A Predictive Model of Enhanced Oil Recovery by Infill Drilling and Its Application

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Abstract: Infill drilling is now recognized as a viable improved recovery process. However, the reliable prediction of incremental recovery by infill drilling cannot be readily and accurately determined by present techniques. This paper proposes a hybrid predictive model of stream tube simulation and numerical simulation by using the contemporary theory of fluid flow in porous media. The model calculates the geometries of stream tubes, remaining oil distribution and water cut at different development stages in the near future, and uses a three-dimensional simulation to track fluid movement in each stream tube slice. This will help reservoir engineers to determine the feasibility of infill drilling. This predictive model is used to forecast the degree of control of well pattern, the ultimate incremental recovery of infill wells within an inverted 5-spot case in an oilfield and the economic benefit is also analyzed.

Key words: Predictive model, infill drilling, stream tube, numerical simulation, recovery process

1. Introduction

Infill drilling for increasing oil production and achieving incremental recovery has been a common industrial practice for many years. Infill drilling can improve reservoir continuity, areal sweep, vertical sweep, recovery of wedge edge oil, and reduce economic limits of a project (Barbe and Schnoebelen, 1987; Barber, *et al.*, 1987). However, it is difficult to determine well spacing economically and effectively. Several researchers studied infill performance in oilfields (Fuller, *et al.*, 1992; Wang, *et al.*, 2004), and they defined optimum well spacing as the density of wells that will result in the greatest ultimate profit to the operator. Their research was concentrated in two aspects: 1) optimum number of wells; 2) and location of wells. The incremental recovery by infill drilling cannot be accurately determined by present models and techniques. Previous approaches involve overly simple stream tube models, or overly complex 3-D numerical simulators combined with separate economic analysis.

The infill drilling predictive model (IDPM) presented in this paper is a three-dimensional (stratified, five-spot), three-phase model, which uses a minimal amount of reservoir and geological data to generate oil production and recovery forecasts for ongoing water flood and infill drilling projects. According to the deliverability of infill well and predicted result of recovery efficiency, reservoir engineers can analyze and evaluate the feasibility of infill drilling program and its economic benefit.

2. Infill drilling predictive model

The IDPM is a combination of stream tube and numerical simulators, introduced separately in the following.

2.1 Stream tube calculation

2.1.1 Pressure field

When ignoring gravity and capillary potential, the pressure equation of a three-dimensional, three-phase system can be expressed as follows (Baek and Hewett, 2000; Wang, *et al.*, 2004):

$$\nabla(\lambda \nabla p) = \phi C_1 \frac{\partial p}{\partial t} \quad (1)$$

$$\lambda = \lambda_o + \lambda_w + \lambda_g$$

$$= \left(\frac{KK_{ro}}{\mu} \right)_o + \left(\frac{KK_{rw}}{\mu} \right)_w + \left(\frac{KK_{rg}}{\mu} \right)_g \quad (2)$$

where λ is fluid mobility, $10^{-3} \mu\text{m}^2/(\text{mPa}\cdot\text{s})$; C_1 is compressibility, 10^{-6}MPa^{-1} ; p is pressure; ϕ is porosity, dimensionless; K is the absolute permeability of medium, $10^{-3} \mu\text{m}^2$; K_{ro} , K_{rw} and K_{rg} are the relative permeability to oil, water, and gas, respectively, fraction; μ is fluid viscosity, $\text{mPa}\cdot\text{s}$; subscripts o, w, and g denote oil, water, and gas phase; subscript l represents o and w, i.e. oil and water phase.

Outer boundary conditions are:

$$\nabla(\lambda h \nabla p) = F \quad (3)$$

where h is reservoir thickness; and F denotes a source term.

For steady-state flow, $F=0$; for pseudosteady-state flow, $F=\phi ch(\partial p/\partial n)$.

Eq. (3) is a Laplace equation if $F=0$, or a Poisson equation if $F\neq 0$, and can be solved by the finite element method. The solution of the Poisson equation is:

$$\frac{\partial}{\partial x}\left(K\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial p}{\partial y}\right)=F \quad (4)$$

In each simulated grid, oil recovery N_p , water cut f_{we} , and total flow rate, q are expressed in dimensionless time. The total flow rate of the grid, q , is calculated by the following equation:

$$q^k = \sum_{i=1}^{N_1} q_i^k = \sum_{i=1}^{N_1} \frac{\Delta p_o}{R_{Ti}^k} \quad (5)$$

where superscript k is time step index and subscript i is stream tube index; N_1 is the total number of stream tubes in the model.

