Production calculation model considering variable start-up pressure gradient in ultra-low permeability reservoirs

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Abstract. Ultra-low permeability reservoir fluid presents nonlinear flow, pressure sensitive effect, permeability changes, resulting in starting pressure gradient changes. At present, the problem of variable-start pressure gradient and pressure-sensitive effect is not considered in the existing production calculation method. To solve these problems, based on the percolation theory of ultra-low permeability reservoir, this study established the variable-start pressure gradient production calculation model based on the pressure sensitivity effect by using the pressure-sensitive effect formula and other laboratory experiment results. Taking Block C of Chaoyanggou Oilfield as an example, the main influencing factors of development effect under the condition of variable start-up pressure gradient are analyzed. The results show that the start-up pressure gradient leads to a significant decline in oil well production. When the variable start-up pressure gradient and pressure sensitive effect are considered simultaneously, the effective production radius of the oil well decreases, and the production of the oil well varies nonlinearly with the change of pressure. Compared with the calculation results of the non-Darcy seepage production model, the calculation accuracy of the model in this paper is improved by 4.17%.

1. Introduction
In recent years, with the decreasing of recoverable reserves and the decreasing of exploitation potential in the old oilfields, extra-low permeability reservoirs in the periphery of Daqing have gradually become an important target for oil field production succession. Because of the high start-up pressure gradient [1-3] in ultra-low permeability reservoirs and the significant influence of pressure sensitivity effect, it increases the technical difficulty and cost of production. In order to ensure the
efficient development of oilfields, it is necessary to deepen the percolation characteristics of ultra-low permeability reservoirs and realize the effective utilization of ultra-low permeability reservoirs [4-5].

Start-up pressure gradient and pressure-sensitive effect exist simultaneously in ultra-low permeability reservoirs [6-8]. In low permeability reservoir development process, it is difficult to establish effective driving system, resulting in a decline in reservoir pressure, causing the overlying rock pressure and rock pore pressure increase, loss of balance between rock and pore, cause the change of porosity and permeability, permeability changes lead to significant start-up pressure gradient changes, fluid seepage characteristic changes, affecting reservoir use scope, the reservoir development effect [9-10]. At present, the effects of pressure sensitivity effect and variable starting pressure gradient are not considered in the existing production models of extra-low permeability reservoirs, and the calculation errors are large, which cannot perfectly describe the characteristics of fluid flow in extra-low permeability reservoirs [11]. In order to solve this problem, this study based on the theory of a low permeable reservoir non-darcy seepage, fully considering the pressure sensitive effect and variable, the function of start-up pressure using the formula of pressure sensitive effect and the start-up pressure gradient formula, variable of start-up pressure gradient model is deduced, based on this, is developed, with the consideration of pressure sensitive effect and the output of start-up pressure gradient calculation model, to improve low permeability reservoir seepage theory.

2. Study on Start-up Pressure Gradient and Pressure Sensitive Effect

2.1 Start-up Pressure Gradient

Ji Bingyu used the actual physical property data of 56 blocks of Fuyu reservoir in Daqing peripheral oilfield to obtain the relationship curve between permeability and starting pressure gradient of Fuyu reservoir in the periphery of Changyuan [12](figure 1). When permeability is less than $3 \times 10^{-3}$ $\mu$m$^2$, the increasing range of starting pressure gradient increases. According to the actual data, the relationship curve between reciprocal permeability and start-up pressure gradient is drawn (figure 2). The regression curve has good linear correlation.

![Figure 1](image1.png)

**Figure 1.** The relationship between permeability and start-up pressure gradient
The relationship between permeability and start-up pressure gradient is satisfied.

\[ K^{-1} = 7.8358 \cdot \lambda \] (1)

Collate:

\[ \lambda = 0.1276 \cdot K^{-1} \] (2)

Formula: \( K \) is permeability, \( 10^{-3}\mu m^2 \); \( \lambda \) is the starting pressure gradient, MPa/m.

2.2 Effect of Pressure Sensitivity

The relationship between cores of different permeability grades and pressure sensitivity coefficient of Fuyu reservoir is measured by laboratory experiments (figure 3). The relationship between permeability and pressure sensitivity coefficient is exponential. With the decrease of permeability, pressure sensitivity coefficient decreases.

\[ M = 0.0432 \cdot e^{0.1298K_0} \] (3)

Formula: \( M \) is pressure sensitive coefficient, MPa\(^{-1}\); \( K_0 \) is initial permeability, \( 10^{-3}\mu m^2 \).

2.3 Study on Variable Start-up Pressure Gradient

In the process of reservoir development, influenced by pressure sensitivity effect, the change of formation pressure leads to the change of reservoir medium, and the permeability and start-up pressure gradient change accordingly, which affect each other. It is assumed that when the injection pressure of the injection well is higher than the original formation pressure, the rock structure does not deform and the pore volume and permeability remain unchanged.

