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Research Article

Study on Evaluation Method of Water Injection Efficiency in Low-Permeability Reservoir

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Low-permeability reservoirs, especially ultralow-permeability reservoirs, usually show a problem of ineffective water injection which leads to low pressure with high injection-production ratio. It is urgent to determine the direction and proportion of ineffective water injection, so as to guide the adjustment of water injection development. Based on the theory of percolation mechanics and combined with the modern well test analysis method, the determination method of effective water injection ratio was established. This method can not only judge the direction of injected water but also determine the proportion of invalid injected water. This method was applied on typical oil reservoirs; the evaluation results showed that extremely low permeability and ultralow permeability usually exist the situation of water holding around the injected well which is almost 20% of the injected water. Some areas existed the water channeling; the evaluation results showed that the water channeling was closely related with sedimentary microfacies rather than microfractures, and the invalid injection accounts are about 45% of the injected water. The method is simple and feasible, which can provide technical reference for the development strategy adjustment of water drive development in low-permeability reservoir.

1. Introduction

At present, low-permeability reservoirs, especially ultralow permeability, generally have the following two characteristics in water development. (1) High injection-production ratio, low reservoir pressure, and low water content. As shown in Figure 1, the reservoirs of Xifeng, Wangyao, Jilin 119, Jilin 228, Santanghu, Z8, and other reservoirs all showed the above problems. For ultralow-permeability reservoirs, the injection-production ratio is around 4, but the formation pressure is still decreasing. Where did the injected water go? (2) Medium and high injection-production ratio, good pressure maintenance level, and high water cut. Generally, this kind of reservoir has strong heterogeneity which is difficult to determine by traditional methods.

In this research, an evaluation method of water injection efficiency in low-permeability reservoir is established which is based on the percolation mechanics and modern well test analysis method.

2. Evaluation Method of Water Flow Direction and Injection Water Utilization Rate in Low-Permeability Reservoir

2.1. Evaluation Methods of Injection Water Utilization in Reservoirs with High Injection-Production Ratio, Low Formation Pressure, and Low Water Cut. The well test interpretation model of low-permeability reservoir is established. It combined with development parameters to determine the direction of injected water and the injection water utilization rate.

2.1.1. Establishment and Solution of Well Test Interpretation Model for Low-Permeability Reservoir. On the basis of the

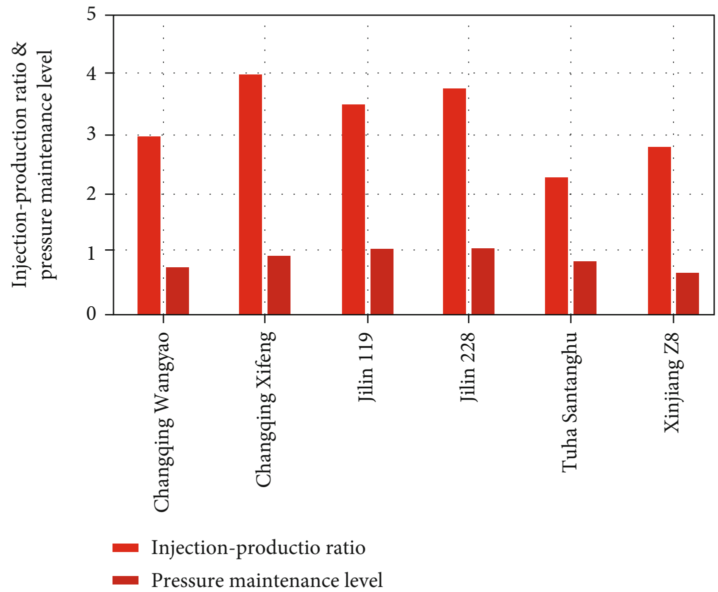

Figure 1: Injection-production ratio and pressure retention levels in typical reservoirs.

conventional well test model, a seepage mathematical model of low-permeability reservoir is established by considering stress sensitivity and complex fracture network. The solution of the model is achieved through perturbation transform and Laplace transform [1–5].

