Energy Proceedings
Vol 42, 2024
ISSN 2004-2965

Pressure Calculation Method and Mechanism of Advance Water Injection in Ultra-low Permeability Reservoirs

Jinchong Zhou[1], Renyi Cao[1*], Meng Zhang[1], Jian Liu[2], Dong Sun[2], Bingchen Lyu[1], Yongjian Feng[2]

1 China University of Petroleum (Beijing)

2 Research Institute of Exploration and Development, Changqing Oilfield Company, PetroChina
(*Corresponding Author: caorenyi@126.com)

ABSTRACT

Advance water injection is one of the effective methods to alleviate the rapid decline of formation pressure in ultra-low permeability reservoirs, to establish an effective displacement system between oil and water wells, and to increase the production of wells. In order to make up for the influence of threshold pressure gradient and stress sensitivity which are not fully considered in the traditional advance water injection pressure calculation model, based on the material balance method, threshold pressure gradient and stress sensitivity equations are introduced, a nonlinear flow model of the relationship between the advance water injection volume and formation pressure is established, and an iterative solution calculation program is compiled. Taking Y2 ultra-low permeability reservoir in Changqing Oilfield, China, as an example, the formation pressure values under different amounts of advance water injection in the well group of this block are calculated and compared with the numerical simulation results, which are basically in agreement with each other, proving that the model for calculating the advance water injection pressure established in this paper has a high calculation accuracy. The pressure and pressure gradient distribution law in the reservoir under different advance water injection volume is further revealed. When the advance water injection volume of the well group is greater than 10,000m^3, the pressure lift becomes slower, and the pressure gradient between the oil and water wells is higher than the threshold pressure gradient, which forms an effective displacement system. The study results can provide theoretical guidance for the development of advance water injection technical programs for ultra-low permeability reservoirs.

Keywords: advance water injection, threshold pressure gradient, stress sensitivity, calculation model, pressure distribution, mechanism

1. INTRODUCTION

China's ultra-low permeability reservoirs are rich in reserves and have huge development potential, and the Ordos Basin is the main production base of ultra-low permeability reservoirs in China[1]. Ultra-low permeability reservoirs are generally characterized by poor properties, strong heterogeneity, poor pore connectivity, and insufficient formation energy, which leads to the difficulty of establishing effective displacement between water injection wells and oil wells, and the rapid decline of oil well production. Adjusting the development idea, supplementing formation energy and lifting the pressure gradient between oil and water wells are the key points and difficulties in the development of ultra-low permeability reservoirs[2]. For ultra-low permeability reservoirs that have not yet been developed, advance water injection is an effective measure to ensure stable and increased production of oil wells.

Advance water injection refers to the injection of water wells before the production of oil wells to supply formation energy in advance, and after the formation pressure is higher than the original formation pressure, the oil wells will be used for oil recovery, so as to maintain the formation energy effectively and keep the production capacity of the oil wells stable at the same time[3-4]. This development method can reasonably supply formation energy, increase formation pressure, prevent reservoir permeability loss, and establish an effective displacement system, thus increasing well production capacity and slowing down the rate of decreasing, which is an effective ultra-low permeability reservoir development method, and is of great significance for improving the effect of water displacement development in this kind of reservoirs.

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

Determination of formation pressure level after advance water injection and research on the mechanism of increasing production by advance water injection are hot spots for scholars at home and abroad. As early as 2007, Liu et al[5] found that the advance water injection technology can effectively solve the problem of threshold pressure and carried out numerical simulation to analyze the characteristics of injection pressure distribution and the mechanism of production increase. Wang Ruifei[6] and others carried out a more detailed study on the mechanism of advance water injection, and it was concluded that the technique can quickly establish a new system for more effective pressure displacement. Kou Xianming et al[7] used the material balance method to study the advance water injection in extra-low permeability reservoirs in Changqing Oilfield, indicating that effective and reasonable water injection parameters are the key to whether the advance water injection technology can exert the best development effect. Wang et al[8] found an inverse correlation between the pressure to volume ratio of oil and water wells using an analytical method of injection to production balance. Li Nan et al[9] compared the pressure profiles of oil and water wells at different moments of advance water injection and explained the effects on formation pressure caused by different injection methods. Yu Kaichun[10] studied the reasonable bottomhole flow pressure and reasonable water injection volume of water injection according to the feasibility of advance water injection. However, in the existing study on the change of formation pressure for advance water injection, the effect of threshold pressure gradient and stress sensitivity on formation pressure is not fully considered, and the failure to consider the threshold pressure gradient and stress sensitivity will lead to a large calculation result of formation pressure, while the actual formation pressure lift is small, resulting in poorer effect of the production increase of the oil wells.

