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Original article

The productivity calculation model of perforated horizontal well and optimization of inflow profile

Xianbo Luo*, Lifu Jiang, Yanchun Su, Kai Huang

Tianjin Branch of CNOOC Ltd., China

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ABSTRACT

Aiming at the large error in productivity predication and incomplete consideration in completion parameters design of perforated horizontal well, a model which coupled the relationship of pressure and flow rate in reservoir seepage, near-wellbore inflow and wellbore flow was established. The impact of near-wellbore heterogeneity, wellbore flow pressure drop and completion parameters on the inflow profile of horizontal well is analysed. Studies showed that with a stronger near-wellbore heterogeneity, the inflow profile would fluctuate more seriously. Perforation density had a great influence on the inflow profile and local changes of it would bring a shunt effect. Completion design of variable density perforated horizontal well with an optimized inflow profile which was close to a standard profile would improve the horizontal well development effect. The achievement can provide directive meanings to productivity predication and completion parameters design of horizontal wells in oilfield.

1. Introduction

In early years of researches on horizontal well productivity, the calculation of horizontal well productivity was mainly based on the comparative evaluation with respect to vertical well, conversion into an equivalent form to vertical well or an assumption that horizontal well was equivalent to an infinite conductivity fracture in isotropic reservoir. These theories did not give enough consideration to the influence of fluid flowing characteristics, formation heterogeneity and pressure drop caused by horizontal wellbore flow on productivity. So the accuracy of the calculation is not satisfactory. Recently, many researchers have made arguments that the calculation can be achieved by calculating segments respectively after dividing horizontal well into several separate segments, with the optimization of completion parameters [1–5]. Based on consideration of the impact of near-wellbore heterogeneity, drilling & completion damage and pressure drop caused by fluid flow through perforation holes& wellbore flow, the author in this paper comes up with a model which couples the relationship of reservoir drainage, near-wellbore anisotropic inflow and horizontal wellbore flow. Then optimized calculation of inflow profile for horizontal well is made to obtain the improvement of horizontal well production prediction.

2. Mathematical model

During the production process of horizontal well, there is dramastic pressure drop in near wellbore area and the effect of formation heterogeneity is also remarkable. On the other hand, pressure drop is small in area far from wellbore and the heterogeneity can be neglected [6]. Assume that the area far from wellbore is homogeneous with average parameters, then the drainage flow model in formation can be established. Considering permeability inhomogeneity, drilling & completion damage and flow streamlines convergence in near wellbore area, the inflow model for each segment along horizontal well can be obtained as well. Additionally, wellbore flow model can be gained by including wellbore flow and inflow from near-wellbore area into wellbore. After combining the relationship of pressure and flow rate from the three models above, the productivity calculation of perforated horizontal wells and optimization of inflow profile can be realized.

* Corresponding author.
E-mail address: luoxb@cnooc.com.cn (X. Luo).
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3. Reservoir drainage model

Divide the horizontal section into N segments from heel to toe, then set up reservoir drainage model according to the theory of seepage and principle of potential superposition [7,8]:

$$\begin{cases} P_e - P_{w1} + \rho g(z_e - z_{w1}) = \dfrac{\mu}{4\pi K}\left[\dfrac{Q_1}{L_1}(\varphi_{11} - \varphi_{e1}) + \dfrac{Q_2}{L_2}(\varphi_{12} - \varphi_{e2}) + \cdots + \dfrac{Q_N}{L_N}(\varphi_{1N} - \varphi_{eN})\right] \\ P_e - P_{w2} + \rho g(z_e - z_{w2}) = \dfrac{\mu}{4\pi K}\left[\dfrac{Q_1}{L_1}(\varphi_{21} - \varphi_{e1}) + \dfrac{Q_2}{L_2}(\varphi_{22} - \varphi_{e2}) + \cdots + \dfrac{Q_N}{L_N}(\varphi_{2N} - \varphi_{eN})\right] \\ P_e - P_{w(N-1)} + \rho g\left(z_e - z_{w(N-1)}\right) = \dfrac{\mu}{4\pi K}\left[\dfrac{Q_1}{L_1}\left(\varphi_{(N-1)1} - \varphi_{e1}\right) + \dfrac{Q_2}{L_2}\left(\varphi_{(N-1)2} - \varphi_{e2}\right) + \cdots + \dfrac{Q_N}{L_N}\left(\varphi_{(N-1)N} - \varphi_{eN}\right)\right] \\ P_e - P_{wN} + \rho g(z_e - z_{wN}) = \dfrac{\mu}{4\pi K}\left[\dfrac{Q_1}{L_1}(\varphi_{N1} - \varphi_{e1}) + \dfrac{Q_2}{L_2}(\varphi_{N2} - \varphi_{e2}) + \cdots + \dfrac{Q_N}{L_N}(\varphi_{NN} - \varphi_{eN})\right] \end{cases}$$

