New Energy and Future Energy Systems
G.L. Kyriakopoulos (Ed.)

doi:10.3233/ATDE231077

Research on the Technical Limit Well Spacing Under the Condition of Variable Starting Pressure Gradient Based on Pressure Sensitivity Effect

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Abstract. Ultra low permeability reservoirs are significantly affected by the pressure sensitive effect, resulting in severe permeability loss, leading to a larger starting pressure gradient and increasing the difficulty of establishing effective displacement. At present, the existing technical limit well spacing formulas only consider the static starting pressure gradient and do not consider the reservoir pressure sensitivity effect, which leads to the problem of dynamic changes in the starting pressure gradient, resulting in the calculation results not being consistent with the actual situation of the mine. In response to this issue, a formula for calculating displacement pressure near oil and water wells considering pressure sensitivity effect and a formula for calculating variable starting pressure gradient were first established. Combined with the traditional formula for calculating the maximum well spacing, a formula for calculating the maximum well spacing between injection and production wells that can establish displacement considering dynamic starting pressure gradient was derived. The relationship between the permeability of ultra-low permeability reservoirs in Chaoyang Gou Oilfield and the technical limit well spacing was calculated. The analysis results indicate that compared with traditional methods, the new method needs to reduce the well spacing by 10m; The technical limit well spacing of Y-3 block is 47m; The demonstration results and case analysis results demonstrate the correctness and applicability of the formula. The results of this article can provide theoretical guidance for infill adjustment and potential tapping measures in ultra-low permeability reservoirs.

Keywords. Ultra low permeability oil reservoirs, Pressure sensitive effect, Variable starting pressure gradient, Technical limit well spacing

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1. Introduction

The physical properties and permeability of ultra-low permeability reservoirs are poor [1-6]. The fluid satisfies low-speed non Darcy flow and has high flow resistance [7-10]. The oil layer is severely affected by the stress sensitivity of the reservoir, resulting in severe permeability loss, increased start-up pressure gradient, and increased difficulty in establishing effective displacement, resulting in poor development effectiveness and benefits [11-13]. Well network encryption is an important adjustment measure to improve the development effect of oil reservoirs. Excessive injection production well spacing, high seepage resistance, and high pressure consumption between injection production wells make it difficult to establish effective displacement; If the distance between injection and production wells is too small, the development cost increases and the benefits decrease. Therefore, it is of great significance to adopt reasonable injection production well spacing for the effective development of ultra-low permeability oil reservoirs based on development technology policies.

Through research, it has been found that in the existing technical limit well spacing calculation formulas, the influence of pressure sensitivity effect on the distribution of displacement pressure between injection and production wells is not considered, and the problem of dynamic changes in starting pressure gradient caused by pressure sensitivity effect is not considered.

Firstly, establish a single well production calculation formula considering the pressure sensitive effect, and analyze the influence of pressure sensitive effect on the displacement pressure (the difference between the boundary supply pressure and the bottom hole pressure) near the injection and production wells based on the formula; Establish a calculation formula for variable starting pressure gradient based on pressure sensitive effect, and clarify the starting pressure gradient of the reservoir under different formation pressure conditions.

2. Calculation Formula for Variable Starting Pressure Gradient

Considering the pressure sensitivity of permeability, the permeability expression:

$$K = K_0 \mathrm{e}^{-M(P_i - \overline{P})} \tag{1}$$

In the formula: P_i is the initial formation pressure MPa; K_0 is the original permeability, mD; M is the pressure sensitive coefficient, MPa^{-1}; K is the Permeability under conditions affected by stress sensitivity, mD; $\overline{P}$ is the current formation pressure, MPa.

The relationship between the mobility and starting pressure gradient of low permeability reservoirs in the periphery of Daqing Placanticline satisfies the equation:

$$\lambda = a\left(\frac{K}{\mu}\right)^{-b} \tag{2}$$

In the formula: λ is the seepage resistance gradient, MPa/m; μ is the viscosity of crude oil, mPa · s; *a* and *b* is a positive real number.

