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A mathematical model considering complex fractures and fractal flow for pressure transient analysis of fractured horizontal wells in unconventional reservoirs

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ABSTRACT

This article is the first investigation on the fracture network heterogeneity flow for multiple fractured horizontal wells in unconventional reservoirs. Currently, most modeling approaches for multiple fractured horizontal wells are based on flow in several distinct scales (matrix/fracture), in which the network of fractures is assumed to be connected and equivalent to a homogeneous medium of Euclidean geometry. To account for more detailed description of unconventional reservoir, fractal permeability and porosity relationship was introduced to represent reservoir heterogeneity. Fractal flow in a dual-continuum porous medium is taken into consideration to establish a model of hydraulically fractured horizontal wells. The coupled fractal-based tri-linear diffusivity equation helps illuminate the reservoir performance and improve the pressure transient analysis. A tri-linear flow mathematical model is used to represent the flow in hydraulic fractures, in the formation between the fractures, and in the formation away from the hydraulic fractures. To solve the equations at different regions, we prescribe the proper boundary conditions and use Laplace transformation and numerical inversion from the Laplace domain to the time domain. The new semi-analytical solutions were validated via numerical simulations.

The type curve of fractal pressure transient behavior was thoroughly examined; which were found to be primarily dependent on the value of the fractal parameters chosen. The proposed model could be used to diagnose the flow regime and interpret the pressure response more accurately for shale/tight oil reservoirs.

1. Introduction

Unconventional oil and gas reservoirs have recently become significant sources of hydrocarbon. Multi-stage fractured horizontal wells have proven to be successful technologies for use in the development of unconventional resources. A complex fracture network generated in the presence of stress isotropy and pre-existing natural fractures immensely extends reservoir contact and improves hydrocarbon production (Wentao et al., 2012). The production performance and pressure transient flow are much more complicated due to the hydraulically induced fracture network system (Medeiros et al., 2008; Jingjing et al., 2012; Fei et al., 2013; Clarkson et al., 2011).

Analytical and semi-analytical approaches have been widely used to model the transient flow behavior of such a planar vertical fracture. A tri-linear flow model was first proposed by Lee and Brockenbrough (1986). The approximate analytical model was divided into three linear flow regions, which were used to study the transient flow behavior of a well intercepted by vertical fractures. Chen and Raghavan (1997) and Raghavan et al. (1997) developed detailed single-porosity analytical models. The effects of the number, location and orientation of the fractures on the pressure response were discussed. Al-Kobaisi et al. (2004) presented a hybrid numerical/analytical model to study the pressure transient characteristics of a horizontal well with vertical fractures. In 2006, he extended the hybrid model to describe the fracture storage, which induced flow regimes for multiple transverse fractured

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horizontal wells (Al-Kobaisi et al., 2006). Medeiros et al. (2008) examined the pressure transient behavior impacted by the fracture network characterized by the dual-porosity system. The proposed method demonstrated that the natural fractures significantly contribute to the productivity of the fractured horizontal wells. Mayerhofer et al. (2006) proposed an approximate analytical solution for finite-conductivity vertical transverse fractures in horizontal wells. Despite the efforts presented in the literature on the pressure transient analysis of fractured wells, most of the models do not consider the characteristics of fracture networks or the flow behavior in the stimulated reservoir volume. Brown et al. (2009) and Ozkan et al. (2011) assumed that the identical fractures along the length of the horizontal well were uniformly distributed. The trilinear-flow model incorporated the dual-porosity model (Warren and Root, 1963) to consider transient fluid flow from the matrix to the fracture network, which was located in the internal zone between hydraulic fractures. The internal stimulated reservoir volume containing a large amount of fracture networks was treated as a homogenous medium. Sometimes, satisfactory results cannot be achieved during pressure transient analysis.

Although many attempts have been focused on developing a fractured horizontal well analytical model to provide an accurate pressure transient analysis (Renshi et al., 2012; Lei et al., 2013; Wei et al., 2014), the complex fracture network remains very challenging to characterize completely and exactly. Reliable characterization of an actual fracture network in the reservoir is severely limited. Microseismic approaches provide some large-scale information regarding the fracture density and the average fracture orientation, but the lack of adequate resolution makes it difficult to directly apply into the flow model. Accordingly, development of an efficient analytical approach to model the heterogeneity of a hydraulic fracture network is very desirable, which can improve the performance evaluation of wells in unconventional reservoirs.

