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Analytical method for performance evaluation of fractured horizontal wells in tight reservoirs

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ABSTRACT

This paper presents an analytical model for horizontal well with multiple hydraulic transverse fractures, producing from a tight oil reservoir. The model combines productivity index model (Guo et al.2009) with non-Darcy flow and fracture heterogeneity.

Although there are numerous analytical models have been proposed for fractured horizontal wells performance, either pseudo-steady conditions or pressure-transient phenomenon. They rarely consider the influence of non-Darcy flow and fracture heterogeneity on fractured horizontal wells performance. Non-Darcy flow behavior has been proved to exist in tight reservoirs by many previous investigators. In the meantime, fracture heterogeneity should not be neglected in the process of hydraulic fracturing.

In this paper, we deduce an analytical production equation in detail, towards fractured wells in tight reservoirs. Based on productivity index model, three flow region are analyzed by seepage characteristics. We make further analysis of pressure distribution in fractured horizontal well by a commercial numerical simulator. In addition, some critical factors on productivity have been considered.

Results show that there are strong correlations between productivity and critical factors by the mathematical model. Further verification of the influences on well productivity is demonstrated. The fractured well productivity with different threshold pressure gradient and deformation coefficient has negative correlation. Fractured well productivity increases as fracture number, half of fracture length, and fracture conductivity increases within a certain range. The effect on fractured well productivity by fracture heterogeneity appears to be complex, not only by the end point influence, but also by fractures of internal interference.

1. Introduction

In recent years, development of conventional reservoirs can't meet the increasing demands, leading to tendency of low permeability reservoirs (e.g. tight oil reservoirs). Thus, unconventional reservoirs are expected to play an important role in the demands of the energy. Accordingly, hydraulic fracturing technology becomes well developed in the reservoir engineering, not only for the advantages of transforming seepage areas near well bore, but also for improving the oil recovery and economic benefit. Numerical studies have indicated that fracturing has been identified as a key method for unconventional reservoir development, and it enhances single well productivity and ultimate recovery (Zhao et al., 2015a, 2015b).

There is no doubt that, it is highly desirable to have access to methods capable of evaluating performance of fractured horizontal wells. These methods can be used to guide the production operations and reservoir management. They can also be used to determine optimal fracture parameters. In a word, it can be conducive to analyze tight oil reservoir development effect, and provide effective theoretical guidance for reservoirs development. Furthermore, there have been many numerical simulation efforts on the reservoir dynamic performance of conventional and unconventional reservoirs subject to acid gas injection (Zhang et al., 2012a, 2012b; Wu et al., 2014), CO_2 sequestration/EOR (Zhang et al., 2015a, 2015b), multiphase flow regimes (Yao et al., 2012; Xiong et al., 2013). The coupled THMC model made plays a key role to understand the driving mechanisms in the reservoir. However, few studies have focused on the reservoir performance evaluation of fractured horizontal wells in tight reservoirs by analytical solutions.

Since the application of fractured horizontal wells in the late 1980s, the research for analyzing productivity of multi-fractured

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horizontal wells provides reservoir engineers a simple and accurate tool. Giger et al., (1984) first provided productivity index evaluating productivity of horizontal wells in homogeneous, isotropic reservoirs, to analyze the influence of anisotropy. These theoretical aspects result in criteria for selecting horizontal wells. Joshi (1988) presented a steady-state model to calculate productivity of horizontal wells, and proved that the model is available for electrical analog. This model takes account of reservoir anisotropy and well eccentricity. They assumed that it is single-phase flow in an infinite reservoir with constant pressure at the well bore and drainage radius. Economides et al., (1989) aimed at confirming the accuracy of Joshi (1988) and proposed a numerical stimulation of horizontal well productivity. Yost and Overbey (1989) compared the multi-fractured horizontal well with vertical well by simulation and found that the productivity of the former is several times as large as the latter. The progress in horizontal well stimulation indicates the advance for developing tight oil reservoirs.

Leif Larsen et al. (1994) considered multi-fractured horizontal wells and analyzed the flow periods with various fractures. Raghavan and Joshi (1993) combined the effective well bore radius concept and the superposition principle to calculate the productivity of a horizontal well with multiple transverse fractures (uniformly-spaced). It is under steady-state condition in a circular and homogeneous drainage area. provided a simple mathematical model to estimate vertical and horizontal wells productivity, considering the couple of flows in the matrix and fracture. However, this model is suitable for a single long fracture, so the model is restricted in some cases. Li et al., (1996) based on reformed flow resistance theory, and proposed a method for predicting performance. Wei and Economides (2005) suggested an analytical model for pseudo-state productivity index of a horizontal well with multiple transverse hydraulic fractures (uniformly-spaced). They assumed that flow geometries are linear flow from the reservoir to fracture, and linear and radial flow in the fracture.