Mathematical model of seepage flow considering complex fracture network and stress sensitivity is shown as follows.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right)+\alpha\left(\partial\frac{\partial p}{\partial r}\right)^2-\frac{\lambda}{r}=e^{\alpha(p_i-p)}\frac{\mu\phi c_t}{3.6k}\frac{\partial p}{\partial t},$$
$$\left(10^3khe^{\alpha((p_i-p))}/1.842B\mu\right)r(\partial p/\partial r-\lambda)|_{r\to 0}=q,p|_{r\to\infty}=p_i,$$
$$p|_{t=0}=p_i. \tag{1}$$

Mathematical model of seepage flow with fracture network is shown as follows.

$$\frac{k_f}{\mu}\frac{\partial p^2}{\partial y^2}+\alpha\frac{k_f}{\mu}\left(\frac{\partial p}{\partial y}\right)^2+\frac{Bq_f}{86.4W_fh_f}=0,$$
$$\frac{k_fh_fW_fe^{\alpha(p_i-p)}}{86.4\mu}\frac{\partial p_f}{\partial y}\bigg|_{y\to y_d}=Bq_d, \tag{2}$$
$$p|_{t=0}=p_i.$$

Perturbation transform and Laplace transform were used to solve the above model to obtain the expression formula of bottom hole pressure [6–9].

$$p_D=-\frac{1}{\alpha_D}\ln\left(1-\alpha_D\zeta_D\right). \tag{3}$$

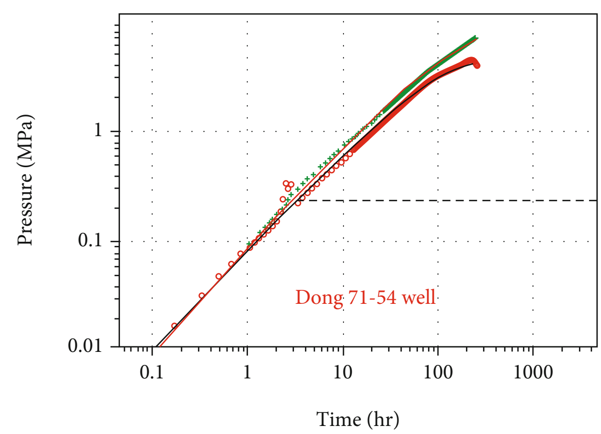

Figure 2: Characteristics of the well test curve in the middle stage of development.

Among them,

$$\zeta_D=\zeta_{D0}+\alpha_D\zeta_{D1}+\alpha_D^2\zeta_{D2}+o\left(\alpha_D^2\right). \tag{4}$$

2.1.2. Analysis of Injection Dynamic Characteristics. Taking a typical oil injection well in Changqing Oilfield as an example, the well test curves at different times are shown in Figures 2 and 3. In the middle stage of development, the well test curve had a character of finite diversion curve (Figure 2). But the current well test curve had a character of composite reservoir (Figure 3). Almost 70% injection well had above characteristics in this reservoir. Meanwhile, in the period of pressure drop test, the downhole pressure drop is small.

The injection data and production data proved that this type of well existed the situation of water holding around the injected well.

Based on the above analysis, it can be concluded that when the injection well meets the following characteristics:

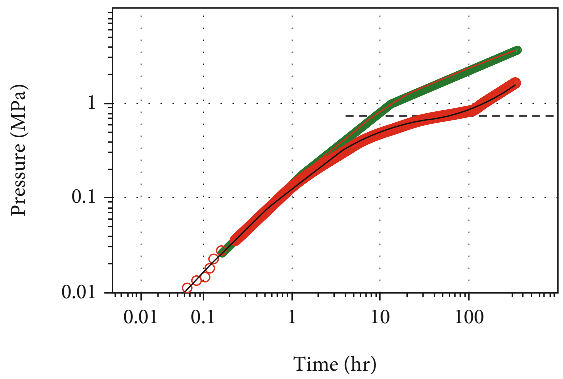

FIGURE 3: Current well test curve characteristics.