Relationship between reservoir permeability and effective overburden pressure:

\[ K = K_0 e^{-M(\rho - \rho)} \] (4)

Among them,
Then the pressure gradient formula of variable start-up based on pressure-sensitive effect can be expressed as:

$$\lambda = a \cdot K_0^{-b} e^{bM(p_i - p)}$$  \hspace{1cm} (6)

When \(b=1\), the upper formula is:

$$\lambda = a \cdot K_0^{-1} e^{M(p_i - p)}$$  \hspace{1cm} (7)

Formula: \(p\) is current formation pressure, MPa; \(p_i\) is original formation pressure, MPa; \(a, b\) are positive real numbers.

3. Study on production calculation model of ultra-low permeability reservoir

The calculation model of non-Darcy seepage yield is as follows:

$$\frac{dq}{dr} = \frac{q \mu B}{2 \pi r h K} + \lambda$$  \hspace{1cm} (8)

Formula: \(q\) is oil production, m³/d; \(r\) is supply radius, m; \(h\) is reservoir thickness, m; \(B\) is fluid volume coefficient; \(\frac{dq}{dr}\) is pressure gradient, MPa/m; \(\mu\) is fluid viscosity, MPa·s.

By introducing formulas (4) and (7) into the above formulas, a production calculation model considering variable start-up pressure gradient and pressure-sensitive effect is obtained:

$$\frac{dq}{dr} = \frac{q \mu B}{2 \pi r h K} \cdot e^{M(p_i - p)} + \frac{a}{K_0} \cdot e^{M(p_i - p)}$$  \hspace{1cm} (9)

Separate variables to obtain:

$$\int_{p_u}^{p_v} K_0 \cdot e^{-M(p_i - p)} dp = \int_{r_u}^{r_v} \left( \frac{q \mu B}{2 \pi r} - a \right) dr$$  \hspace{1cm} (10)

For upper integrals:

$$q = \frac{2 \pi h}{\mu B} \cdot K_0 \left[ e^{-M(p_i - p_u)} - e^{-M(p_i - p_v)} \right] - a \cdot M \cdot \frac{r_e - r_w}{r_w}$$  \hspace{1cm} (11)

As \(p_u = p_v\), the output calculation model considering variable start-up pressure gradient and pressure-sensitive effect was obtained.

$$q = \frac{2 \pi h}{\mu B} \cdot K_0 \left[ 1 - e^{-M(p_i - p_u)} \right] - a \cdot M \cdot \frac{r_e - r_w}{r_w}$$  \hspace{1cm} (12)

As \(M \to 0\), Then formula (12) can be arranged as:

$$q = \lim_{M \to 0} \frac{2 \pi h}{\mu B} \cdot K_0 \cdot \frac{1 - e^{-M(p_i - p_u)}}{M} - \lim_{M \to 0} \frac{2 \pi h a \cdot (r_e - r_w)}{\mu B \ln \frac{r_e}{r_w}}$$  \hspace{1cm} (13)

The results show that:

$$q = \frac{2 \pi h K_0}{\mu B} \cdot \left( p_e - p_w \right) - a \cdot K_0^{-1} \cdot \frac{(r_e - r_w)}{\ln \frac{r_e}{r_w}}$$  \hspace{1cm} (14)

By introducing formula (7) into the upper formula, a production calculation model considering only the start-up pressure gradient is obtained:
As \( a \to 0 \), Then formula (12) can be arranged as follows:

\[
q = \frac{2\pi h K_0}{\mu B} \left( p_e - p_w \right) - \lambda \cdot \frac{2\pi h a (r_e - r_w)}{\ln \frac{r_e}{r_w}}
\]

After calculation, the output calculation model considering only pressure sensitive effect is obtained:

\[
q = \frac{2\pi h K_0}{\mu B} \cdot \frac{1 - e^{-M(p_e - p_w)}}{M \cdot \ln \frac{r_e}{r_w}}
\]

As \( a \to 0 \), \( M \to 0 \), the pressure distribution model under Darcy seepage condition is obtained:

\[
q = \frac{2\pi h K_0}{\mu B} \cdot \frac{p_e - p_w}{\ln \frac{r_e}{r_w}}
\]

### 4. Analysis of Main Influencing Factors of Development Effect

Taking Block C of Chaoyanggou Oilfield in Fuyu Reservoir as an example, the effects of starting pressure gradient, pressure sensitive effect, permeability and well spacing on oil well production are analyzed by using the established model. By the end of 2018, the geological reserves in Block C are \( 147 \times 10^4 \) t, and 50 oil wells and 12 water wells are produced by 250×250 m inverse nine-point method. The permeability of Block C is \( 4.5 \times 10^{-3} \) μm², the porosity is 17%, the effective thickness is 9.6 m, the viscosity of underground crude oil is 14mPa•s, the volume coefficient of crude oil is \( 1.076 \) MPa⁻¹, the original formation pressure is 8.4MPa, and the injection pressure is 12.5MPa. The flowing pressure of the well is 2.6MPa, the recovery degree is 6.26%, the recovery rate is 0.22%, the wellbore radius is 0.127m, and the starting pressure gradient is 0.032MPa·m⁻¹.

