Study on percolation mechanism of low permeability reservoir

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Abstract. The development practice of low permeability reservoir shows that there is start-up pressure gradient in low permeability reservoir, and the lower the permeability is, the higher the start-up pressure gradient is. Therefore, there are different types of sandstones in low-permeability sandstone reservoirs, with different permeability and different starting pressure gradient, resulting in different seepage space. This paper attempts to establish mathematical model and numerical simulation model to simulate the movement law of oil and water in low permeability reservoir by considering different seepage space and its starting pressure, so as to study the distribution and variation law of invalid water injection in space, and provide basis for formulating reasonable injection production ratio and other injection production policies.

1. Introduction
Aiming at the problem that it is difficult to effectively develop and produce the extra low permeability and extra low abundance reservoirs in peripheral oilfields of Daqing, the techniques of space variant wavelet seismic inversion, independent variable analysis and virtual well prediction for identifying thin and narrow sand bodies are studied and formed by comprehensively applying seismic, geological and logging data. The prediction accuracy of sand bodies reaches more than 85%. The production calculation models of different well patterns under the condition of non Darcy flow are established, and the well pattern optimization design method for fractured reservoir is proposed.

2. brief introduction of water injection process in low permeability reservoir

2.1 Distribution characteristics of sand body in low permeability reservoir
Each small layer in an oilfield is relatively thin, and the permeability changes in the vertical direction are quite different, and the heterogeneity of each small layer from bottom to top presents a trend of weak to strong to weak. At the same time, the statistics of sandstone thickness and effective thickness show that the average ratio of effective thickness to total sandstone thickness is 66%, and the ratio of some small layers is even less than 50%. The practice shows that the invalid sandstone and even mudstone of low permeability reservoir also participate in water absorption during water injection development. This is because although the invalid sandstone does not participate in fluid flow under the action of lower pressure gradient, the injected fluid will be absorbed under the action of higher pressure gradient, thus forming "invalid water injection".

According to the different types of sandbodies in low permeability sandstone reservoirs, it can be assumed that there are two kinds of seepage spaces in the reservoir: conventional sandstone layer and ineffective sandstone layer (including partially water absorbing sandstone and mudstone). The former is called "effective layer" or "effective thickness" in practice, which is the main basis for calculating
geological reserves and the focus of development. The latter is the storage space of partially injected water under high injection pressure.

2.2 Analysis of water absorption process in low permeability reservoir

Generally speaking, the physical process of injected water seepage in low permeability reservoir can be approximately expressed as follows: after the injected water enters the effective sandstone before the time, the pressure of the effective sandstone in the area increases first \([1]\). When the pressure increases and exceeds the starting pressure of the ineffective sandstone in the area, a part of the injected water will enter the ineffective sandstone in the area, resulting in "ineffective water injection". At this time, the other part of the injected water overcomes the starting pressure gradient and seepage resistance in the effective sandstone, continues to flow to the other conventional sandstone layer, and enters a new area. At the same time, the formation pressure in the area is increased. When the formation pressure increases, the injected water wave and the ineffective sandstone in the area will be caused. According to this seepage process, the injected water will move from the injection well to the production well. We can establish a new seepage mathematical model of low permeability reservoir according to different regions.

3. new mathematical model of low permeability reservoir seepage

3.1 control equation continuity equation of oil-water two-phase flow mathematical model considering effective layer and ineffective water absorbing layer\(^2\)

Effective oil-water two-phase control equation of sandstone (source and sink terms are not considered):

\[
\nabla \left[ \frac{M_w K_{1w}}{B_{1w} \mu_{1w}} \operatorname{grad}(p_{1w}) - \lambda_{1w} \right] + q_{1w} - \tau_w = \frac{\partial}{\partial t} \left( \frac{S_{1w} \phi_l}{B_{1w}} \right)
\]

\( (1) \)

\[
\nabla \left[ \frac{M_o K_{1o}}{B_{1o} \mu_{1o}} \operatorname{grad}(p_{1o}) - \lambda_{1o} \right] + q_{1o} - \tau_o = \frac{\partial}{\partial t} \left( \frac{S_{1o} \phi_l}{B_{1o}} \right)
\]