P_e: Supply Boundary Pressure, Pa; P_{wi}:Pressure on well wall of horizontal segment i, Pa; ρ: fluid density, kg/m^3 ; g: gravity acceleration, m/s^2; z_e: distance between supply boundary and bottom boundary of oil zone, m; z_{wi}: distance between well wall and bottom boundary of oil zone in horizontal segment i, m; μ: fluid viscosity, Pa·s; K: oil zone average permeability, m^2; Q_i: inflow rate of horizontal segment i, m^3/s; L_i: length of horizontal segment i, m; φ_{ji}: the middle function of potential in horizontal segment j caused by production of horizontal segment i, $\varphi_{ji} = \frac{-4\pi L_i}{Q_i}\left[\frac{K}{\mu}(P_{wj} + \rho g z_{wj}) - C\right]$, C is constant and dimentionless.

4. Model of near-wellbore inhomogeneous inflow and flow through perforation hole

In consideration of drilling & completion damage, the model which demonstrates pressure drop during inflow from confluence boundary through near-wellbore formation reaching outside perforation hole and flow process through perforation hole is as follows [9–11]:

$$\Delta P_{hti} = \Delta P_{hi} + \Delta P_{ri} = \frac{Q_i\mu\left(\ln\frac{L_{ei}}{L_{pi}+R_w} + S\right)}{2\pi K_{ei} L_i} + \frac{\mu Q_i}{2\pi K_{si} n_i L_{pi}}\ln\left(\frac{L_i}{2n_i r_{pi}}\right) + \frac{2.6\times10^{-5} K_{yi}^{-1.2}\rho Q_i^2}{(2\pi n_i L_{Pi})^2}\left(\frac{1}{r_{pi}} - \frac{2n_i}{L_i}\right) + \left(\frac{Q_i}{n_i \pi r_{pi}^2 C_d}\right)\frac{\rho}{2}$$

ΔP_{hti} : total pressure drop caused by near wellbore drainage and flow through perforation hole in horizontal segment i, Pa; ΔP_{hi}:pressure drop during flow from confluence boundary to outsides perforation hole in horizontal segment i, Pa; ΔP_{ri} pressure drop caused by flow through perforation hole in horizontal segment i, Pa; L_{ei}: the radius of confluence boundary in horizontal segment i (non-homogeneity calculation radius), m, $L_{ei} = \frac{h/\sin\left(\frac{\pi z_{wi}}{h}\right)}{2\pi}$, h is the oil layer thickness, m; L_{pi}: perforation depth of horizontal segment i, m; R_w: wellbore radius, m;

S: skin factor of horizontal segment i, dimentionless, $S = S_d + S_p = S_{pg} + S_{pc}$, S_{pg}: geometry skin factor of perforation, S_{pc}: compaction skin factor of perforation; K_{ei}: permeability near wellbore without completion damage in horizontal segment i, m^2; K_{si}: permeability near wellbore with completion damage in horizontal segment i, m^2; K_{yi}: permeability near wellbore with compaction damage in horizontal segment i, m^2; n_i: number of perforation holes in horizontal segment i; r_{pi}: radius of perforation hole in horizontal segment i, m; when$L_{pi}/(2r_p) < 0.5$, $C_d = 0.62$, otherwise $C_d = 0.82$.

5. Wellbore flow model

According to hydromechanics theory, in variable mass flow of horizontal segment i, the pressure drop model is [12–19]:

ΔP_i: pressure drop due to wellbore tube flow in horizontal

$$\begin{cases} \Delta P_i = \Delta P_{fi} + \Delta P_{ai} + \Delta P_{hi} = \dfrac{\lambda_i \rho \upsilon_{1i}^2 L_i}{4R_w}\left[1 + \dfrac{Q_i}{\sum_{j=1}^{i-1} Q_i} + \left(\dfrac{1}{3} + \dfrac{1}{6n_i^2}\right)\left(\dfrac{Q_i}{\sum_{j=1}^{i-1} Q_i}\right)^2\right] + \rho\upsilon_{1i}^2\left[n_i^2\left(\dfrac{r_{pi}}{R_w}\right)^4\left(\dfrac{\upsilon_{ki}}{\upsilon_{1i}}\right)^2 + 2n_i\left(\dfrac{r_{pi}}{R_w}\right)^2\left(\dfrac{\upsilon_{ki}}{\upsilon_{1i}}\right)\right] \\ +\rho\dfrac{Q_i^2 + 2Q_i\sum_{j=1}^{i-1} Q_j}{2(\pi R_w)^2} \\ Q_{lj} = \sum_{i=j}^{N} Q_i \end{cases}$$

$$P_{wj} = P_{w(j-1)} + \frac{\Delta P_j + \Delta P_{(j-1)}}{2}$$