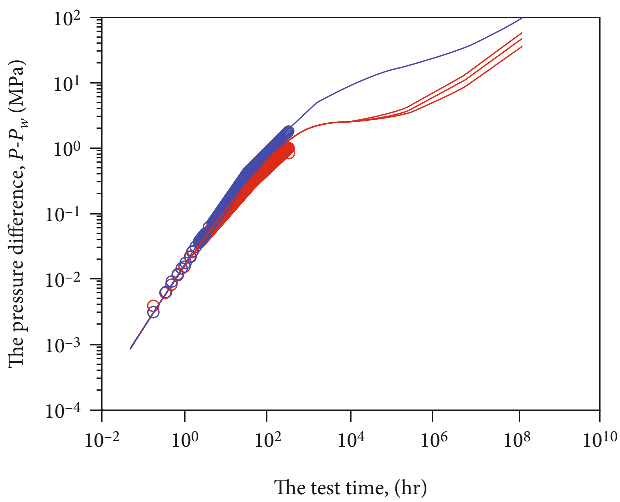

FIGURE 4: Fitting analysis of well test curves of typical wells.

(1) When injection is stopped, the pressure drop is small which indicated that the pressure diffusion of injected water is weak. (2) The injection pressure of the injection well is high and the injection volume drops which indicates the difficulty of water flow. (3) The well test curve shows the characteristics of the composite reservoir. When the above three rules are met, it can be determined that the injection water is not effectively swept and it is held around the injection well.

2.1.3. Evaluation Method of Holding Water Volume. Based on the above understanding, the well test interpretation model can be established to obtain wellbore, reservoir, and other parameters. The radius of the inner zone is the radius of holding water near the injection well which can be calculated by using the volumetric method.

The calculation formula of water storage capacity around the injected well is as follows:

$$V = \pi * r^2 * h * \varphi * \gamma, \tag{5}$$

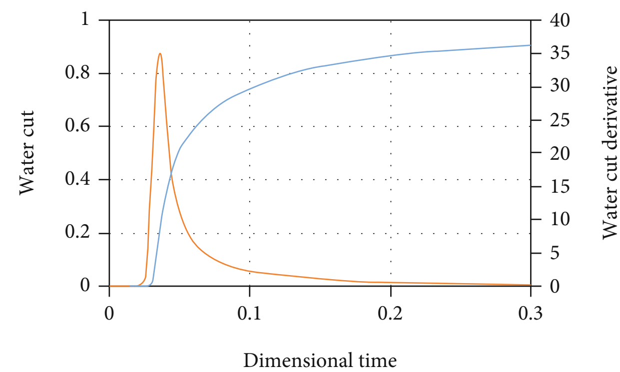

FIGURE 5: Water cut and its derivative curve with dimensionless time when there is no high-water-consumption zone.

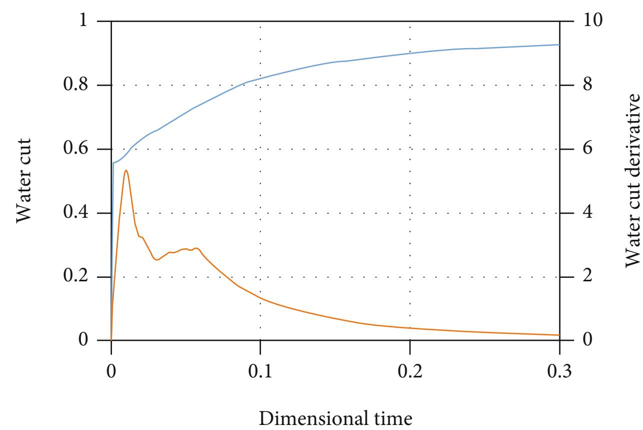

FIGURE 6: Water cut and its derivative change curve with dimensionless time in the presence of high-water-consumption zone.

where V is the water storage capacity around the injected well, r is the radius of injection water gathering area, h is the effective formation thickness, φ is the porosity, and γ is the dispersion coefficient.

