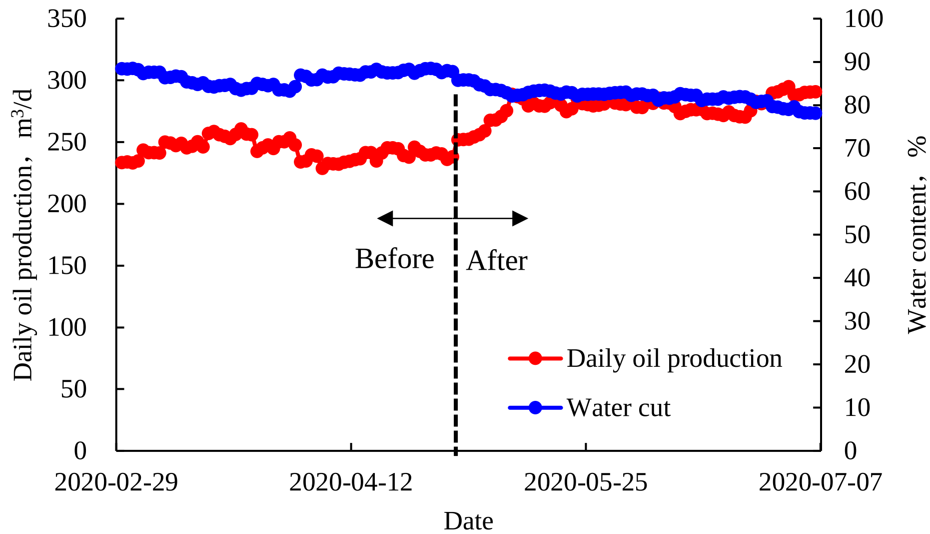

Figure 2--Production dynamic curve of Block H.

Conclusions

Regarding the reservoir with developed dominant channel as the parallel of normal reservoir and dominant channel, a calculation method to quantitatively describe the dominant channel between injection and production wells was established by the invalid circulating water model, volume analog formula and Carman-Kozeny formula. On this basis, the quantitative description of the dominant channels in the well group was realized based on the inter-well connectivity model. The field application results verified the effectiveness of the method, which has important technical guiding significance for the further improvement of water flood recovery in oilfields with high water cut.

Conflicting Interests

The author(s) declare that they have no Conflicting interests.

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