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RESEARCH PAPER

An interwell connectivity inversion model for waterflooded multilayer reservoirs

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Abstract: In view of the limitations that the current connectivity model can only forecast the fluid production dynamic change, can't calculate the dynamics of oil and water phases, and can't analyze the connectivity between wells layer by layer, this study establishes a new interwell connectivity model for multilayer reservoirs which can simulate dynamics of oil and water between wells. The model hierarchically separates the reservoir system into a series of interwell connecting units characterized by parameters such as conductivity and control volume, and by using the material balance equation, the pressure and interwell flow at constant liquid production or constant pressure mode is calculated regarding the connecting unit as a simulation object, which are combined with the frontal advance theory to establish interwell saturation tracking calculation, and finally water production dynamics of every layer at well points can be worked out. On this basis, using simultaneous perturbation stochastic approximation method and gradient projection method, a model parameter inversion method is set up by dynamic fitting. The application cases show that the model has good dynamic fitting and prediction effect, inversed model parameters coincide with the actual geological parameters, verifing the validity of the method. Compared with the current connectivity method, it can obtain the real-time model of hierarchical interwell flow rate distribution coefficient, liquid production of single well and oil split coefficient and other information, and reflect the reservoir horizontal and vertical oil-water flow relation more accurately, providing guidance for production measure adjustment in oilfield.

Key words: multilayer reservoir; interwell conectivity; inversion model; interwell connecting unit; interwell flow rate distribution coefficient; oil split coefficient

Introduction

As the basis of reservoir water-flooding development, the evaluation of interwell connectivity is of great significance for analyzing residual oil distribution, making infill well pattern plan and optimizing injection-production scheme[1–3]. In the oilfield, the common methods to figure out interwell connectivity include tracer test, interwell microseismic, and interference well test[4–5] etc. However, these methods have flaws like disrupting production, long interpretation time and high cost, and can not satisfy the requirement to recognize interwell connectivity of a whole block or oilfield fully.

Simulating inversely interwell connectivity by using abundant injection-production rate is another important kind of method, which features simpler operation, less and faster computation and larger inversion scope etc than traditional numerical simulation methods. The prevailing inversion models mainly include correlation analysis model[6], multiple regression model[7], capacitance-resistance model[8–15], system-analysis model [16] etc. The former two models characterize interwell connectivity with correlation coefficient obtained from matching injection and production rate. The essence of the latter two methods is filtering correct the injection rate of multiple regression model to take the time delay characteristics of injection dynamics into consideration, thus making it tally with the actual flow characteristics of reservoirs better. Among them, the capacitance-resistance model[11–15] is based on the similarity of water and electricity and the material balance principle and considers the time delay characteristic of injection rate; while system-analysis model is based on the one order time delay characteristic of injection-production system[16].

Although the above interwell methods can obtain information on interwell connectivity to some extent, they have some problems: usually the models and methods are too simple and

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ideal, consider few factors, and cannot be applied in multilayer connectivity analysis and calculation, and can't characterize heterogeneity of interlayers; inversion model connectivity parameter lacks of definite geological significance; cannot consider situations such as well shutting-in or conversion of the oil well to injection well, and the inversion results are strongly affected by production measures; only can predict and match liquid production, and cannot incorporate other oil-water dynamic data such as water cut into inversion, which undermines the reliability of the inversion results.

In order to solve the above problems, an interwell connectivity inversion model for oil-water dynamic simulation of multilayer reservoirs has been established in this study, which, combines with optimization algorithm, can simulate and history match all the dynamic parameters in waterflooding, such as water cut, oil production and flowing pressure, work out the connectivity parameters hierarchically, and reflect the relationship between the injection and production wells and the underground oil and water flow dynamics in real time.

1. Establishment of interwell connectivity model

With reference to the method proposed by Gherabati[17], we simply discrete all layers of a reservoir as a series of interwell connecting units (Fig. 1) characterized by parameters such as interwell conductivity and control pore volume etc. Interwell conductivity represents the flow velocity under unit differential pressure, which can reflect the average seepage capability and preferential direction of flow between the wells, while interwell control pore volume characterizes the material basis of the connecting unit, which can reflect the control volume and range of interwell waterflooding. It is obvious that, the smaller the interwell conductivity and the larger the control volume, the longer the water-free oil production period of a connecting unit will be under equal differential pressure. Then we established mass balance equation for every connecting unit and worked out pressure and interwell flow in constant liquid mode and constant pressure mode; finally, combining with front tracking equation, we calculated saturation distribution of interwell connecting units and multilayer production dynamic data.

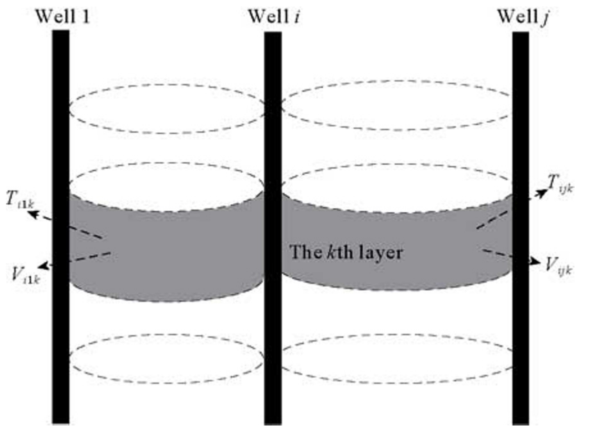

Fig. 1. Connecting unit between wells of every layer.

