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A new semi-analytical model for simulating the effectively stimulated volume of fractured wells in tight reservoirs

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ABSTRACT

The interaction of hydraulic fractures and natural fractures results in a complex fracture network system around a producing well, which is the primary contributing region for production in unconventional reservoirs. Currently, most models for simulating fluid flow in formations penetrated by fractured wells are based on the assumption of a homogeneous dual–porosity medium.

In this paper, a new semi-analytical model is presented for vertically fractured wells with stimulated reservoir volumes (SRV). Specifically, we employ fractal porosity and permeability to describe the heterogeneous distribution of porous media in a SRV. An approach is given for estimating the size and equivalent permeability of the fractal SRV for vertically fractured wells in tight reservoirs. The line source function, Laplace transformation, integral of the modified Bessel function and Stehfest numerical inversion algorithms are used to solve the composite model. Based on the Duhamel principle, the dimensionless pressure responses of tight oil and gas wells in the Laplace domain and time domain are obtained. Flow regime diagnostics of vertically fractured wells in tight reservoirs are characterized. Sensitivity analysis, including the effects of SRV parameters and fractal parameters on pressure responses and linear flow, are performed. The results show that seven primary regimes can be divided into pressure response curves. The size and equivalent permeability of the fractal SRV can be calculated by the dimensionless pressure derivative curves. In a complex fractal reservoir, the larger the connectivity index is and the smaller the fractal dimension is, the more significant the heterogeneity of the fractal SRV is and the larger the slopes of linear flow are, which leads to a smaller equivalent permeability of the fractal SRV radius. The presented model and the results in this paper can enrich the pressure transient analysis models for vertically fractured wells in unconventional reservoirs.

1. Introduction

Vertically fractured wells, as an effective technology to enhance the recovery of unconventional resources, have been applied widely. Hydraulic fracturing makes the natural fractures open and form a complex fracture network, which increases the reservoir conductivity and production (Zhou et al., 2012). The interaction of hydraulic and natural fractures makes the pressure analysis complicated (Luo and Wang, 2010, Clarkson et al., 2011; Xu et al., 2014), and the limited region around the producing well is defined as the stimulated reservoir volume (SRV) (Mayerhofer et al., 2010; Wang et al., 2014a,b,c).

To estimate SRV, micro-seismic monitoring (Preiksaitis et al., 2014; Yang et al., 2015) is commonly used by measuring the length, width and height of the stimulated regions. Astakhov et al. (2012) presented an alternative to the downhole-micro-seismic SRV mapping. Qin et al. (2012) proposed a simulation method to generate highly likely realizations of a fracture network based on micro-seismic data, taking into account the uncertainty of data and shale formation. Suliman et al. (2013) simulated the complex SRV considering the irregular fracture geometry, variable SRV, and multi-phase flow aspects. Although the methods based on micro-seismic monitoring can estimate the SRV accurately, the micro-seismic monitoring is a complicated technology, and the permeability of the SRV is difficult to obtain.

Analytical approaches were used to study the transient flow performance in the fractured multi-scale unconventional reservoirs. Flavio et al. (2008) modeled the performance of a fractured well by using dual-porosity media to describe the fracture network,

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and they found that the natural fractures significantly contributed to the production. Ozkan et al. (2009) and Brown et al. (2009) proposed tri-linear analytical models to study the pressure responses of fractured horizontal wells by assuming that the SRV is rectangular, but some radial flow and transition flow regimes of fractured wells are ignored. Although many analytical and numerical models have been presented for fractured wells in unconventional reservoirs (Ma et al., 2014; Wang et al., 2014a,b,c; Mayerhofer et al., 2006), the stimulated reservoir volume is still difficult to describe. Ketineni and Ertekin (2012) used an equivalent model to simulate the SRV, and they studied the effects of different factors on flow in natural fractures. To study the complete pressure responses of a fractured well, Zhao et al. (2014a,b) and Jiang et al. (2014) used a regular circular volume to characterize the SRV in unconventional reservoirs to carry on the analysis of transient pressure and rate by the point source function. Fan et al. (2015) presented a composite numerical model for a fractured well with a SRV in a tight oil and gas reservoir using the finite element method. All of above models can provide some approaches for further research, but there are still problems, including the characterization of an actual fracture network and a complex solving process.