In this paper, taking Y2 block of Changqing oilfield in China as an example, based on the material balance method, we introduce the threshold pressure gradient and stress sensitivity equation to establish a nonlinear equation for the relationship between the advance water injection volume and the formation pressure, and utilize the programming for iterative solving to obtain the curve of the relationship between the advance water injection volume and the pressure of the ultra-low permeability reservoirs, and combine it with the numerical simulation to validate the accuracy of the model. The pressure propagation law and production increase mechanism of advance water injection are further revealed, and provides theoretical guidance for the formulation of reasonable advance water injection policy in ultra-low permeability reservoirs.

2. CALCULATION MODEL FOR ADVANCE WATER INJECTION PRESSURE CONSIDERING THRESHOLD PRESSURE GRADIENT AND STRESS SENSITIVITY

2.1 Advance water injection volume - formation pressure material balance relationship

Based on the principle of material balance, the equivalence relationship between the cumulative volume of water injected into the formation and the increase in the volume of water in the formation is established, and variable substitution is carried out. The Darcy's law is used to introduce the threshold pressure gradient in the volume of advance water injection and the stress sensitivity coefficient in the permeability K, so as to establish a nonlinear mathematical model of the volume of advance water injection and the formation pressure that takes into account the threshold pressure gradient and the stress sensitivity.

The volume of water in the formation at the initial moment is:

$$V_{wi} = V_w^0 \tag{1}$$

The volume increase of water in the formation at time step 1 is:

$$V_w^1 - V_{wi} = q_w^1 \triangle t^1 \tag{2}$$

The volume increase of water in the formation at time step 2 is:

$$V_w^2 - V_w^1 = q_w^2 \triangle t^2 \tag{3}$$

And so on, the increase in water volume in the formation at the nth time step is:

$$V_w^n - V_w^{n-1} = q_w^n \triangle t^n \tag{4}$$

Where, V_w^n is the volume of water in the formation at the *n*th time step, m^3, and q_w^n is the volume of advance water injection of the nth time step, m^3/d.

Accumulate both sides of the equation from the 1st time step to the *n*th time step to obtain:

$$\begin{aligned} V_w^n - V_{wi} &= q_w^1 \triangle t^1 + q_w^2 \triangle t^2 + \cdots + q_w^{n-1} \triangle t^{n-1} + q_w^n \triangle t^n \\ &= N_w^{n-1} + q_w^n \triangle t^n \end{aligned} \tag{5}$$

This establishes a material balance relationship between the amount of water volume change in the formation and the amount of cumulative advance water injection. The above equation can be written as:

$$\frac{\phi V S_w}{B_w} - \frac{\phi_i V S_{wi}}{B_{wi}} = N_w^{n-1} + q_w^n \triangle t^n \tag{6}$$

where ϕ_i and ϕ are the porosity of the formation at initial and current pressures, respectively, in decimals; V is the volume of the study area, m^3; S_{wi} and S_w are the water saturation of the formation at initial and current pressures, respectively, in decimals; B_{wi} and B_w are the water volume coefficients at initial and current pressures, respectively, in m^3/m^3; N_w^{n-1} is the cumulative advance water injection volume at the *n-1*th time step, m^3.

Since $S_o = \frac{\phi_i V S_{oi} B_o}{V \phi B_{oi}} = \frac{\phi_i S_{oi} B_o}{\phi B_{oi}}$, $S_w = 1 - S_o$, equation (6) can be written as:

$$\frac{\phi V B_{oi} - \phi_i V S_{oi} B_o}{B_w B_{oi}} - \frac{\phi_i V S_{wi}}{B_{wi}} = N_w^{n-1} + q_w^n \triangle t^n \tag{7}$$

From Darcy's formula:

$$q_w^n = \frac{KA(p_{wf} - p - \lambda \cdot l)}{\mu L}, \quad K = K_i e^{\gamma(p - p_i)} \tag{8}$$

where K is the formation permeability, mD; A is the cross-sectional area of the study area, m^3; p_{wf} and p are the bottomhole pressure and the average formation pressure, MPa, respectively; λ is the threshold pressure gradient, MPa/m; l is the supply distance; μ is the viscosity of the formation water, mPa·s; L is the length of the study area, m; K_i is the initial permeability of the formation, mD; γ is the stress sensitivity coefficient, no factorization; and P_i is the original formation pressure.