The results from a pressure transient test in a naturally fractured system often exhibit non-uniform responses (Acuna et al., 1995). Fractal geometry provides a method to account for non-uniform pressure response under the assumption that the fracture networks are fractal in nature. At this point, the fracture network system was no longer characterized by two distinct scales: embedded matrix and fracture. The permeable fracture network was assumed to have a fractal structure, which imposed heterogeneities at all of the lengths of the scales. Chang and Yortsos (1990) proposed the basic formalism for representing fracture networks with naturally fractured fractal objects. The method assumed that fractures are embedded within the matrix in the form of fractal objects rather than a network of linearly arranged “sugar cubes”. They have successfully used this theory to model pressure-transient testing. The hypothesis was further explored via numerical results in 2D fracture networks by Acuna and Yortsos (1991). The simplified fractal formalism of a naturally fractured system was given by Acuna et al. (1995). Beier (1994) adopted the concept of a fractal-fracture network embedded in the matrix to extend the fractal model for a vertical fractured in a reservoir with a fractal structure. They demonstrated that dimensionless pressure is a power-law function of dimensionless time during the linear and radial flow periods. Olarewaju (1996) used fractal theory to establish the heterogeneous reservoir permeability for flow simulation. Lopez and Velazquez (2003) studied the transient and pseudo-steady-state flow regimes to obtain values for the fracture model in a history matching study. Yulong and Zhang (2011) developed the pressure-transient type curves in reservoirs of fractal structure. The outer-boundary condition is the dominant reservoir parameter affecting the shape of the pressure curve. Fractured horizontal well pressure transient analysis is also studied by using simulation method. Even though the numerical method is more powerful tool to construct complex reservoirs, analytical/semi-analytical model still offer fast and more flexibility to account for the detail structure of fractures. Cossio (2012) and Cossio et al. (2013) first introduced fractal relationship to vertical fractured tri-linear flow model. The fractal diffusivity equation was derived based on fractal permeability and porosity relationship and combined with the tri-linear flow model to produce a new semi-analytical solution called the fractal-fracture solution (FFS).

In this study, we incorporate the fractal diffusivity equation and the dual-porosity formulation in a tri-linear flow model to provide a more detailed description of the reservoir and fracture network in tight oil reservoirs. The work is relies on previous work by Cossio (2012), Cossio et al. (2013) and Brown et al. (2009) and we successfully applied in to multiple fractured horizontal wells. The fractal relationship is employed to represent fractal flow in the outer reservoir region, stimulated reservoir (SRV) region and hydraulic fracture flow region. The new solution of the fractal diffusivity equation coupled with the linear flow regions is used to model the production from tight oil reservoirs. This work represents the first time that fractal theory is used in modeling the fluid flow in a multiple hydraulic fracture horizontal well. It can be used to calculate well performance and pressure transient behavior for horizontal oil wells with fractures. Ultimately, this new approach provides an efficient means to investigate the effect of the reservoir and fracture network on the solution type curves.

2. Methodology

Tight oil production in ultra-tight reservoirs mainly involves fluid flow in a matrix and through fractures. It has been recognized that extensive fracture networks with massive contact surface areas are required to support economic productions from reservoirs. These fracture networks exhibit a large variability in scales, fracture density, and extent, which most likely are induced by the hydraulic fracturing process, while such relations and quantitative supports indicate that fracturing may lead to the creation of fractal objects. To account for the fluid flow in fracture network, a set of fractal exponents are considered to represent the complexity of the fracture heterogeneity. The new approach couples the different scales of the fractal fracture network and the embedded fractal matrix into one system, which is known as the fractal dual-mechanism system. The properties of fractal fracture networks (porosity and permeability) in this area were no longer uniform. Fig. 1 shows a sketch of the fractal fracture network distribution in multiple transverse fracture horizontal wells, where the interaction of dashed lines represents complex fracture network in different scales.

2.1. Fractal porosity/permeability relationship (FPPR)

In this work, the general form of the FPPR was used for our equation derivation. Chang and Yortsos (1990) first proposed the basic formalism for representing the fracture networks with naturally fractured fractal objects. Acuna et al. (1995) simplified the equations in a different way; these relationship equations are all derived in a radial coordinate system. Cossio (2012) and Cossio et al. (2013) first developed the FPPR in the Cartesian coordinates system, which has been successfully applied to the solution of the vertical fracture well. In this paper, the general form of the fractal porosity/permeability relationship for a multiple fracture horizontal well was developed.