1.1. Calculation of pressure and interwell flow rate

Considering only the two-phase flow of oil and water and according to Darcy equation, the total mass balance with compressibility and neglecting capillary pressure and channeling between layers for the ith well is,

$$\sum_{k=1}^{N_1}\sum_{j=1}^{N_w} T_{ijk}(t)\left[p_j(t)-p_i(t)\right]+q_i(t)=\frac{\mathrm{d}p_i(t)}{\mathrm{d}t}\sum_{k=1}^{N_1} C_{tk}V_{ik}(t) \tag{1}$$

Arranging Eq. 1, we get:

$$\sum_{k=1}^{N_1}\sum_{j=1}^{N_w} T_{ijk}(t)p_j(t)-p_i(t)\sum_{k=1}^{N_1}\sum_{j=1}^{N_w} T_{ijk}(t)+q_i(t)=\frac{\mathrm{d}p_i(t)}{\mathrm{d}t}\sum_{k=1}^{N_1} C_{tk}V_{ik}(t) \tag{2}$$

Approximating Eq. 2 by the purely-implicit finite-difference method gives:

$$\sum_{k=1}^{N_1}\sum_{j=1}^{N_w} T_{ijk}^n p_j^n - p_i^n\sum_{k=1}^{N_1}\sum_{j=1}^{N_w} T_{ijk}^n + q_i^n=\frac{p_i^n-p_i^{n-1}}{\Delta t^n}\sum_{k=1}^{N_1} C_{tk}V_{ik}^n \tag{3}$$

According to seepage theory[18], conductivity and control pore volume change over time and can be calculated respectively based on saturation and pressure:

$$T_{ijk}^n=11.57\frac{A_{ijk}\lambda_{ijk}^{n-1}}{L_{ijk}}=T_{ijk}^0\frac{\lambda_{ijk}^{n-1}}{\lambda_{ijk}^0} \tag{4}$$

$$V_{ik}^n=V_{ik}^0\left[1+C_{tk}(p_i^{n-1}-p_i^0)\right] \tag{5}$$

λ_{ijk}^n can be obtained by upstream weighting used in numerical simulation[19]:

$$\lambda_{ijk}^n=\begin{cases}\lambda_{ik}^{n-1}=K_{ijk}\left[\dfrac{K_{ro}(S_{wik}^{n-1})}{\mu_{ok}}+\dfrac{K_{rw}(S_{wik}^{n-1})}{\mu_{wk}}\right] & p_i^{n-1}\geqslant p_j^{n-1}\\[2ex] \lambda_{jk}^{n-1}=K_{ijk}\left[\dfrac{K_{ro}(S_{wjk}^{n-1})}{\mu_{ok}}+\dfrac{K_{rw}(S_{wjk}^{n-1})}{\mu_{wk}}\right] & p_i^{n-1}<p_j^{n-1}\end{cases} \tag{6}$$

There are two kinds of inner boundary conditions for source and sink terms: constant pressure and constant liquid production. Two modes can be transformed between each other in actual simulation. Pressure solving process of Eq. 3 is given as follows.

1.1.1. Constant liquid production mode

Constant liquid production mode means q_i^n is a known constant, so Eq. 3 can be stated as below:

$$p_i^n-p_i^{n-1}=\omega_i\sum_{j=1}^{N_w}\eta_{ij}^n p_j^n-p_i^n\psi_i+\zeta_i \tag{7}$$

where

$$\omega_i=\frac{\Delta t^n}{\sum_{k=1}^{N_1}C_{tk}V_{ik}^n},\quad \eta_{ij}^n=\sum_{k=1}^{N_1}T_{ijk}^n,\quad \psi_i=\omega_i\sum_{j=1}^{N_w}\eta_{ij}^n,\quad \zeta_i=\omega_i q_i^n .$$

The pressure relationship between n step and n-1 step can be expressed as:

$$\begin{pmatrix}p_1^{n-1}\\p_2^{n-1}\\\vdots\\p_{N_w}^{n-1}\end{pmatrix}=\begin{pmatrix}\psi_1+1 & -\omega_1\eta_{12}^n & \cdots & -\omega_1\eta_{1N_w}^n\\ -\omega_2\eta_{21}^n & \psi_2+1 & \cdots & -\omega_2\eta_{2N_w}^n\\ \vdots & \vdots & \cdots & \vdots\\ -\omega_{N_w}\eta_{N_w1}^n & -\omega_{N_w}\eta_{N_w2}^n & \cdots & \psi_{N_w}+1\end{pmatrix}\begin{pmatrix}p_1^n\\p_2^n\\\vdots\\p_{N_w}^n\end{pmatrix}-\begin{pmatrix}\zeta_1\\\zeta_2\\\vdots\\\zeta_{N_w}\end{pmatrix} \tag{8}$$