The resulting equation for the advance water injection volume-pressure relationship that takes into account the threshold pressure gradient and stress sensitivity is obtained:

$$\frac{\phi V B_{oi} - \phi_i V S_{oi} B_o}{B_w B_{oi}} - \frac{\phi_i V S_{wi}}{B_{wi}} = N_w^{n-1} + \frac{K_i e^{\gamma(p-p_i)} A(p_{wf} - p - \lambda \cdot l)}{\mu L} \triangle t^n \tag{9}$$

$$\triangle t^n e^{\gamma(p-p_i)}(p_{wf} - p - \lambda \cdot l) = \left(\frac{\phi V B_{oi} - \phi_i V S_{oi} B_o}{B_w B_{oi}} - \frac{\phi_i V S_{wi}}{B_{wi}} - N_w^{n-1} \right) \frac{\mu L}{K_i A} \tag{10}$$

From the rock equation of state $\phi = \phi_i e^{C_t(p-p_i)}$, where C_t is the integrated compressibility coefficient of formation rock, Eq. (9) can be written as:

$$\triangle t^n e^{\gamma(p-p_i)}(p_{wf} - p - \lambda \cdot l) = \left(\frac{\phi_i e^{C_t(p-p_i)} V B_{oi} - \phi V S_{oi} B_o}{B_w B_{oi}} - \frac{\phi_i V S_{wi}}{B_{wi}} - N_w^{n-1} \right) \frac{\mu L}{K_i A} \tag{11}$$

where B_o and B_w are functions of the pressure p. Data can be obtained from in situ experiments of crude oil and formation water properties.

2.2 Methods for solving formation pressure under different advance water injection volumes

The pressure - advance water injection volume relationship equation derived for ultra-low permeability reservoirs is complicated and cannot be calculated directly, so a calculation program is prepared to solve the pressure under different advance water injection volumes, and the calculation flow is shown in Fig. 1.

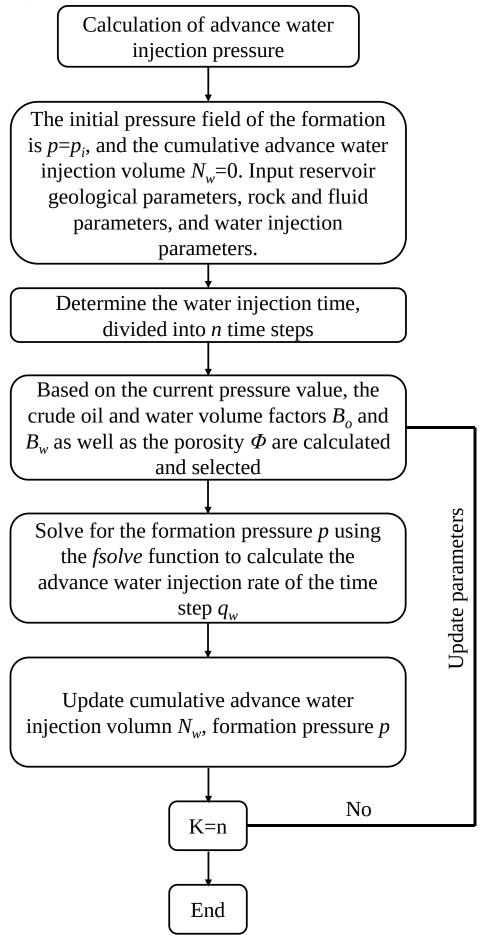

Fig. 1 Flow of iterative coupling calculation of advance water injection volume-pressure

The iterative process in the model of this paper can be described as: ①Input geological parameters such as original formation pressure of the reservoir, rock parameters, physical properties of crude oil and formation water, and water injection parameters, divided into *n* time steps; ②According to the current pressure values, interpolation or extrapolation based on the experimental data of crude oil and formation water volume factors, the crude oil and water volume factors B_o and B_w as well as the porosity Φ are selected; ③Use the prepared program to solve for the formation pressure p at the current advance water injection volume and calculate the advance water injection rate q_w at that time step; ④ Update the cumulative advance water injection volumn N_w and formation pressure p, and transfer the results back to step ② for iterative computation at the next time step up to the nth time step.

