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Pressure transient analysis of multiple fractured horizontal wells in naturally fractured unconventional reservoirs based on fractal theory and fractional calculus

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ABSTRACT

Currently, most models for multiple fractured horizontal wells (MFHWs) in naturally fractured unconventional reservoirs (NFURs) are based on classical Euclidean models which implicitly assume a uniform distribution of natural fractures and that all fractures are homogeneous. While fractal theory provides a powerful method to describe the disorder, heterogeneity, uncertainty and complexity of the NFURs. In this paper, a fractally fractional diffusion model (FFDM) for MFHWs in NFURs is established based on fractal theory and fractional calculus. Particularly, fractal theory is used to describe the heterogeneous, complex fracture network, with consideration of anomalous behavior of diffusion process in NFURs by employing fractional calculus. The Laplace transformation, line source function, dispersion method, and superposition principle are used to solve this new model. The pressure responses in the real time domain are obtained with Stehfest numerical inversion algorithms. The type curves of MFHW with three different outer boundaries are plotted. Sensitivity analysis of some related parameters are discussed as well. This new model provides the relatively more accurate and appropriate evaluation results for pressure transient analysis for MFHWs in NFURs, which could be applied to accurately interpret the real pressure data of an MFHW in field.

1. Introduction

Multiple fractured horizontal wells (MFHWs) were widely used for improving the productivity of unconventional reservoirs. Even though a great deal of work has been devoted to develop an analytical/semi-analytical model to provide a more accurate pressure response for MFHWs in naturally fractured unconventional reservoirs (NFURs) [1–12], all of which are based on classical Euclidean models by implicitly assuming a uniform distribution of natural fractures and that all fractures are homogeneous. So the heterogeneous, complex fracture network remain a challenge to characterize correctly and exactly.

Although some attempts have been made to incorporate the discrete fracture network(DFN) models of naturally fractures to the seepage model of naturally fractured system [13–16], but the complication and computing costs of the DFN model makes it difficult to directly apply. Accordingly, developing a faster, more efficient and more flexibility analytical/semi-analytical seepage model to account for the heterogeneity, uncertainty and complexity of the detail structure of fractures is very desirable, which is the basis for a more accurate and approximate evaluation results for pressure transient analysis for MFHWs in NFURs.

There have been evidence shown that the pressure transient response in a naturally fractured reservoirs often behaves non-uniform responses. While fractal theory is an efficient tool to

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incorporate the non-uniform pressure response, which makes the assumption that the fracture networks are fractal in nature. From 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 was heterogeneous at all of the lengths of the scales. Chang and Yortsos [17] were the first authors introducing the fractal theory to describe the pressure response of a naturally fractured reservoir. Acuna et al. [18] obtained the simplified fractal model of a naturally fractured reservoir. Beier [19] extended the fractal model to a vertical fractured in reservoirs with a fractal structure. Both of them observed that the wellbore pressure is a power-law function of time during the linear and radial flow periods. Olarewaju [20] used fractal theory to develop the heterogeneous reservoir permeability for flow simulation. Lopez and Velazquez [21,22] derived the short and long time asymptotic approximations of the analytical solution from the fractal model with or without matrix participation. Zhao and Zhang [23] developed the pressure-transient type curves in reservoirs of fractal structure. Cossio et al. [24,25] introduced fractal geometry to vertical fractured wells, an improved fractal tri-linear flow model based on fractal permeability and porosity relationship was derived. Wang et al. [26,27] applied the fractal tri-linear flow model to MFHWs in shale/tight oil reservoirs. Sheng et al. [28] and Zhang et al. [29] presented a semi-analytical model for vertically fractured wells by employing fractal porosity and permeability. Tan et al. [30–33] develop transient flow models of tree-shaped fractal reservoirs by embedding a tree-shaped fractal fracture network into a matrix system.

However, as the diffusion process of complex and disordered systems, including fractal system is history dependent, the memory of flow and non-locality are pivotal in all stages of production, for which the classical diffusion equation is no longer applicable, which is called anomalous diffusion. There have been many studies showing that the flow of tight reservoir deviates from Darcy flow behavior [34,35]. As its difficult to capture the memory of a flow in fractal system via integer-order calculus, while fractional calculus incorporates the hereditary of complex processes by introducing a kernel function. Specifically, in the last two decades, there are many works done on modeling anomalous diffusion of fractally fractured reservoirs by applying the fractional calculus to consider the complexity of anomalous diffusion process in fractured system [36–41].