\( (2) \)

The oil-water two-phase governing equation of invalid sandstone is as follows

\[
\nabla \left[ \frac{M_w K_{2w}}{B_{2w} \mu_{2w}} \operatorname{grad}(p_{2w}) - \lambda_{2w} \right] + \tau_w = \frac{\partial}{\partial t} \left( \frac{S_{2w} \phi_l}{B_{2w}} \right)
\]

\( (3) \)

\[
\nabla \left[ \frac{M_o K_{2o}}{B_{2o} \mu_{2o}} \operatorname{grad}(p_{2o}) - \lambda_{2o} \right] + \tau_o = \frac{\partial}{\partial t} \left( \frac{S_{2o} \phi_l}{B_{2o}} \right)
\]

\( (4) \)

Parameter and equation description: in equations 1-1 ~ 1-4, subscripts "w" and "o" denote water phase and oil phase respectively; subscripts "1" and "2" denote effective sandstone space and ineffective water absorption space respectively; \( K_{1w}, K_{1o} \) are relative permeability of water and oil, \( B_{1w}, B_{1o} \) are volume coefficient of water and oil, \( \mu_w, \mu_o \) are viscosity of water and oil, \( \tau_w, \tau_o \) are exchange flow of water and oil between effective sandstone and ineffective sandstone, \( S_{1w}, S_{1o} \) are saturation of water and oil, \( \lambda_{1w}, \lambda_{1o} \) are the starting pressure gradient of water and oil, \( q_{1w}, q_{1o} \) are the daily production (injection) of oil (or water) well, is the porosity, \( t \) is the time and \( p \) is the pressure.

2 Nonlinear seepage coefficient

There are many equations describing nonlinear seepage. In this paper, Yang Qingli equation is used and some modifications are made according to its physical significance\(^5\)

\[
\nu = \frac{K}{\mu} \nabla p \left( 1 - \frac{B}{\nabla p - A + B} \right)
\]

\( (5) \)

In this way, \( M \) in equations 1-1 and 1-2 can be expressed as:
\[ M_e = 1 - \frac{B}{|\nabla p| - A + B} \]  

(6)

In the above formula, \( a \) is the minimum starting pressure gradient and \( B \) is the gradient of the proposed starting pressure.

3. Other parameters

Other parameters

\[ \tau_j = \begin{cases} \beta \frac{K_r K_w}{\mu_t} (p_1 - p_2 - \lambda_n) & (p_1 - p_2 > \lambda_n) \\ 0 & (-\lambda_{out} > p_1 - p_2 > \lambda_n) \\ \beta \frac{K_r K_w}{\mu_t} (p_1 - p_2 - \lambda_{out}) & (p_1 - p_2 < \lambda_{out}) \end{cases} \]  

(7)

Where the subscript "1" denotes "w" or "o". Water phase and oil phase [4]. When the pressure difference between the effective sandstone and the ineffective sandstone is greater than the threshold of the start-up pressure of the fluid in the ineffective sand layer, the fluid can enter the ineffective sandstone; when the pressure difference between the effective sandstone and the ineffective sandstone is greater than the threshold of the start-up pressure of the outflow, the fluid can flow back from the ineffective sandstone to the effective sandstone. It can appear.

4. Solution of seepage mathematical model for low permeability reservoir

In this paper, implicit pressure and explicit saturation (IMPES) method is used to solve the pressure and saturation. For the viscosity, phase permeability, volume coefficient and nonlinear seepage coefficient in the equation are equal to the parameters related to pressure and saturation, explicit and upstream weight methods are adopted. Finally, the sparse matrix incomplete LU decomposition method is used to solve the difference equation for the formed seven diagonal equation [3].