Recent studies show that the classical diffusion equation based on the assumption of homogeneity at distinct scales is not valid in actual reservoirs (Razminia et al., 2015). Acuna and Yortsos (2015) applied fractal geometry to describe the heterogeneities of a fracture network and to analyze the pressure responses of fracture systems. Then, based on the fractal theory, some previous work (Chang and Yortsos, 1990; Acuna and Yortsos, 1991; Olarewaju, 1996) proposed the basic fractal formalism for the properties of a formation. Zhao and Zhang (2011) studied the pressure responses of a fractal reservoir with different outer boundary conditions. Cossio et al. (2013) employed the fractal relationship in a trilinear flow model and derived the fractal diffusivity equation of a vertically fractured well. Sheng et al. (2015) improved the composite model (Ozkan and Raghavan, 1994) using fractal theory to characterize the SRV by an equivalent model. Fractal theory is a powerful tool for studying the analytical or semi-analytical models for fractured wells in tight unconventional reservoirs due to the distribution of properties of a SRV.

In this paper, we present an analytical model for vertically fractured wells coupling fractal relations with a dual-porosity model to simulate the flow in a SRV. According to the previous relevant work on vertically fractured wells (Razminia et al., 2015), we employ fractal theory to describe the SRV and a classical dual−porosity medium to describe the unstimulated region in an unconventional reservoir with vertically fractured wells. Moreover, the method for estimating the size and equivalent permeability of a fractal SRV is discussed. The line source function, Laplace transformation, Stehfest numerical inversion algorithms, integral of the modified Bessel function and the Duhamel principle are used to obtain the solutions of this composite fractal model. Ultimately, the pressure response of a vertically fractured well and the SRV is divided into distinct regimes, and the effects of parameters on fractal SRV equivalent permeability are analyzed. The proposed model can support one effective approach for modeling the transient flow in the SRV of a fractured well in a tight unconventional reservoir.

2. Methodology

For tight unconventional reservoirs, the high conductivity of the fracture network in the SRV has been demonstrated to be the dominant contributor to production. Considering the complex distribution of the fracture network, we use the simplified fractal formalism for matrix and fractures in the SRV produced by Chang and Yortsos (1990) and refined by Acuna and Yortsos (2015), in which the fractal SRV properties (permeability and porosity) are described as power-law functions in a radial coordinate system. Fig. 1(a) is the view of a vertically fractured well with a fractal stimulated reservoir volume in a tight unconventional reservoir. There are three main flow regions: flow in hydraulic fractures, flow in the SRV and flow in the unstimulated region. Based on the dual-porosity formulation, the fractal theory is introduced to describe the fracture network. On account of the hydraulic fracture, we modified the power-law functions of fractal permeability and porosity to derive the fractal diffusivity equations. The fractal permeability and porosity of both the matrix and the fractures in the SRV are given by

$$k(r) = k\left(\frac{r}{x_f}\right)^{d-\theta-2}, \tag{1}$$

$$\phi(r) = \phi\left(\frac{r}{x_f}\right)^{d-2}, \tag{2}$$

where k and ϕ are the permeability and porosity, respectively, at the end of the hydraulic fracture; x_f is the hydraulic fracture half-length; d is the fractal dimension, which represents the dimension of the fractal SRV embedded in the Euclidean matrix; θ is the connectivity index characterizing the diffusion process; and r is the radius of the point of interest in the radial coordinate system.

2.1. Mathematical model

Fig. 1(b) shows the schematic of a vertically fractured well with a fractal stimulated reservoir volume. To derive the analytical model with ease, some assumptions must be made: 1) a circular reservoir with closed upper and lower boundaries, a uniform thickness of h, and a constant initial pressure p_i; 2) two regions, including a SRV and an unstimulated region, each with distinct properties; 3) fractal diffusion equations are used inside of r_1, and the classical dual-porosity model is used outside of r_1; 4) the fully fractured well with a half-length of x_f, located in the center of the reservoir; 5) the well produces a single phase fluid at a constant rate q. Combining the diffusion equation with the initial conditions and boundary conditions, we can derive the continuous line source function in the SRV, and then we can integrate this function along the hydraulic fracture to obtain the pressure response of the well bottom-hole..

2.2. For tight oil

Flow in the fractal stimulated reservoir volume.

The general continuity equations for a slightly compressible fluid in a stimulated reservoir volume are given by

$$-\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v_f\right) = \frac{\partial}{\partial t}\left[\phi_f(r)\rho\right] + q\rho, \tag{3}$$

$$-\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_m) = \frac{\partial}{\partial t}[\phi_m(r)\rho] - q\rho, \tag{4}$$

where ρ is fluid density (kg/m^3), v is the Darcy velocity (m^3/s), ϕ is porosity (dimensionless fraction), q is the quasi-steady crossflow (m^3/s), and the subscripts f and m denote the fracture and matrix systems, respectively.