PAPER • OPEN ACCESS

Transformation rule of water injection capacity of mid-high permeability sandstone oilfield

To cite this article: Chengcheng Feng 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **252** 052030

View the article online for updates and enhancements.

Transformation rule of water injection capacity of mid-high permeability sandstone oilfield

Chengcheng Feng *

Exploration and Development Research Institute of Daqing Oilfield Limited Company Ltd, Daqing, China

*Corresponding author e-mail: fengchengcheng@petrochina.com.cn

Abstract. In the process of waterflood development in the mid-high permeability sandstone oilfield, one of the important indexes to evaluate the injection effect of water injection wells is the water injectivity capacity, which is can be expressed by water injectivity index. Based on the filtration theory and the principle of reservoir engineering, taking A Oilfield as an example which is five-spot pattern, this paper establishes theoretical calculation formula of dimensionless water injectivity index, and determines the transformation rule of actual water injectivity index and theoretical water injectivity index in different water content stages of mid-high permeability sandstone oilfield, this method has certain applicability because the theoretical calculation results and the water injectivity index results which is calculated from actual data is consistent, and it can provide theoretical basis for reasonable allocation and development adjustment of oilfield.

1. Introduction

For waterflooding oilfield, water injection is the basic work of oilfield development. For water flooding oilfield, the key to enlarging the swept volume of injected water in reservoir is to do a good job of water injection and improve the effect of water injection continuously [1] [2]. Therefore, it is necessary to give full play to beneficial factors in water injection development, improve the flood effectiveness, improve water injection capacity, prolong stable production period and enhance oil recovery. Water injectivity index is one of the important indexes to evaluate the injection effect of water injection wells in the process of oilfield water injection development. It is also the main basis for water injection pressure design and surface equipment selection.

The distribution of underground oil and water is more complicated for oilfields as A Oilfield that have entered the stage of ultra-high water content production. The change of water injectivity and flooding efficiency of water injection wells also show different characteristics. Some of the existing literatures [3] [4] [5] [6] only give the calculation results of water injectivity index, but there is no pre-determination of variation trend. In the other part, the formula of water injectivity index is given according to the law of fluid productivity index, which is lack of theoretical basis. Based on the characteristics of oil/water two-phase fluid flow, this paper studies the transformation rule of injectivity in different development phase.

2. Factors affecting water injectivity index

Water injectivity index is the daily water injection rate of water injection wells under unit difference between reservoir pressure and injection pressure. It can reflect the injection capacity of water injection wells and the water injectivity of reservoirs, and can be used to analyze the working conditions of water injection wells and the changes of water injectivity of reservoirs. Its mathematical expression is:

$$\text{Water injectivity index} = \frac{\text{daily water injection rate}}{\text{difference between reservoir pressure and injection pressure}}$$

$$= \frac{\text{daily water injection rate}}{\text{injection well flow pressure - injection well static pressure}}$$

It can be seen from the formula that the water injectivity index is closely related to the daily water injection rate and difference between reservoir pressure and injection pressure, while the water injection rate of the water injection well depends on the effective permeability of the reservoir, oil viscosity and water viscosity, sand thickness, effective radius of the well and completion efficiency of the water injection well. Water injectivity index indicates the water injectivity of the reservoir. Generally speaking, the bigger the water injectivity index, the stronger the water injectivity of the reservoir, and the greater the formation permeability. It is one of the important indexes to evaluate the injection effect of water injection wells in the process of oilfield waterflood development.

3. Derivation of water injectivity index formula

It is impossible to measure the static pressure of injection wells by shutting down wells frequently in normal production of oilfields, so it is impossible to obtain the transformation rule of water injectivity index at each stage. Therefore this paper fetches the theoretical calculation formula of dimensionless water injectivity index.