Medeiros et al., (2007a, 2007b) found a new approach to analyze the production data of hydraulically fractured horizontal wells in tight, heterogeneous formations, and introducedt ransient productivity index that is more accurate. Guo et al., (2009) also suggested a productivity index model in pseudo-steady state conditions. With great difference, they assumed radial flow in the non-fractured area of reservoir, linear flow towards fractures in the fractured region, and linear and radial flow in the fractures toward the well bore.

Besides the research on analytical model for horizontal well productivity evaluation, non-Darcy behavior can't be neglected in low permeability reservoirs. Many experimental results show that fluid comes into flowing when pressure up to a value, pseudo threshold pressure and minimum threshold pressure exist (Wu et al., 2010; Zeng et al., 2011; Zhang 2013; Zhang et al., 2014, 2016).

However, current research on productivity evaluation towards fractured horizontal well in tight oil reservoir is idealized with various assumptions. Especially, the reservoir and fluid properties, fractures characteristics are all affecting the productivity, so creating suitable model to predict corresponding reservoir becomes more significant. Therefore, these studies cannot be easily applied to typical conditions in tight reservoirs.

In this study, we adopt the productivity index model of Guo et al. (2009), which is based on seepage theory in tight reservoirs with hydraulic fractured development. We considered two important effects in tight oil reservoir: threshold pressure gradient and stress sensitivity, combined with fracture heterogeneity mathematic model, and developed the productivity estimation model of horizontal well. To specifically describe the relationship between each other, we analyzed the influence of sensitive parameters on fractured horizontal well productivity. Through the creation of productivity prediction model, we were able to accurately evaluate the production and analyze the pressure variety in low permeability reservoirs. The above model is also suitable for low permeability reservoirs (e.g. tight oil) with fractured horizontal well in China fields.

2. Fractured horizontal well prediction model

A fractured horizontal well is located in a tight oil reservoir, and that is through casing perforation completion. Fractures serve as conduit and connection between wells and reservoirs. So the fluid flows into fractures from reservoirs, and then from the fractures into the horizontal well. The direct seepage process from reservoirs to well is neglected due to the tight porous media. The assumptions are made as follows: (1) The reservoir is horizontal, anisotropic and has low permeability and porosity. (2) The fractures penetrate all the height of reservoir. (3) The fractures are transverse and finite-conductivity fractures perpendicular to the horizontal well. (4) A single phase and slightly-compressible fluid flow in the reservoir. (5) The productivity of fractured horizontal well is equal to all the fractures.

The seepage for a fractured horizontal well in the tight oil reservoir is complex. Guo et al. (2009) proposed a convenient productivity index model. While these assumptions as follows can be easy for us to create a quick evaluation model:

(1) The first radial flow (in fractures): in the fractures, at the center of the horizontal wellbore, presenting radial fluid flow, as shown in Fig. 1(a).
(2) The first linear flow (in fractures): in the fractures, linear flow is universal, as shown in Fig. 1(b).
(3) The second linear flow (on formation): due to the diverging/converging effect of fractures, divided interface to be created between the cracks, both ends of interface flow is linear flow, as shown in Fig. 1(c).
(4) The second radial flow (on formation): the system of horizontal well and fractures can be regarded as an equal vertical well, when the reservoir is infinite, so flow state can be similar to radial fluid flow, as shown in Fig. 1(d).

3. Mathematic model

3.1. Radial flow model on formation (far from the wellbore)

Incomplete uniformly-spaced transverse fractures is considered. The reservoir thickness is h with a fractured horizontal well, n is the number of fractures, x_{fi} is the half length of fractures, w_{fi} is the width of fractures, d_{fi} is the fracture spacing, k_{fi} is the permeability of fractures. Far from the wellbore, we treat fractures and well as a system, the flow can be equal to radial flow (Rahman et al., 2013). We make R_e representative drainage radius, by equivalent radius method, the equal radius of the system is R_L, equivalent of seepage diagram is shown in Fig. 2.

Calculate with the theory of equal seepage area, the equal radius of the system is defined as:

$$R_L = \sqrt{\frac{2n\overline{x_f}\,\overline{d_f}}{\pi}} \tag{1}$$

where, $\overline{x_f}$ is the average of fracture half length, m; $\overline{d_f}$ is the average of fracture spacing, m.

In tight oil reservoir, we usually take the threshold pressure gradient as a constant into account, so the kinematic equation is