Taking a typical well as an example (Figure 4), the well test interpretation model for low-permeability reservoir is adopted to interpret the well. The radius of holding water is 35 m; combined with the reservoir physical parameters, the containment water of the well can be calculated by volumetric method as 23,000 m^3.

2.2. Evaluation Method of Water Injection Direction and Water Injection Utilization Ratio in High-Water-Content Reservoir. Based on the well test theory [10–15], the derivative curve characteristics of the oil-water ratio can be obtained. According to the characteristics, the direction of the injected water flow direction and the water injection utilization ratio can be judged.

During development and production, a large number of production dynamic data of injection-production wells can

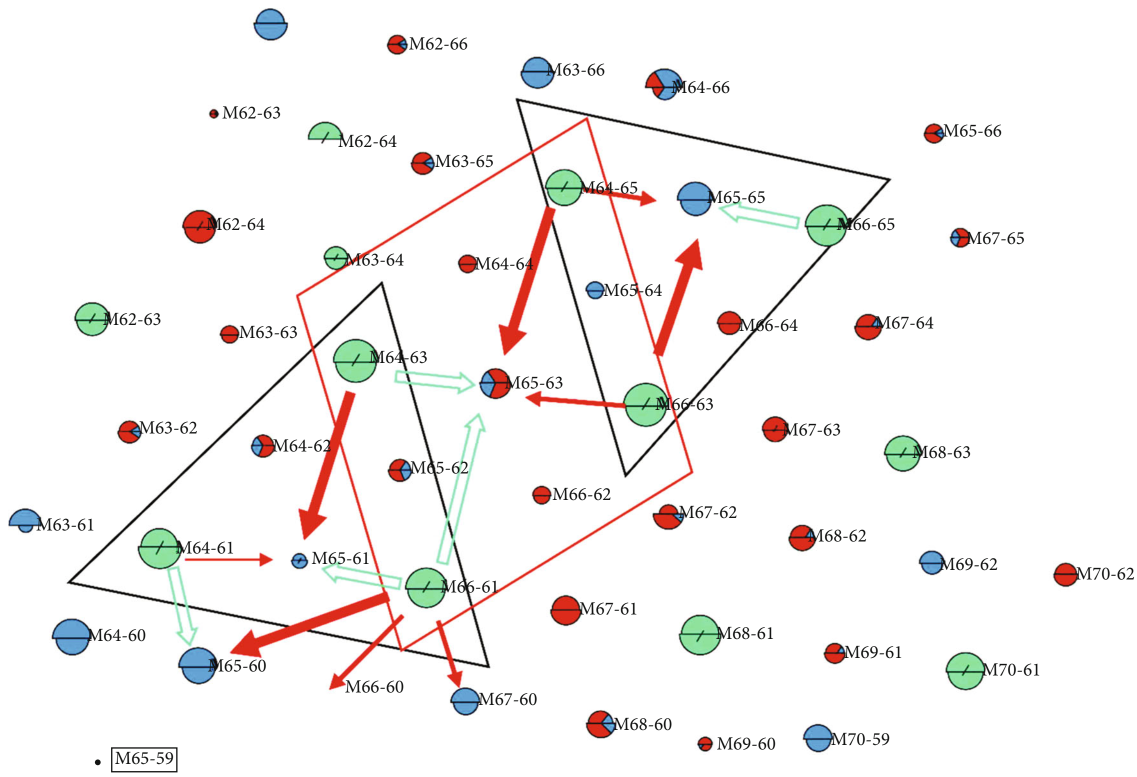

Figure 7: Analysis of channeling direction and channeling ratio of typical well groups (red indicates the direction of channeling, the width of the red arrow reflects the proportion of channeling flow, and the green arrow indicates that there is no channeling.)