From the definition of dimensionless variables, we have

$$R_{Tdi}^k = \frac{R_{Ti}^k}{\Delta p_o / q_{oi}} \quad (6)$$

Substituting Eq. (6) into Eq. (5) gives

$$q^k = \sum_{i=1}^{N_1} \frac{q_{oi}}{R_{Tdi}^k} \quad (7)$$

where Δp_o and q_{oi} are constants; R_{Ti}^k is total stream tube resistance in stream tube i ; R_{Tdi}^k is total dimensionless stream tube resistance.

2.1.2 Calculation of oil recovery and water cut

Using a small time step, e.g., Δt , the cumulative injection, Q_m , is calculated in each grid as

$$Q_m^k = Q_m^{k-1} + \Delta t^k q_m^{k-1} \quad (8)$$

$$\left. \begin{array}{l} Q_m^{k-1} = 0 \\ Q_m^k = q_{om} \end{array} \right\} \text{ at } k=1 \quad (9)$$

where q_{om} is the total flow rate of grid m at the beginning; and k is time step index..

For each producer, total fluid flow rate, q_T , total water flow rate, q_w , and water cut, F_{we} , can be expressed as follows:

$$q_T^k = \sum_{m=1}^N q_m^k \quad (10)$$

$$q_w^k = \sum_{m=1}^N q_m^k f_{wem}^k \quad (11)$$

$$F_{we}^k = \frac{q_w^k}{q_T^k} \quad (12)$$

where N is the total number of grids for the producer.

The field production and injection are calculated by simple summation.

$$Q_T^k = \sum_{m=1}^M Q_m^k \quad (13)$$

$$N_{pT}^k = \sum_{m=1}^M N_{pm}^k \quad (14)$$

where Q_T and N_{pT} are field cumulative injection and field cumulative production; M is the total number of grids in the model. At the next time step ($k+1$), the previous four steps are repeated.

2.2 Reservoir simulation

2.2.1 Fundamental flow equations and their solutions

The flow equations can be expressed as an equivalent but much simpler form (Fanchi, 2001).

For liquids (oil and water):

$$-\nabla \cdot \frac{v_l}{B_l} - \frac{q_l}{\rho_{isc}} = \frac{\partial}{\partial t}(\phi S_l / B_l) \quad (15)$$

For gas:

$$\begin{aligned} & -\nabla \cdot \left(\frac{v_g}{B_g} + \frac{R_{so}}{B_o} v_o + \frac{R_{sw}}{B_w} v_w \right) - \frac{q_g}{\rho_{gsc}} \\ & = \frac{\partial}{\partial t} \left[\phi \left(\frac{S_g}{B_g} + \frac{R_{so} S_o}{B_o} + \frac{R_{sw} S_w}{B_w} \right) \right] \end{aligned} \quad (16)$$

The Darcy velocities may be written as follows:

$$\begin{aligned} v_l &= -K \cdot \lambda_l \nabla \Phi_l \\ &= -\lambda_l \left[iK_x \frac{\partial \Phi_l}{\partial x} + jK_y \frac{\partial \Phi_l}{\partial y} + kK_z \frac{\partial \Phi_l}{\partial z} \right] \end{aligned} \quad (17)$$

$$\begin{aligned} v_g &= -K \cdot \lambda_g \nabla \Phi_g \\ &= -\lambda_g \left[iK_x \frac{\partial \Phi_g}{\partial x} + jK_y \frac{\partial \Phi_g}{\partial y} + kK_z \frac{\partial \Phi_g}{\partial z} \right] \end{aligned} \quad (18)$$

where v_l is the flow velocity of phase l, m/s; v_g is the flow velocity of gas phase, m/s; B is formation volume factor, fraction; ρ_{lsc} and ρ_{gsc} are the densities of phase l and gas phase in standard conditions, kg/m³; S is saturation; R_{so} and R_{sw} are dissolution gas-oil ratio and dissolution gas-water ratio, m³/m³; Φ is fluid potential, $\Phi_o = p_o - g\rho_o D$, $\Phi_w = p_w - g\rho_w D$, $\Phi_g = p_g - g\rho_g D$; and D is reservoir depth, m.

2.2.2 Pressure equation

Pressure equation can be written as:

$$p_l = \frac{\phi}{B_l} \frac{\partial S_l}{\partial t} + \left[\frac{S_l}{B_l} \frac{\partial \phi}{\partial p_l} - \frac{S_l \phi}{B_l^2} \frac{\partial B_l}{\partial p_l} \right] \frac{\partial p_l}{\partial t} \quad (19)$$

