Journal of Petroleum Science and Engineering 170 (2018) 582–591

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

A semi-analytical method for the multilateral well design in different reservoirs based on the drainage area

Zehao Lyu, Xianzhi Song*, Gensheng Li

State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum Beijing, Beijing, 102249, China

ARTICLE INFO

Keywords:
Multilateral well configuration
Drainage area
Fast marching method
Heterogeneity

ABSTRACT

The determination of the optimal multilateral well configuration for different kinds of reservoirs is extremely challenging due to the wide varieties of possible well type. In this paper, we propose a novel method to determine the number of laterals, lateral length and lateral spacing in the multilateral well. The objective in the design is to fully exploit the entire reservoir within a certain period of development time. A geological map is constructed based on the reservoir properties. The fast marching method is used to calculate the drainage area of each lateral in the development time. The drainage area of the designed multilateral well configuration can cover the entire reservoir. The results have been validated by analytical method and specific steps of the method are presented. The applications in both homogeneous and heterogeneous cases are studied. Longer development time can lead to less number of laterals, shorter lateral length and larger lateral spacing. The drainage area is irregular in the heterogeneous case. The algorithm can automatically determine the number of laterals, lateral length and lateral spacing based on the geological characteristics to exploit the reservoir efficiently. The proposed method is appropriate for the field application due to the short computational time.

1. Introduction

Multilateral well has been applied in the oil and gas industries since 1950s (Elyasi, 2016). It is defined as wells with two or more laterals drilled from a common mainbore. This technique can increase the reservoir exposure, improve oil production and greatly reduce development costs. In 1953, the first multilateral well was drilled with 9 laterals (Brister, 1998). Advances in directional drilling and completion have helped increase the number of laterals substantially in the last decade (Yang et al., 2015).

Previous research on the multilateral well mainly focuses on the production analysis. Ulaeto et al. developed a simple semi-analytical model to predict the productivity of horizontal oil wells (Ulaeto et al., 2014). Friction, acceleration, fluid-inflow and flow regime transition effects were considered. Coupling flow from a box-shaped drainage volume to the wellbore was used. Buhulaigah et al. constructed a model to predict the oil flow rate for multilateral wells with good accuracy. Artificial intelligence modeling was employed with surface and reservoir parameters obtained from field data (Buhulaigah et al., 2017). Hassan et al. investigated the effects of parameters (i.e., reservoir parameters, number of laterals, permeability ratio, lateral lengths and lateral spacing) on the productivity of the fishbone well. Several methods, including artificial neural network, adaptive neuro fuzzy interference system, generalized neural network and radial basis function network are used to estimate the production (Hassan et al., 2017). Simonov et al. described a mathematical model of fluid flow to a multilateral well with arbitrary geometric parameters. The model can simulate the behavior of a random-geometry well by dividing the entire length of wellbores into linear intervals and placing linear sources. The approach can be used to determine fluid production trends for wells with various completion types (Simonov et al., 2017).

Studies on the design of multilateral well configuration are relatively scarce. Yeten et al. used genetic algorithm, artificial neural network, hill climber and near-well up-scaling techniques for the optimization of multilateral well configuration. The optimal well configuration varies with the reservoir model and objective function (Yeten et al., 2003). Maricic et al. carried out parametric study through comparison of manually-determined multilateral well configuration, including single-lateral, dual-lateral, tri-lateral, etc., in the coalbed methane. The length of the well and spacing between laterals were also studied (Maricic et al., 2008). Chen et al. studied the impact of permeability on the design of two multilateral well patterns of quad-lateral well and pinnate lateral well in coalbed methane reservoir. Results showed that the effect of the permeability anisotropy ratio change during production is significant (Chen et al., 2012). Elyasi et al. assessed and evaluated the degree of multilateral well performance in oil

* Corresponding author.
E-mail address: songxz@cup.edu.cn (X. Song).