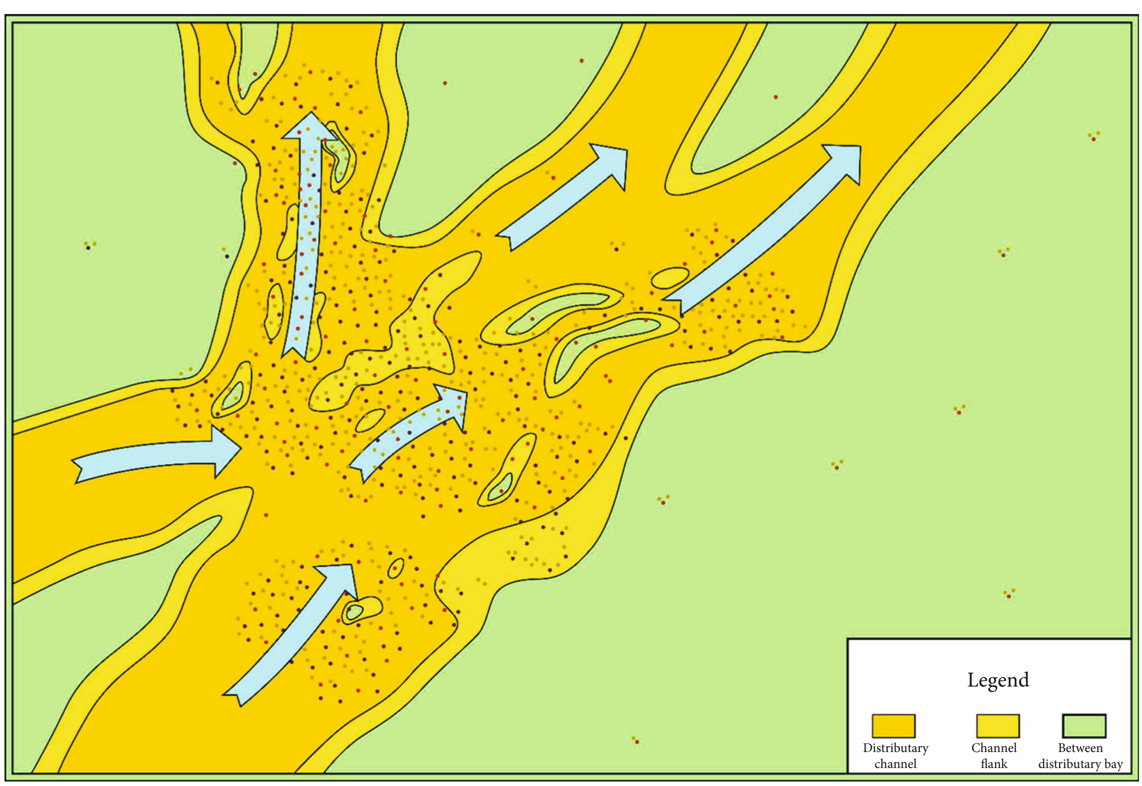

Figure 8: Sedimentary microfacies characteristics of the reservoir.

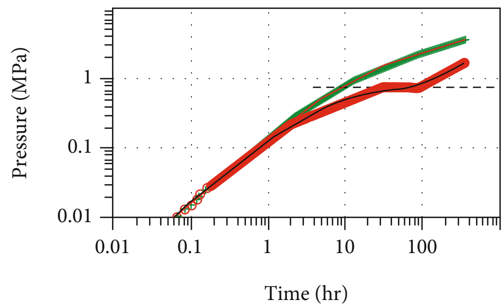

Figure 9: Pressure drop curve characteristics of typical well test, well A.

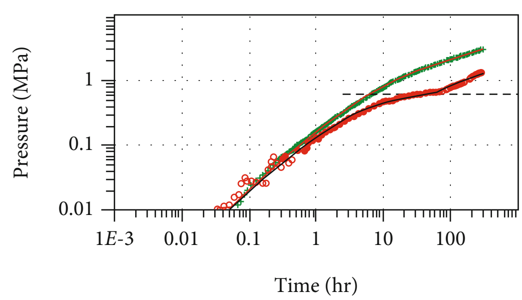

Figure 10: Pressure drop curve characteristics of typical well test, well B.

be obtained, such as injection amount and water cut. In order to facilitate the research, dimensionless time t_D is introduced.

$$t_D = \frac{q_i t}{A\phi h}, \tag{6}$$

where q_i is the injection well injection rate, m^3/d; t is the injection well accumulates injection time, d; A is the reservoir area, m^2; h is the average reservoir thickness, m.

