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Productivity model for gas reservoirs with open-hole multi-fracturing horizontal wells and optimization of hydraulic fracture parameters

Jianqiang Xue [a, b], Nianyin Li [a, *], Xiaobing Lu [b], Suiwang Zhang [b], Yong Wang [b]

[a] State Key Lab of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, Sichuan, China
[b] Research Institute of Oil & Gas Technology, PetroChina Changqing Oilfield Company, Xi'an 710018, Shanxi, China

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ABSTRACT

Multi-fractured horizontal wells are commonly employed to improve the productivity of low and ultra-low permeability gas reservoirs. However, conventional productivity models for open-hole multi-fractured horizontal wells do not consider the interferences between hydraulic fractures and the open-hole segments, resulting in significant errors in calculation results. In this article, a novel productivity prediction model for gas reservoirs with open-hole multi-fractured horizontal wells was proposed based on complex potential theories, potential superimposition, and numerical analysis. Herein, an open-hole segment between two adjacent fractures was regarded as an equivalent fracture, which was discretized as in cases of artificial fractures. The proposed model was then applied to investigate the effects of various parameters, such as the angle between the fracture and horizontal shaft, fracture quantity, fracture length, diversion capacity of fractures, horizontal well length, and inter-fracture distance, on the productivity of low permeability gas reservoirs with multi-fractured horizontal wells. Simulation results revealed that the quantity, length, and distribution of fractures had significant effects on the productivity of low permeability gas reservoirs while the effects of the diversion capacity of fractures and the angle between the fracture and horizontal shaft were negligible. Additionally, a U-shaped distribution of fracture lengths was preferential as the quantity of fractures at shaft ends was twice that in the middle area.

1. Introduction

Horizontal wells have been widely applied in oil and gas industries in virtue of the increased shaft/oil contact surface area, accelerated oil and gas extraction, and enhanced ultimate recovery. However, low and ultra-low permeability gas reservoirs with horizontal wells show limited yields due to the large seepage resistances and poor connectivity, and thus are not suitable for large-scale applications [1,2]. Multi-fracturing techniques are commonly deployed in these cases to increase productivity by creating fractures that serve as flow channels for oil and gas. Efforts have been made in the design of multi-fractured horizontal wells and parameter optimization [3–5], which are highly dependent on the efficacy of productivity prediction [6,7]. To date, both analytical models and numerical models have been proposed for productivity estimation of horizontal wells [8–11]. Despite various studies being conducted on the productivity of fractured horizontal wells, most have focused on those related to perforation completion, and few studies have discussed productivity estimations of fractured horizontal wells by open-hole completion [12–21]. Furthermore, most published studies in this field did not consider interferences between the fractures and the open-hole segments, although interferences between

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[*] Corresponding author.
E-mail address: lnyswpu@163.com (N. Li).
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fractures were taken into consideration. As a result, estimations using these approaches were not consistent with experimental results.

In this article, a gas seepage model and coupling model for open-hole multi-fractured horizontal wells were proposed based on complex potential theories, potential superimposition, and numerical analyses. Herein, an open-hole segment between two adjacent fractures was regarded as an equivalent fracture, which was discretized as in cases of artificial fractures. The proposed model was then applied to investigate the effects of various fracturing parameters on the productivity of low permeability gas reservoirs with multi-fractured horizontal wells.

2. Productivity model for multi-fractured horizontal open-hole wells

As the productivity of gas reservoirs with horizontal open-hole wells is determined by fractures and the fracture lengths are usually significantly larger than the fracture heights, the permeability of fractures is significantly higher than that of the matrix and the vertical seepage of flow in the matrix is not taken into consideration. However, the shafts of multi-fractured horizontal open-hole wells are exposed to gas flows and the fluid supplies from fractures and the matrix are continuous, as shown in Fig. 1. Due to interferences between fractures and contact between the matrix and the shaft, matrix-fracture-shaft double linear flows and matrix-well radial flows were observed. The interactions between these flows were taken into consideration in productivity simulations.

2.1. Matrix-fracture-shaft double linear flow model

In this multi-fracture system, each fracture was divided into 2 n sections (n on the left and n on the right), with each section regarded as a point sink. As the fractures and the shaft receive fluids in a similar way, a shaft section between two adjacent fractures was regarded as an equivalent fracture with a thickness of πr_w and length of Δx_i and divided into n shares (point sink). In this way, the shaft shared a coordination system with fractures (see Fig. 1).