In a reservoir, for any well pattern system, the cross section between the injection well and the producing well is large compared to the subminiature cross section at the well site, so these wells actually provide all the flow resistance. Therefore, taking five-spot pattern as an example, it is assumed that it represents the radial flow system to simulate the injection well pattern. According to the model in Figure 1, the total pressure drop between the injection well and the producing well is the sum of the pressure drop between the injection side and the producing side of the well pattern. Its expression is:

$$P_{wi} - P_{wp} = \Delta P_i + \Delta P_p \qquad (1)$$

P_{wi} —B.H.P.F. bottom hole flowing pressure in injection well, MPa; P_{wp} —B.H.P. bottom hole pressure of producing well, MPa; ΔP_i —the pressure drop of the injection well side, MPa; ΔP_p —the pressure drop of the producing well side, MPa.
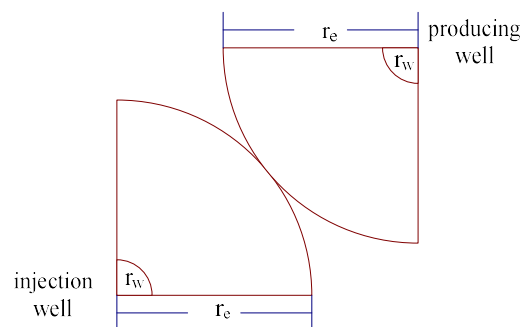
Figure 1. The model of five-spot pattern quadrant.

According to the radial fluid flow, assuming that the radius ratio of the injection side and the producing side is equal, the producing well only produces oil when there is no water, and considering the balanced injection and production rate in the oilfield development period, the formula (1) of total pressure drop can be written as follows:

$$P_{wi} - P_{wp} = \frac{i_0 \cdot \frac{\mu_w}{k_w} \cdot \ln\frac{r_e}{r_w}}{2\pi h} + \frac{i_0 \cdot \frac{\mu_o}{k_o} \cdot \ln\frac{r_e}{r_w}}{2\pi h} \qquad (2)$$

i_0—the intake volume of producing well without water, m^3/d; μ_w—viscosity of water, $mPa \cdot s$; k_w—effective permeability of water phase, μm^2; r_e—radius of radial flow area, m; r_w—well diameter, m; μ_o—viscosity of crude oil, $mPa \cdot s$; k_o—effective permeability of oil phase, μm^2; h—effective thickness, m.

So the intake volume is:

$$i_0 = \frac{2\pi(P_{wi} - P_{wp}) / \ln\frac{r_e}{r_w}}{\frac{\mu_w}{k_w} + \frac{\mu_o}{k_o}} \qquad (3)$$

Therefore, when there is no water in the producing well, its water injectivity index is:

$$I_0 = \frac{i_0}{(\Delta P_{zs})_0} \qquad (4)$$

ΔP_{zs}—difference between reservoir pressure and injection pressure, MPa.

When water breakthrough occurs in the producing well, the pressure drop on the oil-producing side of the model is based on the production of water, and according to formula (1)B, the total pressure drop is as follows:

$$P_{wi} - P_{wp} = \Delta P_i + \Delta P_p = \frac{i_t \cdot \frac{\mu_w}{k_w} \cdot \ln\frac{r_e}{r_w}}{2\pi h} + \frac{q_w \cdot \frac{\mu_w}{k_w} \cdot \ln\frac{r_e}{r_w}}{2\pi h_w} \qquad (5)$$

According to the principle of balanced injection and production rate, water production can be obtained:

$$q_w = i_t \cdot f_w \qquad (6)$$

q_w—water production, m^3/d; i_t—the intake volume at any time when water breakthrough occurs in the producing well, m^3/d; f_w—water cut, %.

The cross section of water flowing through is only a fraction of the total cross section of the producing well when water breaks through. If it is unit mobility ratio, the total cross section of the flowing water in the producing well will be the same as the water cut. Therefore, the thickness of the produced water will be the product of the water content and the overall thickness. However, when it is non-unit mobility ratio, the thickness of water production should be

$$h_w = \frac{f_w h}{f_w + (1 - f_w)M} \tag{7}$$

M —mobility ratio, zero dimension.

The formula (6) and the formula (7) are substituted (5), we can obtain as follows:

$$i_t = \frac{2\pi (P_{wi} - P_{wp}) \Big/ \ln \frac{r_e}{r_w}}{\frac{\mu_w}{k_w}[1 + f_w + (1 - f_w)M]} \tag{8}$$

Therefore, when water breakthrough occurs in the producing well, its water injectivity index is:

$$I_t = \frac{i_t}{(\Delta P_{zs})_t} \tag{9}$$

Similar to the dimensionless fluid productivity index, we define the dimensionless water injectivity index $\overline{I_t}$ as the ratio of the water injectivity index at any time to the water injectivity index ($f_w = 0$) when there is no water in the producing well.

$$\overline{I_t} = \frac{I_t}{I_0} \tag{10}$$

$\overline{I_t}$ —dimensionless water injectivity index, zero dimension; I_t —the water injectivity index at any time when water breakthrough occurs in the producing well, $m^3 \big/ (d \cdot MPa)$; I_0 —the water injectivity index when there is no water in the producing well, $m^3 \big/ (d \cdot MPa)$.

