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Original Article

Stabilized oil production conditions in the development equilibrium of a water-flooding reservoir

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ABSTRACT

Water injection can compensate for pressure depletion of production. This paper firstly investigated into the equilibrium issue among water influx, water injection and production. Equilibrium principle was elaborated through deduction of equilibrium equation and presentation of equilibrium curves with an "equilibrium point". Influences of artificial controllable factors (e.g. well ratio of injection to production and total well number) on equilibrium were particularly analyzed using field data. It was found that the influences were mainly reflected as the location move of equilibrium point with factor change. Then reservoir pressure maintenance level was especially introduced to reveal the variation law of liquid rate and oil rate with the rising of water cut. It was also found that, even if reservoir pressure kept constant, oil rate still inevitably declined. However, in the field, a stabilized oil rate was always pursued for development efficiency. Therefore, the equilibrium issue of stabilized oil production was studied deeply through probing into some effective measures to realize oil rate stability after the increase of water cut for the example reservoir. Successful example application indicated that the integrated approach was very practical and feasible, and hence could be used to the other similar reservoir.

1. Introduction

After natural flow production, the depletion of reservoir pressure became more and more serious, and then water injection technology was universally applied in oil reservoir development to compensate for the pressure depletion caused by reservoir production [1]. Water injection has gained more and more interests to the research community, such as resource researchers, energy experts, petroleum engineers, geologists, and water scientists. The related investigation about water injection technology has never stopped in many kinds of aspects, such as injection tools [2], injection technical approaches [3], laboratory experiments [4], water flooding mechanisms [5] and theoretical simulations [6].

In some situations, there is a natural water body in the periphery of reservoir. For this type of oil reservoir with natural water, the natural water inevitably invades into the interior of reservoir when reservoir pressure depletes. There were lots of researches on the calculation of natural water influx. Early in 1971, Fetkovich [7] gave a simplified approach to calculate the water influx rate for a reservoir with a finite aquifer system. Leung (1986) [8] presented a convolution method to calculate the water influx rate for both finite and infinite aquifer bodies. Allard and Chen (1988) [9] put forward a calculation approach of water influx for bottom-water drive reservoirs. Nashawi and Elkamel (1998) [10] studied a neural network model to estimate water influx rate into a petroleum reservoir. Machado (2012) [11] calculated water influx rate by numerical Laplace inversion method for petroleum reservoirs with connected aquifers. Generally speaking, the calculation theory of natural water influx rate has been developed well.

Despite the copious literatures on water injection and natural water influx as described above, to our knowledge, there are not

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any literatures about the research which considers the influences of both water injection and natural water influx on oil reservoir development at the same time. In reality, natural water influx, water injection and production interact with each other in any period of water injection development. Moreover, there undoubtedly exists equilibrium among them. Therefore, this paper firstly investigated the equilibrium of oil reservoir development among natural water influx, water injection and production. In our investigation, equilibrium relationship equation and equilibrium relationship curves were introduced to elaborate equilibrium principle. Using the real field data from a sandstone oil reservoir of China, the influence factors of equilibrium were particularly analyzed. Based on the definition of reservoir pressure maintenance level, the stabilized oil production conditions were predicted by the equilibrium principle for the example reservoir. It is worth noting that this paper suffers two aspects of limitation. On the one hand, the calculations of fluid productivity index and water injectivity index for a specified water cut must depend on the empirical formulas that were obtained not by rigorous theoretical deduction but by the regression to production history data. Because no theoretical formulas could be found by our efforts to calculate the two indexes, we had to utilize this kind of processing method. On the other hand, for the section of equilibrium under stabilized oil production condition, more techniques, such as polymer flooding, were not considered to keep oil rate stable because this paper only focused on the equilibrium issue of water injection development, and also because the analysis of stabilized oil production for the example reservoir was the extended application of the researched equilibrium theory. However, the proposed research idea and method in this paper could lay theoretical foundation for reservoir harmonious development during the period.