$$\begin{aligned} p_g = & \left(\frac{\phi R_{so}}{B_o} - \frac{\phi}{B_g} \right) \frac{\partial S_o}{\partial t} + \left(\frac{\phi R_{sw}}{B_w} - \frac{\phi}{B_g} \right) \frac{\partial S_w}{\partial t} \\ & + \left\{ \frac{S_g}{B_g} \frac{\partial \phi}{\partial p_o} - \frac{S_g \phi}{B_g^2} \frac{\partial B_g}{\partial p_o} + \frac{S_o R_{so}}{B_o} \frac{\partial \phi}{\partial p_o} \right. \\ & + \frac{\phi S_o}{B_o} \frac{\partial R_{so}}{\partial p_o} - \frac{\phi S_o R_{so}}{B_o^2} \frac{\partial B_o}{\partial p_o} + \frac{S_w R_{sw}}{B_w} \frac{\partial \phi}{\partial p_o} \\ & \left. + \frac{\phi S_w}{B_w} \frac{\partial R_{sw}}{\partial p_o} - \frac{\phi S_w R_{sw}}{B_w^2} \frac{\partial B_w}{\partial p_o} \right\} \frac{\partial p_o}{\partial t} \end{aligned} \quad (20)$$

2.2.3 Definite conditions

1) Boundary condition:

$$\left. \frac{\partial p}{\partial \Sigma} \right|_{\Sigma \in f(x,y,z)} = 0 \quad (21)$$

2) Initial condition:

$$p_i(x, y, z, 0) = p_i(x, y, z) \quad (22)$$

2.2.4 Subsidiary conditions

1) Saturation equation:

$$S_o + S_w + S_g = 1 \quad (23)$$

2) Capillary pressure:

$$p_g = p_o + p_{cgo} \quad (24)$$

$$p_w = p_o - p_{cow} \quad (25)$$

3) Equation of state:

Relative permeability

$$K_{ro} = K_{ro}(S_g, S_w) \quad (26)$$

$$K_{rg} = K_{rg}(S_g) \quad (27)$$

$$K_{rw} = K_{rw}(S_w) \quad (28)$$

Capillary pressure:

$$p_{cgo} = p_{cgo}(S_g) \quad (29)$$

$$p_{cow} = p_{cow}(S_w) \quad (30)$$

Fundamental flow equations, pressure equation and definite conditions form the entire mathematical equation, which can be solved by using the finite difference method combining subsidiary conditions.

3. Model performance

To illustrate the model proposed, a simple application where water was injected into a low permeability oil reservoir was presented. In the present work, it was considered that wells were arranged in a quarter 5-spot pattern with different permeability distribution. After infilling drilling, the 5-spot pattern was changed to 9-spot pattern, which had one injector and eight producers, as shown in Fig. 2. The calculated results indicated that the stream tubes were only concentrated near the main stream lines between producers and injector before infill drilling (Fig. 1), but after infill drilling the stream tubes controlled the whole well pattern, and the water flood swept region increased greatly (Fig. 2). The recovery efficiency increased by 4.54% after infill drilling.

Fig. 1 The stream tube geometry and remaining oil saturation distribution for a quarter inverted 5-spot case (Before infill drilling)

Fig. 2 The stream tube geometry and remaining oil saturation distribution for a inverted 9-spot case (After infill drilling)

4. Economic benefit analysis

The economic benefit from infill drilling can be deduced by using the input/output rule:

$$M = \Delta R \cdot N_o \cdot R_c (P_o - C_p) - n \cdot (D_v \cdot C_v + C_{fh})(1+R)^{T/2} - C_{other} \quad (31)$$

where N_o is oil in place, 10^4 t; R_c is the commodity ratio of crude oil, fraction; P_o is the after-tax oil price, 10^4 Yuan(RMB)/t; n is the number of infill wells; D_v is well depth, m; C_v is the drilling cost per meter, 10^4 Yuan/m; C_{fh} is the ground construction cost per well, 10^4 Yuan/well; C_p is oil production cost, 10^4 Yuan/t; C_{other} is other expenses, 10^4 Yuan; and R is the investment lending rate, fraction.

Example The following reservoir properties and economic exponents are as follows: $\Delta R=4.536\%$, $N_o=91.2 \times 10^4$ t, $R_c=0.95$, $n=4$, $D_v=3000$ m, $C_v=1050$ Yuan/m, $C_{fh}=120 \times 10^4$ Yuan, $C_p=300$ Yuan/t, $R=0.05$. Substituting the above parameters into Eq. (31) gives the economic benefit of four infill wells i.e. 77.76 million Yuan, so the infill development program is economically and technically feasible.

5. Conclusions

1) A hybrid predictive model is proposed by combining stream tube simulation with numerical simulation. The liquid, oil and gas withdrawal rates can be calculated, and the movement of fluid can be traced

by using the hybrid predictive model.

2) The variation of oil saturation distribution after infill drilling can be predicted, the stream tube distribution and the degree of control of water flood can be analyzed by using the hybrid predictive model. The technical feasibility of infill drilling program can be determined by evaluating infill drilling effectiveness.

3) According to the infill drilling effectiveness, the economic benefit can be evaluated, and the economic feasibility of infill drilling program can be determined.

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