3. MODEL VALIDATION

3.1 Block overview

In this paper, we take an example of the advance water injection test area in Y2 block of Changqing oilfield in China, which is located in the southern part of the Ordos Basin slope, with a reservoir thickness of 19.7m, porosity of 11.7%, permeability of 0.34mD, and belongs to the ultra-low permeability reservoirs. The block has carried out the development test of short horizontal wells with advance water injection and achieved good results, and is ready to be promoted in the blank area and developed with five-point short horizontal well network with advance water injection. The basic parameters of the block and well network are shown in Table 1, and Fig. 2 shows the schematic diagram of the five-point well network for short horizontal wells.

Table. 1 Main parameters of the target area model

Parameter	Value
Stress sensitivity factor	0.222
Initial formation pressure	15.8MPa
Bottomhole pressure	35MPa
Threshold pressure gradient	0.05MPa/m
Initial oil volume factor	1.41
Initial porosity	0.12
Study area volume	4800000m^3
Initial oil saturation	0.55
Initial water saturation	0.45
Initial water volume factor	1.012
Water viscosity	0.6mPa·s
Length of study area	400m
Initial pemeability	0.34mD
Cross-sectional area of the study area	12000m^3

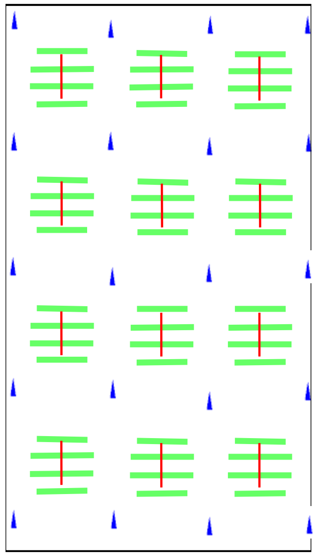

Fig. 2 Schematic diagram of five-point well network for short horizontal wells

3.2 Validation results

According to the parameters of the target block, the formation pressure curve of the well group under different advance water injection volume is calculated by using the prepared program, and the numerical simulation model of five-point horizontal well group is established by using commercial numerical simulation software as shown in Fig. 3, in which the injection wells are straight wells, to simulate the distribution of the pressure of the well group under different advance water injection volume and calculate the average pressure of the formation of the well group, and to get the value of the formation pressure under different advance water injection volume. The results obtained from the software calculations are compared with the program calculations, and the comparison results are shown in Fig. 4, which shows that the advance water injection volume - formation pressure curve calculated by the model in this paper is basically consistent with the numerical simulation results, which illustrates the accuracy of the model in this paper.

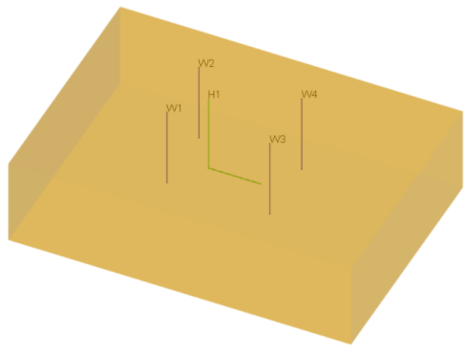

Fig. 3 Numerical simulation model of a five-point short horizontal well group

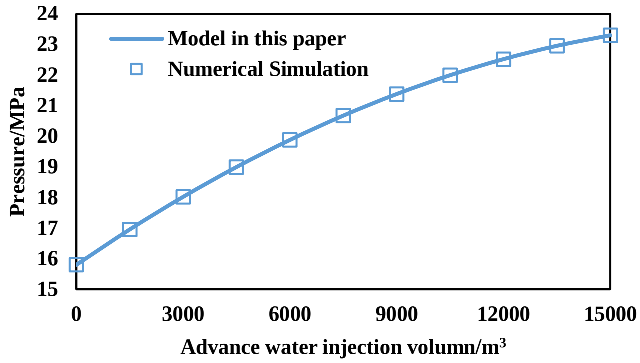

Fig. 4 Comparison between the model in this paper and numerical simulation results

As can be seen from Fig. 4, with the increase of water injection volume, the formation pressure of the well group is increasing continuously, due to the stress sensitivity of the ultra-low permeability reservoir, with the increasing formation pressure, the porosity and permeability of the reservoir also increase, and more space can be stored for water, therefore, the pressure increase after the injection of water is gradually becoming smaller, and the slope of the curve shows a decreasing trend.

4. LAWS OF PRESSURE PROPAGATION DURING ADVANCE WATER INJECTION

4.1 Characteristics of pressure propagation

The formation pressure distribution profiles between an injection well and the heel end of a horizontal well with different advance water injection volumn are shown in Fig. 5.

