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Fractured horizontal well productivity prediction in tight oil reservoirs

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ABSTRACT

Horizontal wells productivity prediction and its influence factors analysis have important meanings in development of tight oil reservoirs. The purpose of a reservoir engineering study is to maintain a stable production rate. Although a scientific development plan can benefit yield stability, it needs to match with adjustments of a well production system. Especially for extra low permeability and tight oil reservoirs, an unsteady well production system may increase difficulties of well productivity prediction. Taking a tight oil reservoir in Daqing oilfield as the research subject, on the basis of an unsteady percolation mechanics theory and the superposition principle, a numerical model is built to calculate and analyze the fractured horizontal well productivity. In order to study horizontal well productivity better, a power law exponential decline model is also used to calculate and predict well productivity. Comparing with the numerical model and the power law model, the results show that the numerical model can be used to analyze productivity influence factors, and both models have a good match with actual production data for wells with the stable production system wells. Considering a well's unsteady production system and a model's practicability, the power law model can also be used to calculate and predict horizontal wells productivity in this research oilfield. The results of this study provide a reference for horizontal well productivity calculations and prediction in similar reservoirs.

1. Introduction

A tight oil reservoir is defined as a reservoir whose pore air permeability is below 2×10^{-3} μm^2 (Yao et al., 2013a, 2013b; Kuang et al., 2012). In tight oil reservoirs, single well productivity is always very low. Horizontal well drilling and hydraulic fracturing technologies are widely used to improve well productivity. Then horizontal well productivity calculations and prediction become a very topic issue for reservoir engineers.

Penmatcha and Aziz (1998) presented a comprehensive, transient, semi-analytical model for predicting the performance of horizontal wells. By using the principles of superposition in space and time and by using mass balance equations in a reservoir and wellbore, they solved this model in an implicit manner. Egberts and Fokker (2001) presented an analytical method to calculate the productivity index of a vertical or horizontal well taking into account different horizontal and vertical permeability and multiple layers. Wan and Aziz (2002) described a new semi-analytical solution for horizontal wells with multiple hydraulic fractures. The fractures could be rotated at any angle to a well, and they did not need to fully penetrate a formation in the vertical direction. Al-Kobaisi and Ozkan(2004) presented a hybrid numerical-analytical model for the pressure-transient response of a finite-conductivity vertical fracture intercepted by a horizontal well. This model dynamically coupled a numerical fracture model with an analytical reservoir model. This approach allowed us to include details of the fracture characteristics while keeping the computational work manageable.

Valkó, Amini (2007) proposed a DVS (Distributed Volumetric Sources) method to predict productivity from a horizontal well with multiple transverse fractures in a closed outer boundary. Brown et al. (2009) and Stalgorova and Mattar (2012) used a classical tri-linear flow model to simulate fluid flow and production behaviors of multi-frac horizontal wells in a tight reservoir. Based on Fick's law in the matrix and Darcy's flow in cleats and hydraulic fractures, Wang et al. (2013) presented a semi-analytical model considering the effects of boundary conditions to investigate pressure-transient behavior for asymmetrically fractured wells in coal reservoirs. Luo et al. (2014) studied the pressure behavior of a horizontal well intercepted by multiple non-planar fractures. By means of conformal transformation and an equivalent flow resistance method, Deng et al. (2014) obtained the productivity formula for vertical and horizontal fractured wells con-

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sidering diffusion, slip, desorption and absorption was obtained, which could predict a production rate of fractured wells, and provides a theoretical basis for production optimization. Wang et al. (2015) built a semi-analytical model based on fractal tri-linear flow for multi-stage hydraulically fractured horizontal wells in tight oil reservoirs. To account for the heterogeneity of a Stimulated Reservoir Volume (SRV), they used porosity and permeability functions that reflected the fractal nature of a fracture network in the SRV. Liu et al. (2016) investigated the impact of this flow consistency on a production rate through the development of a numerical simulation model and its application to a shale gas reservoir. Most of these papers focused on dimensionless variables and analytical model.

Alvaro and Faruk (1999) indicated that a fluid can flow through a porous medium only if the fluid force is sufficient to overcome a threshold pressure gradient and, therefore, Darcy's law should be corrected for this effect. Li et al. (2008) studied nonlinear seepage flow in ultra-low permeability reservoirs. The results showed that the productivity decreasing rate in low permeability reservoir was faster than that in middle or high permeability reservoir. Meanwhile, non-linear factors had a significant effect on the oil-water two-phase seepage when the seepage rate was lower. Zeng et al. (2012) designed experimental equipment to investigate single-phase oil/water flow in ultra-low permeability cores by using a capillary flow meter to achieve accurate measurements of a fluid volume. The results confirmed that the single-phase oil/water flow in ultra-low permeability cores was not consistent with that from Darcy's law.

Yao et al. (2013a, 2013b) presented a numerical method for the solution of a moving boundary problem of one-dimensional flow in semi-infinite long porous media with a threshold pressure gradient (TPG) in the case of a constant flow rate at the inner boundary. Guo et al. (2015) studied non-Darcy's flow in water-bearing cores from a tight sandstone reservoir, and developed and validated a numerical simulator for multi-stage fractured horizontal wells based on a low velocity of a non-Darcy's flow model.

