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A semi-analytical fractal model for production from tight oil reservoirs with hydraulically fractured horizontal wells

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ABSTRACT

One of the key technologies that made the development of unconventional formations possible is the creation of a complex fracture network. In most recent analytical models for flow in hydraulically fractured reservoirs, diffusivity flow in a fracture network equivalent to a homogeneous medium of Euclidean geometry has been considered. In this paper we incorporate a more detailed description of complex fracture networks to improve the pressure transient analysis of hydraulically fractured tight oil formations. Specifically, we employ a Fractal Diffusivity approach in which characteristics of flow in a dual-continuum porous medium are taken into consideration using fractal theory. In the proposed model, we represent the porosity and permeability of the fracture network in the Stimulated Reservoir Volume (SRV) using the fractal porosity–permeability relations. We use a trilinear flow model to represent the flow in hydraulic fractures, the SRV, and the formation away from hydraulic fractures. To solve the equations in different regions, we define proper boundary conditions and use Laplace transformation followed by numerical inversion to the time domain. We conduct several model validation and sensitivity studies. The proposed model provides a more realistic representation of flow in different regions around a fractured horizontal well, thereby giving rise to more reliable type curves that can be used for pressure transient analysis of tight oil formations.

1. Introduction

Multi-stage fractured horizontal well has proven to be an effective technology for production from unconventional resources. The hydraulic fracturing process generates a complex fracture network around fracture stages, and thus immensely extends reservoir contact and improves hydrocarbon production [1]. The stimulated area around hydraulic fracture stages is often referred to as the Stimulated Reservoir Volume (SRV). The presence of a complex fracture network in the SRV has a significant impact on the pressure transient analysis of unconventional reservoirs [2–5]. Analytical and semi-analytical approaches have been used to model the transient flow behavior in such systems. An approximate analytical solution was derived by Lee and Brockenbrough [6] for a trilinear flow model, representing the transient flow behavior of a well intercepted by vertical fractures. Chen and Raghavan [7], and Raghavan et al. [8], developed a detailed single-porosity analytical model to investigate the effect of number, location and orientation of fractures on pressure response. Al-Kobaisi et al. [9] presented a hybrid numerical/analytical model to study the pressure transient characteristics of horizontal wells with vertical fractures. They further extended the hybrid model to account for fracture storage and the corresponding flow regimes for multiple transverse fractured horizontal wells [10]. Flavio et al. [2] investigated the pressure transient behavior impacted by the dual-porosity nature of the fracture network. They demonstrated that natural fractures have significant contribution to the productivity of fractured horizontal wells. Mayerhofer et al. [11] proposed an approximate analytical solution for finite-conductivity vertical transverse fractures in horizontal wells. Brown et al. [12] and Ozkan et al. [13] assumed a uniform distribution for identical fractures along the length of the horizontal well.

Although several attempts have been made to provide analytical solutions for pressure transient analysis of multi-stage fractured wells [14,15], incorporating the complex fracture network still remains challenging due to the limitations of analytical solutions for complex systems of equations. Reliable characterization of actual fracture networks is severely limited. Accordingly, development of analytical solutions that incorporate the heterogeneity of the fracture network is desirable. Acuna et al. [16] assumed

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Nomenclature

B	oil formation volume factor
b_f	hydraulic fracture half-width
b_d	dimensionless hydraulic fracture half-width
C_{df}	dimensionless wellbore storage coefficient
c_{tf}	compressibility of the fracture network in region 2
c_{tm}	total compressibility (matrix and fluid)
c_{t1}	total compressibility of the hydraulic fracture (region 1)
c_{t2}	total compressibility of region 2 (matrix and fracture)
D	fractal dimension of the fracture network in region 2
h	reservoir thickness
k_f	fracture permeability in region 2 at the edge of the hydraulic fracture
k_m	matrix permeability
k_1	hydraulic fracture (region 1) permeability
p_f	fracture pressure in region 2 (same as p_2)
p_{fd}	dimensionless pressure of the fracture network in region 2
p_i	initial pressure
p_m	matrix pressure in region 2
p_{md}	dimensionless matrix pressure in region 2
p_n	pressure of the n^{th} flow region, n = 1, 2, 3, 4
p_{nd}	dimensionless pressure of the n^{th} flow region, n = 1, 2, 3, 4
q	production rate
q_{mf}	interporosity mass flow rate per unit bulk volume in region 2
q_{21}	mass flow rate per unit bulk volume, from region 2 to region 1
q_{32}	mass flow rate per unit bulk volume, from region 3 to region 2
S	skin factor
s	Laplace parameter
t	time
t_d	dimensionless time
x_d	dimensionless distance in the x-direction
x_e	reservoir size in the x-direction
x_{ed}	dimensionless reservoir size in the x-direction
x_f	hydraulic fracture half-length
y_d	dimensionless distance in the y-direction
y_e	reservoir size in the y-direction
y_{ed}	dimensionless reservoir size in the y-direction
ϕ_m	matrix porosity
ϕ_f	fracture porosity in region 2 at the edge of the hydraulic fracture
ϕ_1	hydraulic fracture (region 1) porosity
ϕ_2	total porosity of region 2 (matrix and fracture)
λ	interporosity flow coefficient of region 2
ω	storativity ratio of region 2
θ	connectivity index of the fracture network in region 2
μ	oil viscosity
α	shape factor for fluid transfer from matrix to fracture in region 2