The formula (3),the formula (4) and the formula (9) are substituted to formula (10), we can obtain as follows:

$$\overline{I_t} = \frac{1+M}{1+M+(1-M)f_w} \bullet \frac{\left(\frac{\Delta P_{zs}}{\Delta P_{zc}}\right)_0}{\left(\frac{\Delta P_{zs}}{\Delta P_{zc}}\right)_t} = \frac{1+M}{1+M+(1-M)f_w} \bullet R \tag{11}$$

ΔP_{zc} —injection/production pressure difference, MPa; R —pressure difference coefficient, zero dimension.

It can be seen from the formula (11) that the dimensionless water injectivity index depends on the oil/water mobility ratio, composite water cut and the R value. The mobility ratio depends on the change of relative permeability curve, that is, dimensionless water injectivity index changes with the change of relative permeability curve form; the R value is related to difference between reservoir pressure and injection pressure and injection/production pressure difference, the definition R value is pressure difference coefficient.

4. Determination of parameters

In formula (11), it is difficult to describe R as the pressure difference coefficient accurately when the mobility ratio of a given reservoir is known. Because the distribution of the reservoir pressure system is

too complex. Therefore, in view of the long development time in A Oilfield, so much pressure data of oil/ water wells have been obtained, and we use these field data to determine the R value.
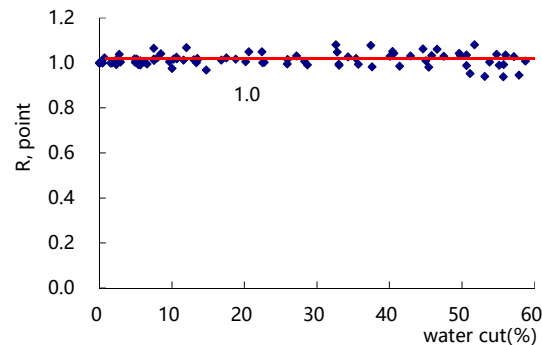
Figure 2. R value of the middle and low water cut stage in A Oilfield.

In China, the development phase of waterflooding oilfields is divided into low water cut stage (water cut less than 20%), middle water cut stage (water cut between 20% and 60%) and high water cut stage (water cut between 60% and 90%) .The high water cut stage (water cut between 60% and 90%) is divided into early stage of high water cut (water cut between 60% and 80%), late stage of high water cut (water cut between 80% and 90%) and extra-high water cut stage (water cut more than 90%). According to this standard, we have separately counted the R value at each development phase of A Oilfield (Fig. 2~3). According to the statistical results, the R values are generally greater than 1. When the water content is 0, the R value is 1, and the R value of the middle and low water cut stage (water cut is less than 60%) is basically 1. In the high water cut stage and the extra-high water cut stage the R value is approximately linear with water cut. According to this rule, theoretical dimensionless water injectivity index can be calculated. It can also provide reference for the calculation of water injectivity index for similar sandstone reservoirs.
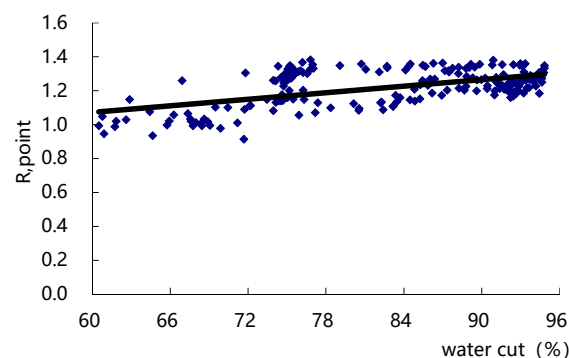

Figure 3. The R value of the high water cut stage and the extra-high water cut stage in A Oilfield.