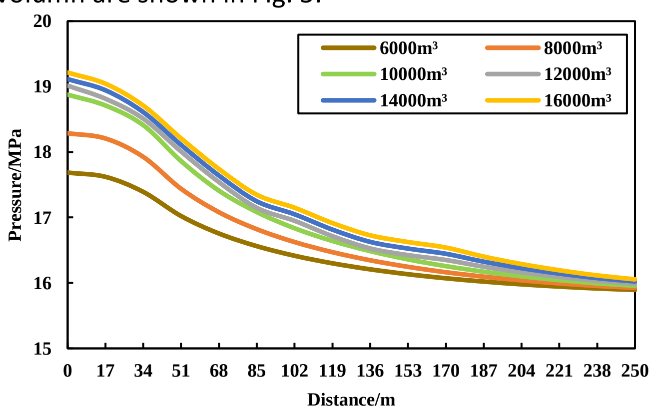

Fig. 5 Pressure profile between injection well and horizontal well

4.2 Mechanism of advance water injection

Further analyzing the production increase mechanism of ultra-low permeability reservoirs with ultra-low permeability water injection from the perspective of pressure distribution of ultra-low permeability reservoirs, the pressure gradient distribution at each point in the formation is calculated according to the results of the calculation of pressure distribution of ultra-low permeability water injection formation, and the pressure gradient distribution profile of the two injection wells and the horizontal wells connecting the lines in the diagonal of the five-point well network is shown in Fig. 6. For ultra-low permeability reservoirs, fluid flow occurs at a point in the formation when the pressure gradient at that point is higher than the threshold pressure gradient, so effective displacement can only be established when the pressure gradient between injection and oil wells is higher than the threshold pressure gradient. As can be seen from Fig.6, the threshold pressure gradient of this block is 0.05 MPa/m. With the increase of the advance water injection volume, the formation pressure is rising, and the pressure gradient of the diagonal two injection wells and the horizontal well connecting the line profiles are also rising, and the pressure gradient around the horizontal wells near the wells is lower than the threshold pressure gradient when the advance water injection volume is less than 10,000 m^3, indicating that there is no effective displacement formed among the injection and production wells. When the volumn of advance water injection exceeds 10,000m^3, the pressure gradient between the injection and oil well is higher than the threshold pressure gradient, so the advance water injection can establish the effective displacement in advance before the production of wells, and at the same time supplement the energy of the formation in advance, so as to achieve the purpose of increasing the production.

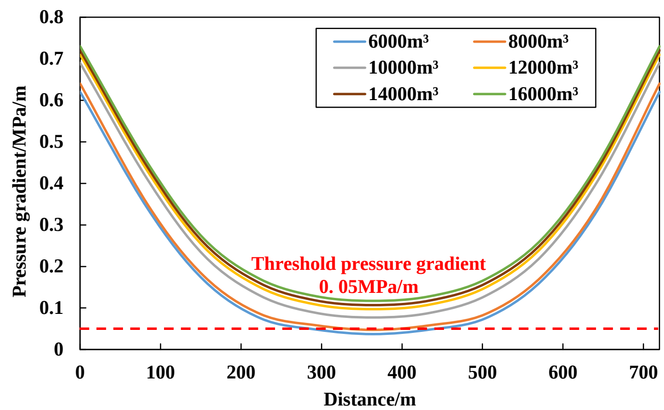

Fig. 6 Pressure gradient profile between injection and horizontal well

5. CONCLUSIONS

(1) An ultra-low permeability reservoir advance water injection pressure calculation model considering the threshold pressure gradient and stress sensitivity is established, and the calculated advance water injection

volume-pressure relationship curve of the target block in the model basically coincide with the result of numerical simulation, which proves that the model established in this paper has a high calculation accuracy;

(2) The distribution of formation pressure under different advance water injection volumes shows that the formation pressure increases with the increase of advance water injection volume, and when the advance water injection volume is more than 10,000m^3, the elevation of formation pressure gradually decreases;

(3) Advance water injection can increase the pressure gradient between oil and water wells. When the amount of advance water injection exceeds 10,000m^3, the pressure gradient between oil and water wells is higher than the threshold pressure gradient, and an effective displacement system is established in advance.

ACKNOWLEDGEMENT

The authors acknowledge that this study was partially supported by the National Natural Science Foundation of China (No. 52174038 and No. 52004307), China Petroleum Science and Technology Project-major project-Research on tight oil-shale oil reservoir engineering methods and key technologies in Ordos Basin (ZLZX2020-02-04) and Science Foundation of China University of Petroleum, Beijing (No. 2462018YJRC015).

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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