4.1 IMPES method

1) Implicit pressure equation

By multiplying the two ends of equations 1-1 and 1-2, the implicit pressure equation for effective sandstone can be obtained:

\[ c_y P_{i+1,j}^{n+1} + a_y P_{i-1,j}^{n+1} + e_y P_{i,j+1}^{n+1} + b_y P_{i,j-1}^{n+1} + d_y P_{i+1,j}^{n+1} + h_y P_{2i,j}^{n+1} = f_y \]

Among

\[ a_y = B_{iw} \alpha_{w} + B_{io} \alpha_{o} = B_{iw} \lambda_{w} \left( \frac{1}{2} \right)^{\frac{1}{2}} \cdot T_{w,j}^{1-\frac{1}{2}} + B_{io} \lambda_{o} \left( \frac{1}{2} \right)^{\frac{1}{2}} \cdot T_{o,j}^{1-\frac{1}{2}} \]

\[ b_y = B_{iw} b_{w} + B_{io} b_{o} = B_{iw} \lambda_{w} \left( \frac{1}{2} \right)^{\frac{1}{2}} \cdot T_{w,j}^{1-\frac{1}{2}} + B_{io} \lambda_{o} \left( \frac{1}{2} \right)^{\frac{1}{2}} \cdot T_{o,j}^{1-\frac{1}{2}} \]

\[ c_y = B_{iw} c_{w} + B_{io} c_{o} = B_{iw} \lambda_{w} \left( \frac{1}{2} \right)^{\frac{1}{2}} \cdot T_{w,j}^{1-\frac{1}{2}} + B_{io} \lambda_{o} \left( \frac{1}{2} \right)^{\frac{1}{2}} \cdot T_{o,j}^{1-\frac{1}{2}} \]

\[ d_y = B_{iw} d_{w} + B_{io} d_{o} = B_{iw} \lambda_{w} \left( \frac{1}{2} \right)^{\frac{1}{2}} \cdot T_{w,j}^{1-\frac{1}{2}} + B_{io} \lambda_{o} \left( \frac{1}{2} \right)^{\frac{1}{2}} \cdot T_{o,j}^{1-\frac{1}{2}} \]

\[ e_y = -\left( a_y + b_y + c_y + d_y \right) - \frac{\phi \cdot V_{sb}}{\Delta t} \left[ C_{ip} - \frac{S_{iw}}{B_{iw}} \frac{dB_{iw}}{dp} + \frac{S_{io}}{B_{io}} \frac{dB_{io}}{dp} \right] \]
Similarly, the implicit pressure equation of invalid sandstone can be obtained

\[ c_{ij} P_{2i-1,j}^{n+1} + a_{ij} P_{2i,j}^{n+1} + b_{ij} P_{2i+1,j}^{n+1} + d_{ij} P_{2i,j+1}^{n+1} + h_{ij} P_{1i,j}^{n+1} = f_{ij}^{n+1} \quad (9) \]

(2) Explicit saturation equation

The oil and water equations 1-8 and 1-9 are directly added and substituted into the pressure sum obtained by solving the implicit pressure equation

\[ c_{oij} P_{1o,i,j-1}^{n+1} + c_{wij} P_{1w,i,j-1}^{n+1} + a_{oij} P_{1o,i-1,j}^{n+1} + a_{wij} P_{1w,i-1,j}^{n+1} + b_{oij} P_{1o,i,j}^{n+1} + b_{wij} P_{1w,i,j}^{n+1} + b_{wij} P_{1w,i,j+1}^{n+1} \]

\[ + d_{oij} P_{1o,i,j+1}^{n+1} + d_{wij} P_{1w,i,j+1}^{n+1} = V_{ij} \phi \left( \rho_o - \rho_w \right) \frac{S_{1w,i,j}^{n+1} - S_{1w,i,j}^{n}}{\Delta t} \]

The water saturation can be calculated by the explicit saturation equation, and then the oil saturation can be calculated by the auxiliary equation of oil-water saturation.

5. Conclusions

(1) There are a large number of ineffective water absorbing layers in low / ultra-low permeability reservoirs, such as dry sandstone and mudstone, which have a serious impact on the movement of injected water;

(2) The more invalid water absorption layer, the greater the influence on water content;

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