https://doi.org/10.1016/j.petrol.2018.07.007
Received 3 April 2018; Received in revised form 30 June 2018; Accepted 3 July 2018
Available online 04 July 2018
0920-4105/

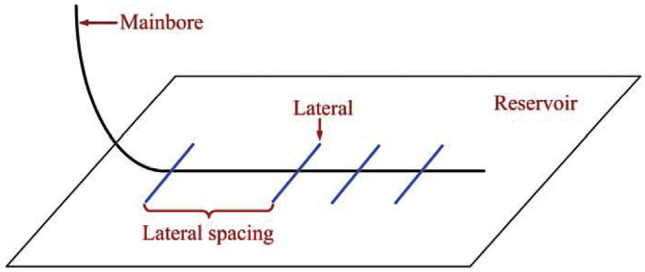

Fig. 1. Schematic of the multilateral well in the reservoir.

recovery in a fractured reservoir. An integrated completion-planning method was developed to investigate the role of two kinds of multilateral wells (i.e., planar dual-lateral and dual opposite laterals) (Elyasi et al., 2014). Ayokunle et al. analyzed the effects of number of laterals, length of horizontal sections of lateral, reservoir thickness and permeability anisotropy using Response Surface Methodology. Results showed that the productivity is more associated with the horizontal section length and reservoir thickness (Ayokunle and Hashem, 2016).

As described above, most of the studies in the literature assume a priori regular shapes (e.g., only two laterals) for the multilateral well, which may not be maximally optimized for the specific reservoir. In this paper, we propose a design method which can automatically determine the multilateral well parameters (i.e., number of laterals, lateral length and lateral spacing as shown in Fig. 1) for different kinds of reservoirs. First, the background of the algorithm is provided and the method is validated through comparison with analytical results. Second, the specific steps of the method are given and a homogeneous reservoir example is illustrated. Third, a synthetic heterogeneous example is presented. Finally, some discussions are made and conclusions are drawn.

2. Methodology

In this paper, we propose a novel forward model to design the multilateral well given reservoir parameters. The method is based on the rapid drainage area computation (Datta-Gupta et al., 2011). The major objective is avoiding interferences between laterals to maximize the effect of each lateral and develop the entire oil field.

2.1. Drainage area calculation using the fast marching method

We define the drainage area in this paper based on the radius of investigation given by Lee (2003). The radius of investigation is defined as the propagation distance of a "peak" pressure disturbance for an impulse source.

Here, we obtain the radius of drainage area based on the high frequency asymptotic solution to the pressure diffusion equation. According the continuity equation and Darcy's law, the transient pressure response from a heterogeneous reservoir can be depicted by Eq. (1).

$$\phi(x)\mu c_t \frac{\partial P(x,t)}{\partial t} - \nabla\cdot(k(x)\nabla P(x,t)) = 0 \tag{1}$$

where ϕ is the reservoir porosity and μ represents the fluid viscosity. c_t is the total compressibility. P is the pressure and t is the time. k is the reservoir permeability. We can obtain Eq. (2) after using Fourier transform (Kim et al., 2009).

$$\frac{\phi(x)\mu c_t}{k(x)}(-i\omega)\widetilde{P}(x,\omega) = \nabla^2\widetilde{P}(x,\omega) + \frac{\nabla k(x)}{k(x)}\cdot\nabla^2\widetilde{P}(x,\omega) \tag{2}$$

The asymptotic approach is used to solve the diffusive pressure equation. The solution is (Xie et al., 2012a)

$$\widetilde{P}(x,\omega) = e^{-\sqrt{-i\omega}\,\tau(x)}\sum_{k=0}^{\infty}\frac{A_k(x)}{(\sqrt{-i\omega})^k} \tag{3}$$

where $\tau(x)$ is the phase of a propagating wave (i.e., propagating front). $A_k(x)$ represents the amplitude of the wave and ω is the frequency. To calculate the propagation of the pressure front, only the zero-th order expansion is considered as shown in Eq. (4) (Sehibi et al., 2011).