5. Transformation rule of water injectivity index in A Oilfield

5.1. Transformation rule of theoretical dimensionless water injectivity index
Based on the above research, the variation curves of theoretical dimensionless water injectivity index and theoretical dimensionless fluid productivity index with water cut in A Oilfield are drawn (Fig.4). According to the curve form, the transformation rule of water injectivity index and fluid productivity index is consistent; water injectivity index of the low-to-moderate water cut stage is smooth. In the late stage of high water cut and extra-high water cut stage, the phenomenon of capillary occluded oil is

serious because of hydrophobic rocks, and the utilization rate of injected water is very low. Crude oil can only be produced by a large amount of water washing. Therefore, with the continuous injection of injection wells, the dimensionless water injectivity index rises sharply. From the comparison of water injectivity index and fluid productivity index, the increase of water injectivity index after high water cut stage is obviously greater than that of fluid productivity index, which further shows that the inefficient and ineffective circulation of injected water is becoming more and more serious after high water cut stage because of the formation of dominant seepage channel. However, the existing research results [7]also shows that the extra-high water cut stage is an important development phase of water drive oilfields, most of the reserves to be produced in this stage (about 8 percent of the reserves in A Oilfield to be produced after 90 percent water cut). Therefore, in theory, this stage can increase water injection, but the actual situation of oilfield such as composite water cut and water injection well pollution should be considered.
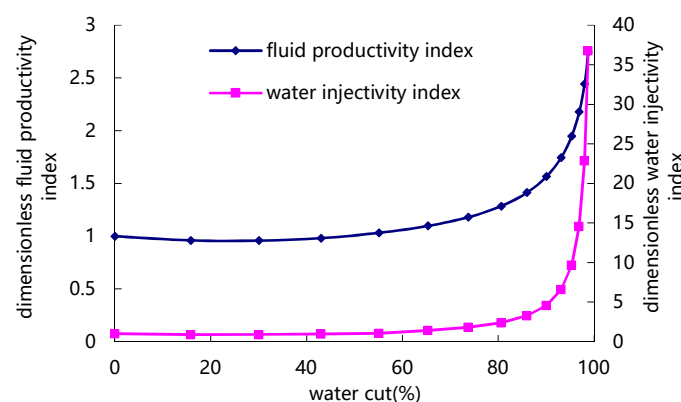

Figure 4. The variation curves of theoretical dimensionless water injectivity index and theoretical dimensionless fluid productivity index.

5.2. Transformation rule of water injectivity index of monolayer water drive producing in small well spacing
In practical application, when analyzing the water injectivity index, it is necessary to test the water injection well to obtain the flow pressure data. But in routine analysis, the apparent water injectivity index is often used to express the water injectivity in order to grasp the change of water injectivity in time. It is the daily water injection divided by the wellhead pressure.

In order to rationally develop heterogeneous and multizone oilfields, A Oilfield has carried out monolayer water drive producing test in small well spacing to reflect the rule of the entire oilfield development process, on the basis of in house laboratory investigation. Using two producing wells and three injection wells around the small well spacing test area, the fluid productivity index and apparent water injectivity index are calculated respectively. According to the calculation results (Fig. 5), the transformation rule of the liquid productivity index and water injectivity index is consistent with the theoretical calculation results. Both the fluid productivity index and water injectivity index are gradually increasing with the increasing of water cut. In the high water cut and extra-high water cut stage, the fluid productivity index and water injectivity index increase sharply. The actual data shows that during the period of high water injection multiple productions, the water injection multiple increases by 4.2 times and the degree of reserve recovery increases by 7.3 percentage points. This proves that after water cut reaches 98%, enhanced water injection and forced fluid withdrawal can still be used to improve oil recovery.
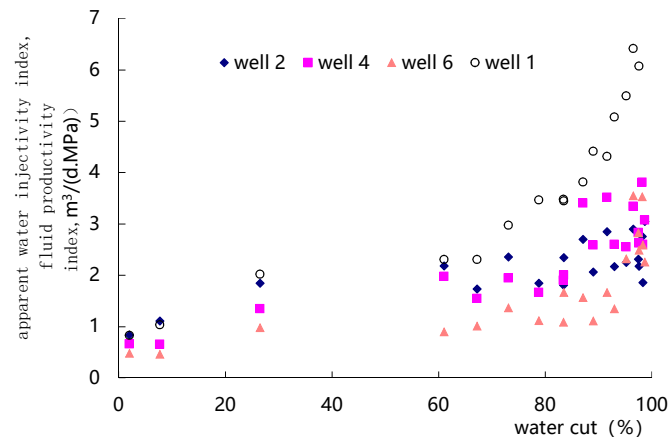
Figure 5. The change off fluid productivity index, apparent water injectivity index in B subzone in 1 borefild

