Spacing Chart for Ultra-low Permeability Reservoirs

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Abstract. The foreign TM oilfield is an ultra-low permeability reservoir with deep burial, poor reservoir properties, poor seepage capacity and severe heterogeneity. The production declined rapidly during water injection development process, and the absorption capacity of the injection well is poor. Some production wells are not affected by the injection wells. In order to improve the effect of water injection development, it is necessary to infill the existing well pattern, reduce the injection-production well spacing, and establish an effective driving system for the reservoir to improve the reserves utilization. This paper classifies the effect of water injection development in foreign TM oilfield, establishes the relationship between injection-production well spacing and formation permeability, and then obtains the effective driving well spacing under different permeability of ultra-low permeability reservoirs. This method plays an important role in the study of well pattern deployment in the water injection development process of ultra-low permeability reservoir.

Key words: ultra-low permeability reservoir, reasonable injection-production well spacing, effective driving well spacing, permeability, reservoir heterogeneity.

1. Introduction
The overall performance of the foreign TM oilfield is complex structure, strong reservoir heterogeneity, large dip angle, poor reservoir properties, and complex oil-water relationship. With the continuous development of water injection, it gradually appeared that some production wells are not affected and some water injection wells are difficult to be injected due to long distance between injection-production wells. How to realize early production and fast production during the development period has become a serious problem facing foreign oilfield development. Due to the presence of a starting pressure gradient during the development of ultra-low permeability reservoirs, the excessively large well spacing will seriously affect the pressure loss. The most direct and effective method is to deploy infill wells on the existing well pattern to reduce the injection-production well spacing. Establish an effective driving system to improve oil recovery. Therefore, it is important to determine the reasonable injection-production well spacing for the economic and effective development of ultra-low permeability oilfields.

2. SJ fault block overview
The SJ fault block in TM oilfield is the fault block with the largest oil-bearing area of the oilfield and the largest number of wells in the oilfield. It contains all the oil layers and all lithology types in the oilfield, and is the most representative fault block in the oilfield. From top to bottom, the SJ fault block
develops three sets of oil layers including N2 formation, N1 formation and T formation. The main oil layer is T formation. T formation is a fan delta frontier facies deposit, with tuffaceous glutenite in the north and tuffaceous sandstone in the south. The average net pay thickness of the fault block is 37.5m, the formation dip angle is 14.8°, the porosity is 11.5%, and the permeability is 1.85mD. The fault block design adopts the same layer series of development, a triangular well pattern, the well spacing is 300m and the edge with a point water injection method.

3. Analysis of water injection development effect
The SJ fault block began mass production in September 2011, and water injection development began in August 2012. At present, 98 production wells and 48 water injection wells have been put into operation. The average daily production of single wells is 4.1t, the water cut is 33.2%, the cumulative oil production is 57.68×10⁴ t, the oil production rate is 0.69%, and the recovery degree is 3.80%, the average single well daily water injection is 25.3m³, the injection pressure is 16.5MPa, the accumulative water injection is 93.13×10⁴ m³, and the cumulative injection-production ratio is 0.96.

At the beginning of the production, the output was high, the daily oil production was 9.7t. Due to the serious loss of the formation energy, the production decreased rapidly, the annual decline rate is 14.7%. Some wells have difficulty in water injection, oil well production is low, water injection is not effective, and not effective wells account for 35.1%. There are many reasons for analyzing the effect of water injection development on the fault block [1,2].

3.1. Reservoir physical
Due to the large number of production wells in the SJ fault block, but the physical data of the core well is limited. Based on the well logging data, and combined with the indoor core permeability test data. The multivariate regression method is used to establish the porosity and permeability interpretation model. Calculate the porosity and permeability data of each oil layer in each well. The single well porosity data is obtained by the thickness weighted average method.

The statistical results show that the average porosity of the oil layer of the T formation in the SJ fault block is 10.4%, the average permeability is 1.77mD, which is a low porosity and ultra-low permeability reservoir. From the distribution of single well porosity-permeability data, the oil layer of T formation is relatively poor, the porosity is mainly distributed in 10%~15%, accounting for 62.0%; the permeability is mainly distributed in 1~10mD, accounting for 58.3%. By using the reservoir porosity data and permeability data to calculate the interlayer variation coefficient of the fault block is 0.9, and the value is close to 1, indicating that the reservoir heterogeneity of the fault block is strong, which is a key factor affecting the development of oilfields.