Recently, in the light of the source solution, Raghavan and Chen [42–46] introduced fractional derivatives to study anomalous diffusion performance of vertical fractured wells and MFHWs in reservoir with single porosity, by considering the continuous time random walk (CTRW) in the hydraulic fractured reservoir. Ozcan et al. [47,48] incorporate the anomalous diffusion model into the trilinear flow model to study the pressure transient response in a fractal unconventional reservoir. While their models do not strictly reflect the sense of fractal geometry.

Ren and Guo [49] improved the model proposed by Raghavan and Chen to double porosity model for MFHWs in shale gas reservoirs with consideration of anomalous diffusion. However their models are on the basis of classical Euclidean geometry, that is, their models haven't taken into account of the disorder, heterogeneity, uncertainty and complexity of the naturally fractures.

By using fractional calculus to consider the complexity of anomalous diffusion process in fractal system, several authors have developed some fractional diffusion models on the basis of the fractal geometry, which we can be called fractally fractional diffusion model (FFDM). Velazquez et al. [50] developed a FFDM for naturally fractured reservoirs with fractal fractures, and investigate the production decline behavior in a naturally fractured reservoirs of single porosity and double porosity system with fractal fractures networks, which includes the generalization of diffusion equations with a temporal fractional derivative.

Razminia et al. [51–53] obtained an appropriate analytical solution of productivity for FFDM in double-porosity reservoirs with fractal fractures, and fractal radial composite single-porosity reservoirs. Razminia et al. [54] then analyze the pressure behavior of a vertical well with an infinite conductivity vertical fracture in a fractal single-porosity reservoir on the basis of temporal fractional derivative, by employing the line source function.

Based on the tri-linear flow model, Wei et al. [55] and Wang et al. [56] also use the fractal theory to describe the fracture network in SRV, and consider the flow characteristics of anomalous diffusion in the complex system by employing fractional calculus, they both improve the tri-linear flow model to fractally fractional tri-linear flow model for MFHWs in unconventional reservoirs.

In this paper, a FFDM for MFHWs in NFURs is established based on fractal theory and fractional calculus. Laplace transformation and the line source function are adopted to obtain the basic line-source solution, then the pressure response of MFHWs in NFURs is derived by dispersion method, and superposition principle based on the line-source solutions. Type curves are then plotted by employing Stehfest numerical inversion algorithm, and different flow regimes of MFHWs in NFURs are identified. The effects of relevant parameters, especially the fractal dimension and anomalous diffusion index on transient pressure response are analyzed.

The presented FFDM take a comprehensive consideration of fractal nature of natural fractures and fractional anomalous diffusion of the dual-porosity system by applying the temporal fractional derivative, which provides a new understanding of the pressure response of MFHWs in NFURs, and can be applied to a more accurate and appropriate interpretation of the real pressure data in field.

2. Physical model

Fig. 1 is the schematic of MFHW in an NFUR from top view. The simplified schematic illustration in Fig. 2 shows that an MFHW with completely penetrating hydraulic fractures in an

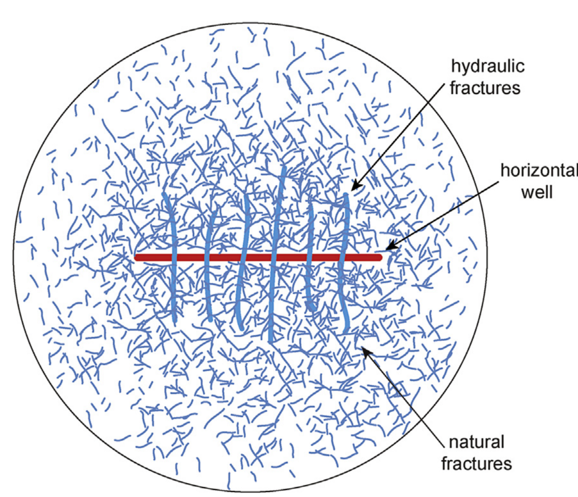

Fig. 1. Schematic of MFHW in NFURs from top view.