fractal geometry to account for the non-uniform pressure response of naturally fractured systems. Based on their approach, fracture network was no longer characterized by two distinct scales, i.e., matrix and fracture. Chang and Yortsos [17] proposed the basic formalism for representing fracture networks using fractal objects. They assumed that fractures are embedded within matrix in the form of fractal objects rather than a network of linearly arranged sugar cubes. The hypothesis was further verified using numerical simulations for 2D fracture networks by Acuna and Yortsos [18]. The simplified fractal formalism for naturally fractured systems was given by Acuna et al. [16], in the form of power-law expressions for porosity and permeability in cylindrical coordinate system. In another study conducted by Beier [19] the concept of fractal network embedded in matrix was employed to model production from a well with vertical fracture in a reservoir with fractal structure. The study demonstrated that dimensionless pressure is a power-law function of dimensionless time during the linear and radial flow periods. Olarewaju [20] used fractal theory to build a heterogeneous reservoir permeability for flow simulation. Flamenco-Lopez and Camacho-Velazquez [21] conducted a history matching study to determine fractal parameters using pressure transient data. Zhao and Zhang [22] developed pressure-transient type curves for a reservoir with fractal structure. They studied the effect of the outer boundary conditions on the shape of pressure type curves. Yang et al. [23] studied the impact of fractal dimension on adsorption capacity in shale plays and demonstrated that the organic matter is the controlling factor on fractal dimension. In recent studies, Cossio et al. [24,25] employed fractal theory to address flow in finite-conductivity vertical fractures in porous media. They incorporated fractal relationships in a trilinear flow model to derive the Fractal Diffusivity equation for a vertically fractured well. Fractured horizontal well pressure transient behavior is also studied using numerical simulation [26].

In this study we employ fractal fracture relations coupled with dual-porosity formulation in a trilinear flow model to represent flow in the Stimulated Reservoir Volume (SRV) and to provide a more detailed description of fracture networks in tight oil reservoirs with hydraulically fractured horizontal wells. While we acknowledge previous related work on fractured wells by Cossio et al. [24,25], and Brown et al. [12], we use fractal relations to account for complex fracture networks in tight oil reservoirs [27]. The generated solution type curves account for variation of porosity and permeability in the SRV and thus can be used for pressure transient analysis of tight reservoirs.

2. Methodology

Fig. 1 presents the schematic of the trilinear flow model for a fractured horizontal well. We consider three linear flow regions, including flow inside the hydraulic fracture (Region 1), flow in the Stimulated Reservoir Volume (Region 2), and flow in the outer reservoir region (Region 3). Similar to most pressure transient analysis studies, our formulation is limited to single-phase flow, as two-phase properties (e.g., relative permeability) of tight formations are not well understood. To account for the fracture network in the SRV, we couple the dual-porosity formulation [28] with fractal description of the fracture network. We use power-law expressions for fractal permeability and porosity to derive the Fractal Fracture Diffusivity equation. The fractal permeability and porosity relationships flow in the y-direction are given by

$$k(y) = k_f \left(\frac{y}{b_f}\right)^{D-2-\theta}, \phi(y) = \phi_f \left(\frac{y}{b_f}\right)^{D-2}, \quad (1)$$

where D denotes fractal dimension representing the dimension of the fractal fracture network embedded in the Euclidean matrix, θ is the connectivity index characterizing the diffusion process [17,16], b_f is half-width of the hydraulic fracture and k_f and ϕ_f denote fracture permeability and porosity at the boundary shared by the hydraulic fracture stage and the SRV.