Then, bring equation (1) into equation (2) to obtain the calculation formula for the variable starting pressure gradient:

$$\lambda = a\left(\frac{K_0}{\mu}\right)^{-b} \mathrm{e}^{bM(P_\mathrm{i}-\bar{P})} \tag{3}$$

3. A Formula for Calculating Displacement Pressure Considering Pressure Sensitivity Effect

The formula for calculating the yield of a single well can be expressed as:

$$\frac{\mathrm{d}P}{\mathrm{d}r} = \frac{q\mu B}{2\pi rh} \cdot \frac{1}{K} \tag{4}$$

In the formula: q is the output, $\mathrm{m^3/d}$; B is the volume coefficient of the fluid.

Substitute formula (1) into formula (4) to obtain the yield calculation formula considering stress sensitivity:

$$q = \frac{2\pi hK_0}{\mu B} \cdot \frac{\dfrac{1-\mathrm{e}^{-M(p_\mathrm{h}-p_\mathrm{w})}}{M}}{\ln\dfrac{r_\mathrm{h}}{r_\mathrm{w}}} \tag{5}$$

In the formula: r_h is the supply radius, m; r_w is the radius of the well, m; P_h is the supply pressure, MPa;

Through analysis, $\dfrac{1-\mathrm{e}^{-M(p_\mathrm{h}-p_\mathrm{w})}}{M}$ is the displacement pressure, the production (with positive outflow and negative inflow) can be expressed as:

Oil well production:

$$q_1 = \frac{2\pi h K_0}{\mu B} \cdot \frac{\dfrac{1-\mathrm{e}^{-M_\mathrm{o}(p_\mathrm{h}-p_\mathrm{w})}}{M_\mathrm{o}}}{\ln \dfrac{r_\mathrm{h}}{r_\mathrm{w}}} \tag{6}$$

Water well production:

$$q_2 = -\frac{2\pi h K_0}{\mu B} \cdot \frac{\dfrac{1-\mathrm{e}^{-M_\mathrm{w}(p_\mathrm{h}-p_\mathrm{e})}}{M_\mathrm{w}}}{\ln \dfrac{r_\mathrm{h}}{r_\mathrm{w}}} \tag{7}$$

Namely:

$$q_2 = \frac{2\pi h K_0}{\mu B} \cdot \frac{\dfrac{\mathrm{e}^{-M_\mathrm{w}(p_\mathrm{h}-p_\mathrm{e})}-1}{M_\mathrm{w}}}{\ln \dfrac{r_\mathrm{h}}{r_\mathrm{w}}} \tag{8}$$

In the formula: q_1 is the the oil production, m^3/d; q_2 is the water production well, m^3/d; P_e is the bottom hole pressure of the injection well, MPa; P_w is the bottom hole pressure of the oil production well, MPa.

According to formulas (6) and (8), the displacement pressures near oil and water wells are:

Displacement pressure near the oil well:

$$\Delta P_1 = \frac{1-\mathrm{e}^{-M_\mathrm{o}(p_\mathrm{h}-p_\mathrm{w})}}{M_\mathrm{o}} \tag{9}$$

Displacement pressure near the water well:

$$\Delta P_2 = \frac{\mathrm{e}^{-M_\mathrm{w}(p_\mathrm{h}-p_\mathrm{e})}-1}{M_\mathrm{w}} \tag{10}$$

M_o is the stress sensitivity coefficient at the extraction end, MPa^{-1}; M_w is the stress sensitivity coefficient of the injection end, MPa^{-1}; ΔP_1 is the guess the displacement pressure after overcoming resistance at the end, MPa; ΔP_2 is the displacement pressure after overcoming resistance at the injection end, MPa.