2. Equilibrium principle of reservoir development

2.1. Reservoir production rate

(1) Relationship of fluid productivity index with water cut

For water flooding reservoirs, as time goes on, the water cut of reservoir production increases. And the increase of water cut means the increase of water saturation in the reservoirs. Given constant oil and water viscosities, the increase of water saturation in the reservoirs will cause the decrease of the total viscosity of the oil and water mixture. Then the decrease of total viscosity leads to the increase of fluid productivity index. Therefore, fluid productivity index is the function of water cut. The relationship of fluid productivity index with water cut can be empirically described as the following polynomial function [12,13]:

$$J_L = A_1 + A_2 f_w + A_3 f_w^2 + A_4 f_w^3 + A_5 f_w^4 + \cdots \quad (1)$$

where: J_L is average fluid productivity index per well, m^3/(d MPa); f_w is water cut, fraction; A_1 ~ A_5 are undetermined coefficients.

(2) Minimum allowable bottom-hole flowing pressure for pump well

Most oil reservoirs have a period of natural flow production, in which the reservoir pressure depletes continually. When the reservoir pressure depletes to a certain degree, it is necessary to use pump to maintain the production. Water injection is applied to complement the depletion of reservoir pressure after the natural flow production. Before water injection development the pump production pattern has been adopted for almost all the wells. The minimum allowable bottom-hole flowing pressure is surely less than the bubble point pressure, so the fluids sucked into the pump cylinder are oil, water and gas. Efficient work of pump requires a minimum coefficient of fullness that is usually not less than 0.7, which means that the free gas volume at the entrance of pump is less than 30% of the total fluid volume [14]. The minimum submerged pressure of pump is the pump suction pressure on the condition of the minimum coefficient of fullness.

Submerged pressure of pump can be derived by the following method:

$$V_o = V_L(1 - f_w) \quad (2)$$

$$V_g = V_o(R_p - R_s) \quad (3)$$

$$R_s = \alpha p \quad (4)$$

$$c = \frac{V_L}{V_L + V_g} \quad (5)$$

where: V_o is oil volume, m^3; V_L is liquid volume, m^3; V_g is gas volume, m^3; R_p is production gas-oil ratio (GOR), m^3/m^3; R_s is dissolved gas-oil ratio, m^3/m^3; c is full coefficient of pump; α is dissolution coefficient of gas in oil, m^3/(m$^3 \cdot$MPa).

Substitute Eqs. (2) and (3) into Eq. (5), so

$$c = \frac{V_L}{V_L + V_g} = \frac{V_o/(1 - f_w)}{V_o/(1 - f_w) + V_o(R_p - R_s)} \quad (6)$$

Change the form of Eq. (6), then we can obtain

$$R_s = \frac{R_p(1 - f_w) - (1/c - 1)}{(1 - f_w)} \quad (7)$$

Substitute Eq. (4) into Eq. (7):

$$p_p = \frac{R_p(1 - f_w) - (1/c - 1)}{\alpha(1 - f_w)} \quad (8)$$

where: p_p is submerged pressure of pump, MPa.

Eq. (8) is the calculation formula of submerged pressure of pump for a specified water cut. When coefficient of fullness is taken as the minimum ($c_{min} = 0.7$), the submerged pressure of pump will reach the minimum (p_{pmin}).

The pressure of liquid column from pump suction to bottom-hole can be calculated by

$$p_h = 0.001\rho_H g(H_z - H_p) \quad (9)$$

$$\rho_H = \frac{\rho_o \rho_w}{\rho_w + (\rho_o - \rho_w) f_w} \quad (10)$$

where: p_h is mixed liquid column pressure from pump suction to the midpoint of formation, MPa; H_z is formation midpoint depth, m; H_p is depth of pump suction, m; ρ_H is density of the mixed liquid column from pump suction to the midpoint of formation, g/cm^3; ρ_o is oil density, g/cm^3; ρ_w is water density, g/cm^3.

The minimum allowable bottom-hole flowing pressure for pump wells is equal to the sum of the minimum submerged pressure of pump and the pressure of liquid column:

$$p_{wfmin} = p_{pmin} + p_h \quad (11)$$