Table 1. Physical property statistics of logging interpretation in SJ fault block.

| Formation | Well quantity | Porosity (%) | Permeability (mD) |
|-----------|---------------|--------------|-------------------|
|           |               | Minimum | Maximum | Average | Minimum | Maximum | Average |
| N2        | 26            | 14.9    | 20.3    | 17.7    | 1.03    | 358     | 44.3    |
| N1        | 40            | 11.4    | 16.6    | 13.6    | 0.37    | 23.7    | 1.99    |
| T         | 108           | 8.5     | 13.6    | 10.4    | 0.22    | 7.64    | 1.77    |
3.2. Formation dip angle
The formation dip angle data of the fault block is statistically calculated. Based on the sub-flow equation and refer to the phase permeability data of the fault block, the reservoir numerical simulation method is applied to study the influence of the formation dip angle on the water injection development. Under the same permeability, when the water cut is the same, if the formation dip angle is larger, the gravity effect is more obvious, and the oil production well located in the lower part of the water injection well is more quickly effected and the water cut increases faster. Conversely, the oil production well above the water injection well is slower. The formation dip angle of the fault block is very big; it is 14.8°, it has a certain impact on the effectiveness of the production well.

3.3. Fracture direction
It can be seen from the core observation that the natural fracture of the fault block is not developed, and the direction of the artificial fracture is mainly northeastward, which is 53.1° in the northeast. Since the fault block is a low-porosity and ultra-low permeability reservoir, the method of fracturing should be adopted to increase the output of single well. In order to optimize the effect of water injection after fracturing, the design of the well array direction is parallel to the artificial fracture direction after fractured (53.1° in the northeast). Due to the complex reservoir shape of the fault block, the fault is developed and the structure is broken. In order to avoid the fault occlusion and improve the injection and production well pattern during the well placement, the water injection direction of some injection wells is close to the direction of the artificial fracture, so the water appears faster and the effect is obvious.

4. Plate creation
The water injection effect of SJ fault block production well is counted, and the relationship chart between injection-production well spacing and permeability is established. According to the different ratio of water injection effect, the chart is divided into three regions: A, B and C, and the relationship formula between injection-production well spacing and permeability is regressed. Most of the production wells in A area are effective in water injection, and the effective ratio is 88.2%. The injection-production well spacing is less than the calculated of regression relationship in table 2. The proportion of effective wells in C area is only 13.0%, that is, most of the wells are not effective. B area is between A area and C area. The effective wells and not effective wells are mixed in the B area, and the proportions are 57.7% and 42.3%. The permeability in this range does not play a significant dominant role (other factors mainly include structure, connectivity and well pattern, etc.). Therefore, when the formation permeability parameter is known, the effective driving well spacing of the block can be determined according to the relationship formula between the injection-production well spacing and the permeability of the A area. Under the same lithological conditions, the larger of the reservoir permeability, the larger of the effective driving well spacing. On the contrary, the smaller of the reservoir permeability, the smaller of the effective driving well spacing. When the actual injection - production well spacing is less than the well spacing calculated by the A area formula, most of the production wells
are effective. Most of the production wells are not effective when the actual injection-production well spacing is larger than the well spacing calculated by the C area formula[3-5].

**Table 2.** Injection-production well spacing and permeability relationship table.

| Classification                              | Feature description                                                                 | Water injection efficiency ratio (%) | Water injection ineffective ratio (%) | Relationship formula between injection-production well spacing and permeability |
|---------------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------------------------------------------------|
| Water injection effect area (A zone)        | The injection-production well spacing meets the regression relationship, which ensures that most of the well water injection is effective. | 88.2                                 | 11.8                                 | $L < 95\lg k + 171$                                                                |
| Other factors affecting the area (B zone)   | Influenced by many factors such as physical properties, structure, connectivity and well pattern. | 57.7                                 | 42.3                                 | $95\lg k + 171 < L < 50\lg k + 247$                                              |
| Water injection is not effective area (C zone) | Most of the wells in this area are not effective.                              | 13.0                                 | 87.0                                 | $L > 50\lg k + 247$                                                              |