5.3. Transformation rule of actual water injectivity index in A Oilfield

Applying the actual dynamic document of water injection wells in each development area of A Oilfield, the apparent water injectivity index is calculated. According to the calculation results(Fig.6), the apparent water injectivity index is constantly changing in the production process of the oilfield, whichi can be divided into two stages.The first stage is that the oilfield is in the low-to-moderate water cut stage and early stage of high water cut. With the increase of the number of injection wells, the intake volume increases, the oil phase is displaced by aqueous phase gradually, and the apparent water injectivity index increases with the increase of water cut. The second stage is that the oilfield is in the late stage of high water cut and extra-high water cut stage, with the increase of water cut in production wells, in order to control the rising rate of water cut in this large multi-layer heterogeneous reservoir, the adjustment measures of injection wells are also increasing. According to statistics, the workload of injection wells accounted for 40% of the total injection wells. Therefore, the actual water injection of injection wells is decreasing, resulting in the apparent water injectivity index is decreasing, resulting in the apparent water injectivity index is decreasing with the increase of water cut.
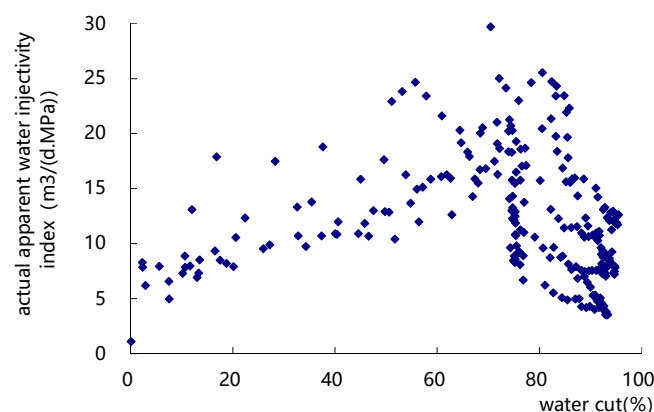
Figure 6. The change of actual apparent water injectivity index in A Oilfield

6. Conclusion

(1) Based on the principle of reservoir engineering and the filtration theory, the theoretical formula of dimensionless water injectivity index is deduced, and the transformation rule of water injectivity index in the whole development phase is studied in combination with the actual field situation of A Oilfield.

The theoretical formula is verified by the actual production performance of small well spacing. Combined with field practice, it has good applicability in practice.

(2) The development practice of A Oilfield shows that the change of actual water injectivity index is not only related to the property of reservoir fluids, but also closely related to various adjustment measures in the process of oilfield development.

References

[1] Junkui Wang, The Research and application of reservior engineering method[M], Beijing:Petroleum Industry Press. (1998)160-161.

[2] Fujun Li, Yanwei Shen, Erfu lu, Wenfang Cai, The study on transformation rule of water injectivity in west of Bei third distric[J], Petrochemical Industry Application, 2014,33 (11): 1-6.

[3] Wankui Guo, Jie Wang, Fengyu Miao, Yanfeng Wang, The study on transformation rule of water injectivity index during oilfield development[J], Journal of Daqing Petroleum Institute, 1994,18 (3): 30-33.

[4] Jun Han, Jun Hou, Zonghao Xue, Jianguo Sun, Study on policy limits for development of Putaohua oilfield in high water cut stage[J], Journal of Xi'an Petroleum University (Natural Science Edition), 2004,19(1):44-48

[5] Lili Li, Kaoping Song, Li Gao, Pengzhen Wang, Study on characteristics of water flooding in ultra- high water cut stage[J], Petroleum Drilling Techniques, 2009,37(3):91-94.

[6] Shuang Ge, Jinbo Song, Yabin He, Research of Percolation Characteristics for Chang 8 Reservoir in DZ44150 Well Area GG Block [J], Value Engineering, 2013,9:71-72.

[7] Xiaohui Wu, Bangji Wang, Xu Liang, Qiuyu Hao, The recovery level of La Sa Xing Oilfield in ultra-high water cut stage[J], Petroleum Geology & Oilfield Development in Daqing, 2014,33 (6): 52-56.