On the basis of graphically extrapolating production semi-log plots (log *q* vs *t*) to abandonment, Arps's decline curve analysis was established (1945). There are three types of decline models using the concept of a loss-ratio and its derivative: Exponential, Hyperbolic, and Harmonic. For unconventional oil-gas reservoir exploration and development, especially for tight and shale gas reservoir development, several decline analysis models were developed, and the differences between the empirical decline curve models had been compared and analyzed (Ilk, 2008; Kabir et al., 2011; Kanfar and Wattenbarger, 2012; Nobakht et al., 2012; Clarkson et al., 2015; Zhang et al., 2015). However, these papers focused on shale gas reservoirs, and performed limited research on tight oil reservoir.

In this paper, to study the characteristics of tight oil flow and production behavior in Daqing oilfield, a numerical model and an empirical decline model are developed. This paper was organized as follows: Firstly, the numerical model is established to calculate and analyze fractured horizontal well productivity on the basis of an unsteady percolation mechanics theory and the superposition principle. Then, power law decline model is presented for the same purpose. Finally, taking a tight oil reservoir in Daqing oilfield as an example, these two models are used to calculate horizontal well productivity, and some conclusions are drawn.

2. Productivity calculation model for a fractured horizontal well

According to the characteristics of fluid flow in a tight oil reservoir, the fluid flow in a fractured horizontal well can be divided into three regions. The first region is a non-Darcy's flow region, which is far away from hydraulic fractures and considers the effect of a threshold pressure gradient on fluid flow. The second region is an elliptic flow region, which is controlled by hydraulic fractures and the matrix around these hydraulic fractures. The last region is a linear flow region from which the fluid flows into a well bottom along horizontal wellbore. Some assumptions are made to build a horizontal well productivity model. (1) The reservoir rock and fluid are compressible. (2) The hydraulic fracture height is equal to the reservoir thickness. (3) A single-phase non-Darcy's unsteady flow in the reservoir is considered. (4) The fluid flowing along the fracture surfaces can enter the wellbore but it does not directly enter the wellbore, which means that the fluid flows from the matrix to the hydraulic fractures first, and then into wellbore (Fig. 1).

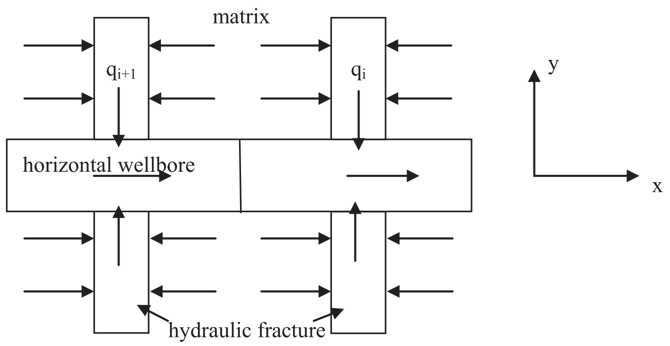

Fig. 1. A diagram of reservoir-fracture-horizontal wellbore fluid flow.

Multi-stage hydraulically fracturing is always used in tight oil reservoirs to improve single well productivity. Due to the influence of different stress distributions along the horizontal wellbore, the limitation of the fracturing technology and their connection with natural cracks, hydraulic fractures may have different length, azimuth, and conductivity capacity. These will bring more difficulties in building a horizontal well productivity model. Different relationships between fractures and horizontal wellbore can be seen in Fig. 2.

A pressure decline model in an infinite homogeneous formation is used in the fundamental theory when time is very short, and production can be assumed to be constant. A pressure decline equation can be expressed as follows:

$$p_i - p(x,\ y,\ t) = \frac{q\mu}{4\pi kh}\left[-Ei\left(-\frac{r^2}{4\eta t}\right)\right] \tag{1}$$

where $\eta = k/(\phi\mu C_t)$, p_i is the initial reservoir pressure, Pa; $p(x,y,t)$ is the reservoir pressure at point (x,y) in the reservoir, Pa; q is underground production, m^3/s; μ is the fluid viscosity, Pa s; k is the reservoir permeability, m^2; h is the reservoir thickness, m; r is the radial distance, m; ϕ is the reservoir porosity; t is production time, s; C_t is a compression coefficient, 1/Pa; η is a pressure transmitting coefficient, m^2/s.

A volume coefficient and a threshold pressure gradient should be considered, and using a rectangular plane coordinate system, Eq. (1) is changed to:

$$p_i - p(x,\ y,\ t) - G\cdot r = \frac{q_c B\mu}{4\pi kh}\left[-Ei\left(-\frac{(x-x_0)^2+(y-y_0)^2}{4\eta t}\right)\right] \tag{2}$$

where B is a volume coefficient; G is a threshold pressure gradient, Pa/m; q_c is surface production, m^3/s; $(x_0,\ y_0)$ are the coordinates of the point sink.

In a Cartesian coordinate system, the angle between the horizontal wellbore (the y-axis) and hydraulic fracture is defined as α. The two

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