The displacement pressure between injection and production wells under pressure sensitive conditions can be expressed as:

$$\Delta P = \frac{1-e^{-M_o(p_h-p_w)}}{M_o} + \frac{e^{-M_w(p_h-p_e)}-1}{M_w} \tag{11}$$

To simplify the problem, if $P_h=P_i$, the above equation can be organized as:

$$\Delta P = \frac{1-e^{-M_o(p_i-p_w)}}{M_o} + \frac{e^{-M_w(p_i-p_e)}-1}{M_w} \tag{12}$$

4. A Calculation Formula for Technical Limit Well Spacing Considering Variable Starting Pressure Gradient

The traditional technical limit well spacing is expressed as

$$\frac{\Delta P}{\ln(R/r_w)} \cdot \frac{2}{R} = \lambda \tag{13}$$

$$\Delta P = P_e - P_w \tag{14}$$

ΔP is the displacement pressure, MPa; R is the technical limit well spacing, m.

Bring formulas (3) and (12) into formula (13) to obtain the formula for calculating the ultimate well spacing of variable starting pressure gradient technology based on pressure sensitivity effect:

$$\frac{\dfrac{1-e^{-M_o(p_i-p_w)}}{M_o} + \dfrac{e^{-M_w(p_i-p_e)}-1}{M_w}}{\ln(R/r_w)} \cdot \frac{2}{R} = a\left(\frac{K_0}{\mu}\right)^{-b} e^{bM(P_i-\bar{P})} \tag{15}$$

5. Application and Analysis of Formulas

5.1. Validation of Formulas

When the pressure sensitive coefficient is not considered, the two paragraphs of formula (15) can be organized as follows:

$$\lim_{\substack{M_o \to 0 \\ M_w \to 0}} \frac{\dfrac{1-e^{-M_o(p_i-p_w)}}{M_o}+\dfrac{e^{-M_w(p_i-p_e)}-1}{M_w}}{\ln(R/r_w)}\cdot\frac{2}{R}=\lim_{\substack{M_o \to 0 \\ M_w \to 0}} a\left(\frac{K_0}{\mu}\right)^{-b} e^{bM(P_i-\bar{P})} \tag{16}$$

Simplify to obtain:

$$\frac{(p_i-p_w)-(p_i-p_e)}{\ln(R/r_w)}\cdot\frac{2}{R}=a\left(\frac{K_0}{\mu}\right)^{-b} \tag{17}$$

Further organize and obtain formula (13) to prove the accuracy of the formula derivation process.

5.2. Case Study

Taking the Y-3 block of Zhaoyuan Oilfield as an example (see Table 1), the block was put into operation in 2008. Due to the continuous increase in injection pressure and approaching fracture pressure, the water absorption capacity rapidly decreased, and the injection was stopped in 2014. In order to achieve effective displacement and improve the development effect of the block, corresponding fracturing measures were taken for oil and water wells in July 2018. The initial water absorption capacity of the block was strong, but the injection pressure showed a rapid upward trend, while the injection volume continued to decline. The block has not yet established effective displacement (see Table 2). The calculated result using the new formula is 47m, which is smaller than the actual well spacing of the block. Based on the actual situation of the mine, the calculation results of the formula established in this article are more in line with the actual situation of the mine, proving the applicability of the formula.

Table 1. Statistics of basic parameters of Y-3 block.

parameter	numerical value	parameter	numerical value	parameter	numerical value
Air Permeability /mD	1.5	wellbore radius /m	0.127	Oil well pressure sensitivity coefficient /MPa^{-1}	0.0356
Underground crude oil viscosity /mPa·s	8.7	original formation pressure /MPa	14.8	Water well pressure sensitivity coefficient /MPa^{-1}	0.0036
starting pressure gradient /(MPa·m^{-1})	0.102	fracturing pressure /MPa	13.3	Medium depth of oil layer /m	1002

Table 2. Statistics of current development indicators of block Y-3(November 2019).