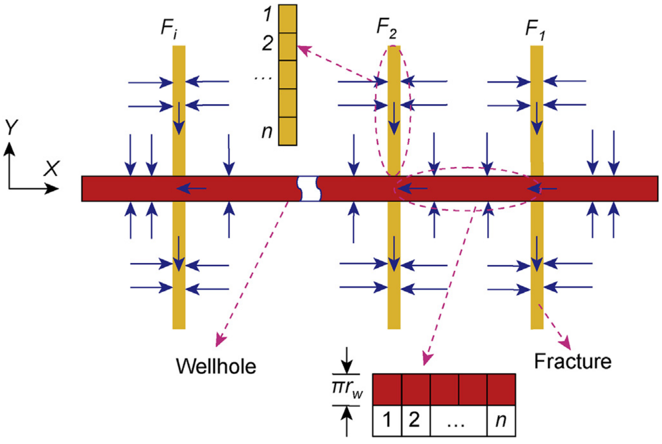

Fig. 1. Physical model of multi-fractured horizontal wells.

The pressure drop at any location of the stratum can be calculated based on that of point sinks in an infinitely large and homogeneous stratum at a constant flow. Taking interferences between N fractures and $N+1$ shaft sections, the pressure drop at (x, y) can be obtained by the following equation:

$$P_i^2 - P^2(x,y,t) = \sum_{i=1}^{N}\left\{\sum_{j=1}^{n}\frac{q_{scflij}p_{sc}T\mu_i Z_i}{2\pi khT_{sc}Z_{sc}}[-E_i(-\varphi_1)] + \sum_{j=1}^{n}\frac{q_{scfrij}p_{sc}T\mu_i Z_i}{2\pi khT_{sc}Z_{sc}}[-E_i(-\varphi_2)]\right\} + \sum_{i=1}^{N+1}\frac{q_{mscfij}p_{sc}T\mu_i Z_i}{2\pi^2 kr_w T_{sc}Z_{sc}}[-E_i(-\varphi_3)] \quad (1)$$

where

$$\varphi_1 = \frac{\left[x-\left(x_i+\frac{2n-2j+1}{2n}y_{fli}cos\alpha(i)\right)\right]^2+\left[y+\frac{2n-2j+1}{2n}y_{fli}sin\alpha(i)\right]^2}{4\eta t}$$

$$\varphi_2 = \frac{\left[x-\left(x_i+\frac{2j-1}{2n}y_{fri}\cos\alpha(i)\right)\right]^2+\left[y-\frac{2j+1}{2n}y_{fri}\sin\alpha(i)\right]^2}{4\eta t}$$

$$\varphi_3 = \frac{\left[x-\left(x_{i-1}+\frac{2j-1}{2n}\Delta x_i\right)\right]^2+y^2}{4\eta t}$$

With the tip points of the left and right wings of kth fracture defined as (x_{fkl}, y_{fkl}) and $(x_{fkr}, \mathrm{y}_{\mathrm{fkr}})$, respectively, the pressures at these points were P_{lk} and P_{rk}, and the lengths of these wings were $\mathrm{y}_{\mathrm{flk}}$ and $\mathrm{y}_{\mathrm{frk}}$. The pressures at the tip points of the left and right wings of kth fracture can be obtained by substituting (x_{fkl}, y_{fkl}) and $(x_{fkr}, \mathrm{y}_{\mathrm{fkr}})$ into Equation (1). In cases where fractures are not homogeneously distributed, the tip pressure of ith fracture can be defined as the average pressure at the left and right tip points.

If the fracture half-length was significantly larger than the radius of the horizontal shaft, the seepage region between two adjacent fractures and the corresponding shaft can be regarded as a miniaturized gas reservoir with radius $= R$, thickness $= h$, outer boundary pressure $= P(x_{fi}, y_{fi}, t)$ (fracture tip pressure), and inner boundary pressure $= P_{wfi}$ (well bottom flow pressure) based on the equivalent area principles.

Herein,

$$R = \sqrt{\frac{\left(y_{fli}+y_{fri}\right)h}{\pi}}$$

Gas seepage within fractures can be described by the following:

$$p^2\left(x_{fi},y_{fi},t\right)-p_{wfi}^2=\frac{q_{scfi}p_{sc}T\mu_i Z_i}{\pi khT_{sc}Z_{sc}}\left[ln\left(\frac{1}{r_w}\sqrt{\frac{\left(y_{fli}+y_{fri}\right)h}{\pi}}\right)+s\right] \quad (2)$$

A matrix-fracture-shaft double linear flow model with interferences between the fractures and the open-hole segments taken into consideration can be obtained based on tip pressures of the fractures and Equation (2).

2.2. Matrix-well radial flow model

Equations were established at the shaft ends and intersections of the fractures and the horizontal shaft based on Equation (1). The coordinates of the ith intersection of the fracture, shaft, and shaft end points were $(x_i, 0)$ and $(L, 0)$,

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