$$\widetilde{P}(x,\omega) = e^{-\sqrt{-i\omega}\,\tau(x)}A_k(x) \tag{4}$$

Substituting Eq. (4) into Eq. (2), we can obtain Eq. (5) by collecting terms with the highest order of $\sqrt{-i\omega}$ (Xie et al., 2012b).

$$\sqrt{\alpha(x)}\,|\nabla\tau(x)| = 1 \tag{5}$$

where $\alpha(x)$ is the diffusivity, given by (Zhang et al., 2013)

$$\alpha(x) = \frac{k(x)}{\phi(x)\mu c_t} \tag{6}$$

Next, we need to correlate the propagating front $\tau(x)$ with the real observed time. As described above, the radius of investigation is defined as the propagation distance of the maximum pressure disturbance corresponding to an impulse source at any given time. In a 2D medium, Eq. (7) can be obtained (Kang et al., 2013).

$$P(t) = A_0(x)\frac{\tau(x)}{2\sqrt{\pi}\,t}\exp\left(-\frac{\tau^2(x)}{4t}\right) \tag{7}$$

The pressure response in Eq. (7) is maximized when the time derivative is zero as shown in Eq. (8).

$$\frac{\partial P(t)}{\partial t} = A_0(x)\frac{\tau(x)}{2\sqrt{\pi}}\left[-t^{-2}\exp\left(-\frac{\tau^2(x)}{4t}\right) + \frac{\tau^2(x)}{4t^3}\exp\left(-\frac{\tau^2(x)}{4t}\right)\right] = 0 \tag{8}$$

Thus, we can obtain the relationship between the real observed time t and propagation front $\tau(x)$ (Sharifi et al., 2014).

$$t = \frac{\tau^2(x)}{4} \tag{9}$$

To solve Eq. (5), the fast marching method is adopted because Eq. (5) is a form of Eikonal equation as shown in Eq. (10). The fast marching method was first proposed for monotonically advancing fronts from a start position with various speeds (Sethian and Vladimirsky, 2000).

$$|\nabla T(x)|V(x) = 1 \tag{10}$$

where $T(x)$ is the arrival time at point x and $V(x)$ is the propagating speed from the start position. If we try to solve $T_{(x,y)}$ in point (x, y), the neighbor of (x, y) has four elements of $(x+\Delta x, y)$, $(x-\Delta x, y)$, $(x, y+\Delta y)$ and $(x, y-\Delta y)$. $T_{(x,y)}$ can be obtained by (Liu et al., 2017):

$$T_1 = \min(T_{(x-\Delta x,y)}, T_{(x+\Delta x,y)}) \tag{11}$$

$$T_2 = \min(T_{(x,y-\Delta y)}, T_{(x,y+\Delta y)}) \tag{12}$$

$$\left|\nabla T_{(x,y)}\right| = \sqrt{\left(\frac{T_{(x,y)}-T_1}{\Delta x}\right)^2 + \left(\frac{T_{(x,y)}-T_2}{\Delta y}\right)^2} \tag{13}$$

$$\sqrt{\left(\frac{T_{(x,y)}-T_1}{\Delta x}\right)^2 + \left(\frac{T_{(x,y)}-T_2}{\Delta y}\right)^2} = \frac{1}{(V_{(x,y)})^2} \tag{14}$$

where Δx and Δy are the grid spacing in x and y directions. Finally, the solution $T_{(x,y)}$ of Eq. (13) is $T_1 + 1/V_{(x,y)}$ (if $T_2 > T > T_1$), or $T_2 + 1/V_{(x,y)}$ (if $T_1 > T > T_2$), or quadratic solution of Eq. (13) (if $T > \max(T_1, T_2)$).

To further illustrate the fast marching algorithm, a simple case of a 5-stencil Cartesian grid is shown in Fig. 2 with the middle point being the starting point (red square in Fig. 2 (a)). A flowchart of the solution process is summarized as shown in Fig. 3. All grid points can be divided into three groups: Far (the points of which arrival times have not been