Injection well		Production well			Block
injection pressure /MPa	Daily injection volume /(m^3·d^{-1})	Daily liquid production /(t·d^{-1})	daily oil production /(t·d^{-1})	bottom hole flowing pressure /MPa	Formation Pressure /MPa
13.3	0.68	0.43	0.3354	3	7.3

5.3. Application of Formulas

Taking Chaoyanggou Oilfield outside Changyuan as an example, under the current working system conditions, calculate the technical limit well spacing of each block (see Table 3). The calculation results indicate that the maximum well spacing distribution using the new formula is between 46-189m.

Because of sensitivity on reservoir stress and the influence of dynamic start-up pressure gradient, the well spacing should be reduced by 1-18m, with an average reduction of 10m.

Table 3. Calculation results of technical limit well spacing in some blocks

block	Air Permeability /mD	Technical limit well spacing /m Traditional formula	New formula/m	Difference in well spacing	block	Air Permeability /mD	Technical limit well spacing /m Traditional formula	New formula/m	Difference in well spacing
C94Y	2.0	58	46	12	C631	6.4	155	139	16
C2D	2.6	82	80	2	L31	6.4	129	115	14
C945Y	3.1	93	75	18	YBJQ	6.5	146	137	9
C691	3.5	101	95	6	C202Z	7.0	141	137	4
C83	3.5	89	88	1	C86	8.6	165	160	5
C02YB	4.5	122	114	8	C521	9.2	192	174	18
L46	4.6	114	98	16	C522	9.2	178	168	10
C202YB	5.0	124	119	5	C661B	9.2	169	159	10
FSTC89	6.2	152	142	10	C601	9.6	197	189	8
C503	6.4	169	154	15	CQ3	9.8	177	170	7
C02Z	6.4	142	131	11	total	6.2	138	128	10

Analyze the relationship between permeability and technical limit well spacing based on the calculation results (see Figure 1). The calculation results indicate that there is a good linear correlation between permeability and the technical limit well spacing. As the permeability increases, the technical limit well spacing increases. When the permeability is less than 10mD, the technical limit well spacing is 189m, and when the permeability is less than 5mD, the technical limit well spacing is less than 114m.

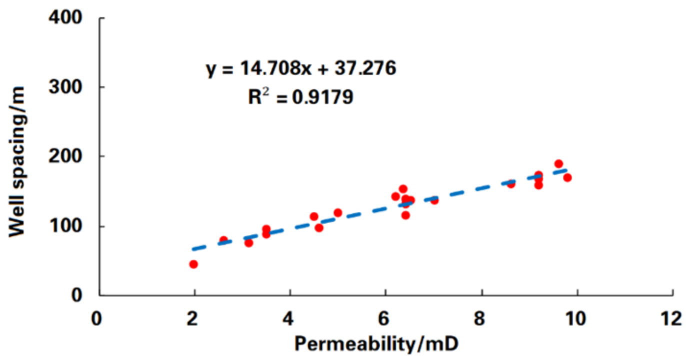

Fig.1. Relationship between permeability and technical limit well spacing.

6. Conclusion

(1) Using the permeability calculation formula considering pressure sensitivity effect and calculation formula, the starting pressure gradient calculation formula under different formation pressure conditions was derived; A formula for calculating displacement pressure near injection production wells has been established using a single well production calculation formula that considers pressure sensitive effects.

(2) Through theoretical analysis, the correctness of the formula derivation process has been proven; Taking the Y-3 block of Zhaoyuan Oilfield as an example, the technical limit well spacing of this block is calculated to be 47m, which is more in line with the actual situation of the mine.

(3) Compared with the traditional method calculation results, the formula established in this article needs to further reduce the technical limit well spacing by 1-18m, with an average reduction of 10m; Based on the injection and production parameters of the ultra-low permeability block in Chaoyang Gou Oilfield, the required adjustment of injection and production well spacing has been determined.

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