(1) Variable start-up pressure gradient seriously restricts development effect

In view of the model and calculation data, the following aspects should be improved: first, the accuracy of laboratory test results should be improved. The model is based on the test results of starting pressure gradient and pressure sensitive effect. If the experimental errors are large, there will be a big deviation between the calculation results and the actual data. Second, the influence of fracture parameters on production should be deepened. Third, the calculation by stages should be considered. In the actual production process of the mine, the flowing pressure is different in different stages, so the calculation of flowing pressure in different stages can be considered (figure 4).
Figure 4. Start-up pressure gradient and pressure-sensitive effect versus yield curve

Figure 5. The relationship between well spacing and production

(2) The smaller the injection-production well spacing, the better the development effect.

From the curve of well spacing versus production considering variable starting pressure gradient (see figure 5), it can be seen that the smaller the injection-production well spacing is, the better the development effect is. The smaller the well spacing is, the smaller the flow resistance needs to be overcome, the easier it is to establish an effective driving system and the higher the sweep efficiency.

(3) The more serious the pressure sensitive effect is, the worse the development effect is.

According to the relationship curve between pressure sensitivity effect and production (see figure 6), the bigger the pressure sensitivity coefficient is, the bigger the permeability change of reservoir under unit pressure difference is, and the bigger the change of starting pressure is, which leads to the further decline of oil well production in low permeability reservoir, and the output varies nonlinearly with the change of pressure sensitivity coefficient.

(4) The greater the permeability, the better the development effect.

From the relationship curve between permeability and production (figure 7), it can be seen that the production of oil wells increases with the increase of permeability, the greater the permeability, the non-linear change of production. When the permeability is less than 3mD, the change range of production is smaller and the production is lower.
5. Example analysis

According to the actual production data of Block C in Shengli Oilfield, the model was validated. The calculation results show that the actual cumulative oil production of 50 oil wells is $9.21 \times 10^4$ t, and the cumulative oil production calculated by non-Darcy production calculation model is $10.07 \times 10^4$ t with an error of 9.34%. The cumulative oil production calculated by the model is $8.73 \times 10^4$ t with an error of 5.17%. The cumulative oil production calculated by non-Darcy production calculation model is $10.07 \times 10^4$ t with an error of 9.34%. The results show that the calculation accuracy of the model is improved by 4.17% compared with that of the actual index, and it is basically consistent with the change rule of the actual index (figure 8).

Figure 8. Curves of actual cumulative oil production and calculated cumulative oil production with time in Block C

In view of the model and calculation data, the following aspects should be improved: first, the accuracy of laboratory test results should be improved. The model is based on the test results of starting pressure gradient and pressure sensitive effect. If the experimental errors are large, there will be a big deviation between the calculation results and the actual data. Second, the influence of fracture parameters on production should be deepened. Third, the calculation by stages should be considered.
In the actual production process of the mine, the flowing pressure is different in different stages, so the calculation of flowing pressure in different stages can be considered.

6. Conclusion

- Based on the pressure sensitive effect formula and the starting pressure gradient formula, the calculating formula considering the variable starting pressure gradient is deduced.
- Aiming at the low permeability reservoir in Fuyu reservoir on the periphery of Changyuan, considering the effect of pressure sensitivity on the start-up pressure gradient and permeability, the productivity model of Fuyu reservoir on the periphery of Changyuan considering variable start-up pressure gradient is deduced, which makes up for the deficiency of the existing productivity model of low permeability reservoir.
- When considering variable start-up pressure gradient, the production curve varies nonlinearly with pressure. The influence of start-up pressure on oil well production is greater than that of pressure-sensitive effect, which indicates that start-up pressure has a greater impact on low permeability reservoir production. The change of start-up pressure in low permeability reservoir caused by pressure-sensitive effect leads to oil well production considering variable start-up pressure gradient and pressure-sensitive effect. Further decline.
- The calculation results of an example show the accuracy and applicability of the established model, which can be used to evaluate the development effect of ultra-low permeability reservoirs and to compile development plans for similar reservoirs.

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