Dimensionless time t_D is obtained by T, which not only introduces time T but also considers the injection amount and reservoir volume of the injection well. Then, derivative of water cut can be obtained. The definition of derivative of water cut of production well is as follows:

$$f_w'(t_D) = \frac{df_w}{dt_D}, \tag{7}$$

where f_w is the water cut of production well, t_D is the dimensional time, and $f_w'(t_D)$ is the derivative of water cut of production well with respect to dimensionless time.

When there is no interference between injection and production wells, the dimensionless derivative curve of water cut is characterized by a single peak; when there is interference between injection and production wells, the dimensionless derivative curve of water cut is characterized by a double peak, as shown in Figures 5 and 6. According to this feature, it is possible to judge whether there is channeling between injection-production wells and determine the water flow direction.

3. Application Instance

Taking a reservoir in Changqing as an example, the average permeability of this reservoir is 0.8 mD, which is an ultralow-permeability reservoir. The current injection-production ratio is 5, and the average reservoir pressure remains at the same level as the original formation pressure, which indicated that 80% of the injected water is not effective, so it is urgent to determine the direction of water injection and guide the adjustment of water injection development.

3.1. Analysis of Water Injection Flow Direction and Water Injection Utilization Ratio. This area is a reservoir with high water cut and low permeability. The formation pressure is maintained at a high level. It is necessary to determine the direction of water flow. The established identification method was used to evaluate the area, and the results are shown in Figure 7. In order to verify the reliability of the evaluation results, the tracer method was used for monitoring. The tracer test results were very consistent with the evaluation results which indicate that the evaluation method had good reliability.

The above methods are used to analyze the current interfacial flow direction and flow rate of the injected water in this area. The evaluation results show that 45% of the injected water has interfacial flow. The direction of the injected water interfacial flow in this area has a good corresponding characteristic with the sedimentary microfacies. The sedimentary characteristics of this area are the main inducement of the interfacial flow in this area, rather than the microfracture previously believed, as shown in Figure 8.

3.2. The Evaluation of Holding Water Volume. At present, the cumulative injection-production ratio in the West 34 well area and the West 25 well area is 4.38, and the actual average formation pressure remains at 100%, that is, about 70% of the injected water is not effectively utilized. 75% of injection wells (Figures 9 and 10) in this area are characterized by a composite reservoir and meet the following rules: (1) The average pressure drop test time is about 15 days, but the pressure drop is about 2 MPa and the pressure drop is small. (2) Before the test, the average wellhead oil pressure was 18 MPa, the formation injection pressure was above 38 MPa, and the injection pressure was very high, but the injection volume decreased. (3) Well test curve shows the characteristics of composite reservoir. According to the previous understanding, we can judge the characteristics of water holding in wells in this area.

According to the data collected, the average cumulative injection volume per well in this area is 116,400 m^3, and about 20% of the injected water is not effectively swept. If a well is drained at a rate of 100 m^3/d, it will drain for 200 days.

4. Conclusion

(1) For the high-water-cut reservoirs, the evaluation method of water injection destination and water injection utilization rate was established. The reliability of the method was verified by comparing with the

tracer test results. This method only needs to produce dynamic data to judge the direction of channeling and the proportion of channeling

(2) For reservoirs with high injection-production ratio and low formation pressure maintenance level, a well test interpretation model based on well testing is established, and the judgment standard for water holding is determined. Well test analysis method can be used to determine the holding volume of the injected water

(3) By using the above methods on a typical reservoir, the injected water flow direction and the holding water showed that about 45% of the injected water had channeling and the water injection was ineffective. In the water holding area, about 20% of the injected water is held near the bottom of the well. The above results can provide data reference for the adjustment of water flooding in this reservoir

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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