**Figure 2.** Diagram of injection-production well spacing and permeability.

5. **Example analysis**

The ST fault block is another major development fault block in the oilfield. It mainly develops the T formation oil layer, and the lithology mainly develops tuffaceous sandstone. At present, a total of 14 production wells and 10 injection wells have been put into operation. The average perforated net pay thickness of the production wells is 36.5m and the permeability is 3.8mD. The average daily oil production per well is 2.9t, the water cut is 35.6%, the accumulative oil production is $8.95\times10^4$ t, and the accumulative water production is $3.85\times10^4$ m$^3$. The average perforated thickness of the injection well is 54.6m, the permeability is 2.9mD, and the fracture pressure is 22.6MPa. The average single well daily water injection is 21.4m$^3$, the injection pressure is 16.6MPa, and the accumulated water injection is $27.55\times10^4$ m$^3$.

According to the relationship chart of injection-production well spacing and permeability, the permeability of ST fault block is 3.8mD, and the relationship between injection-production well spacing and permeability is applied in the water injection effective area. The upper limit of effective driving well spacing of injection-production well is calculated to be 226m. At present, the injection-production well spacing is 300m, which is larger than the effective driving well spacing. It is impossible to establish an effective driving system without infilling wells. According to the economic limit well spacing calculation formula, the economic limit well spacing of the ST fault block is 165m. By adopting the triangle center infilling method, the well spacing is finally determined to be 173m, and the value is between the economic limit well spacing and the effective driving well spacing to meet the economically effective development conditions of the oilfield. In the initial stage of the infill well, the average daily...
oil production per well is 6.0t-12.7t, and the water cut is 20.8-37.0%, which exceeded the economic limit output of the single well (5.9t). After infilling, the single well control reserves is $6.94 \times 10^4$ t, the control degree of water flooding is 89.3%, the increase is 19.6 percentage points, the connection ratio of multi-directional is 55.0%, which is increased by 36.9 percentage points, and obtained a better infilling effect.

**Table 3. Basic parameter table of encrypted block.**

| Formation | Well quantity Oil Water | Oil-bearing area (km²) | Geological reserve($10^4$t) | Net pay thickness(m) | Reserve abundance ($10^4$t/km²) | Daily oil production(t) | Well depth (m) | PermeabilityPorosity (mD) (%) |
|-----------|-------------------------|------------------------|-----------------------------|---------------------|---------------------------------|------------------------|---------------|-----------------------------|
| T         | 14                      | 1.49                   | 277.46                      | 45.6                | 186                             | 300                    | 9.6           | 2774                         |

**Table 4. Well position deployment result table of encrypted block.**

| Encryption mode | Infill oil well | Infill water well | Oil-water well ratio | Average well depth(m) | Well-controlled reserves ($10^4$t) | Control degree of water flooding (%) | Single direction | Multiple directions | Total |
|-----------------|-----------------|-------------------|----------------------|-----------------------|------------------------------------|--------------------------------------|------------------|---------------------|-------|
| Now well pattern |                 |                   |                      |                       |                                    |                                      |                  |                     |       |
| Triangular well pattern center encryption | 15 | 1 | 1.7 | 173 | 6.94 | 34.3 | 55.0 | 89.3 |

6. Conclusion

By classifying the effective conditions of the SJ fault production wells, the relationship formula between the reservoir physical properties and the injection-production well spacing is determined, and the reasonable effective driving well spacing under different permeability is obtained. When the actual injection-production well spacing is less than the formula calculation well spacing, most of the production wells are effective in water injection.

According to the relationship formula between the reservoir physical properties and the injection-production well spacing regressed in this paper, under the same lithological conditions, the larger of the reservoir permeability, the larger of the effective drive well spacing. On the contrary, the smaller of the reservoir permeability, the effective drive well spacing is smaller.

Applying the new model to guide the design of the ST block to infill the well pattern, and determine the reasonable and effective driving well spacing is 173m. After the infilling, the oil well is obviously effective and achieves the infilling effect. The example application results show that the method described in this paper is simple and practical. It can widely used in mine work and provide guidance for the development and adjustment of this type of reservoir.

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