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A generalized framework model for simulating transient response of a well with complex fracture network by use of source and Green's function

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ABSTRACT

The focus of this paper is a generalized model to account for various complex-geometrical fractures with different particularities (conductivity, azimuth, length and connectivity etc.). In this study, a semi-analytical approach was established to facilitate transient response analysis in a 2D infinite reservoir containing a complex fracture network. In this model, according to superposition principle, the flow behavior in reservoir is modeled by using the classical instantaneous Green's function, and each fracture is explicitly represented by using continuous source solution. For the treatment of complex interplay of flow caused by interconnected fractures, a novel approach using mass balance equation is incorporated by restraining the vector sum of sources to determine flow redistribution of fracture segments neighboring interconnection. Furthermore, a set of case studies, from simple planar symmetry fracture to complex fracture network, were performed to demonstrate the accuracy of the generalized model by verifying with existing reliable solutions and alternative numerical simulators. In addition, the representative flow regimes were investigated to capture the physics of the transient response for complex fracture network. Finally, a real-field example was presented to illustrate the potential of our model in practical application. This work can provide a critical compromise in filling the gap between mesh-free solution and mesh-relying numerical methods in petroleum engineering.

1. Introduction

In the development of unconventional reservoirs, the combination of horizontal-well drilling and multistage fracturing technologies could generate complex multi-scaled fracture network because of the presence of stress isotropy and pre-existing natural fractures. The resulting fracture network profoundly determines the production performance. Therefore, the topic of simulating well performance from complex fracture network has been receiving more and more attention in reservoir-simulation studies (Biryukov and Kuchuk, 2012; Yu et al., 2014). Through reviewing some representative works in the past decades, the geometries of fractures are summarized as three patterns, usually described as *continuum model*, *planar fracture model*, and *irregularly-shape fracture model*, which are given:

Continuum model contains dual-porosity and dual-permeability models, where fractures are often uniformly distributed and intersected each other globally. Warren and Root (1963) provided a representative model, i.e., dual-porosity model with sugar-cube matrix block surrounded by fracture system. It needs to be emphasized that the bilinear model (Cinco-Ley and Samaniego-V, 1981) and trilinear model (Lee and Brockenbrough, 1986) are equivalent to dual-porosity model in essence. Up to now, more than hundreds of papers have been published in the petroleum literature on the use of continuum models for performing pressure/rate transient analysis. However, continuum model is not adequate enough for modeling the complexity of realistic complex fracture network and capturing the influence of fracture conductivity on production performance (Kuchuk and Biryukov, 2014, 2015), which is a fictitious homogeneous porous media not containing actual fractures. The transient behavior of fractured media depends on the spatial variability of fracture properties, not the local variability of matrix properties at the microscopic level (Kuchuk et al., 2014). Therefore, continuum model cannot capture the intrinsic behavior of complex fracture network.

Planar fracture model refers to the fracture with regularly-shape geometry in this study. Gringarten et al. (1974) provided a unified solution for infinite-conductivity fracture by using Green's function, where hydraulic fracture is explicitly described as a spatial integral of point-source solution. After introducing the concept of fracture conductivity, (semi)analytical and numerical solutions have been incorporated to model the production performance of planar vertical fractures (Cinco-Ley et al., 1978; Berumen et al., 2000; Brown et al., 2009), horizontal fractures (Gringarten et al., 1974; Valko and

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Economides, 1997), and slanted fractures (Rbeawi and Tiab, 2013; Jia et al., 2016). Subsequently, multi-branched hydraulic fractured well (Escobar et al., 2001) and multiple fractured horizontal well (Chen and Raghavan, 1997) were presented to extend the planar fracture model into practical application. The secondary-fracture network connected to main fractures intercepting horizontal well was taken into account in the works of Chen et al. (2016) and Teng et al. (2016), and a vertical-well model with multiple dendritic infinite-conductivity fractures was established by Restrepo and Tiab (2009). Further, the influence of fracture number, height, interval, asymmetry, azimuth, and intersected angle on performance was investigated and analyzed by many researchers (Escobar et al., 2003; Valko and Amini, 2007; Luo and Tang, 2014; Yu et al., 2014).

Irregularly-shaped fracture model enables to describe the complex geometry of fractures. To model complex fracture network, McClure et al. (2015) developed a framework model through combing the automatic generation of an unstructured grid and the lasted numerical algorithm. Jiang and Younis presented a hybrid coupled discrete-fracture/matrix and multi-continuum models and associated upscaling process to model different scaled fractures. Moradi et al. (2017) presented a sequential implicit numerical model by using Finite Element method with unstructured gridding to solve the spatially 3D flow problem. In addition to numerical approach, Izadi and Yildiz (2007) and Zeng et al. (2012) established different discretely-fractured systems containing randomly distributed fractures by using semi-analytical approach. However, their model assumes that fractures are distributed without interconnection. Modeling the interconnected fractures is the most critical step to highlight the interplay of flow caused by interconnected fractures. After discretizing the fractures into a series of pressure differential equations, Star-Delta transformation (Jia et al., 2015a, 2015b, 2016) and the constraint of pressure/flux continuities (Zhou et al., 2014; Biryukov and Kuchuk, 2015) are common approaches of modeling the flowing around intersection of fractures and determining the flow redirection automatically.

It is noted that each math model mentioned previously has its significance and advantage in either capturing the physical essence of fracture geometry (Biryukov and Kuchuk, 2012, 2015; Yu et al., 2014) or enabling rapid calculation (Brown et al., 2009; Zhou et al., 2014). Through a comprehensive overview, we conclude that the complex fracture network model using semi-analytical approach is currently the best compromise in practical application. In this study, a semi-analytical-solution methodology of production simulation for complex fracture network is developed to analyze the transient response. In this model, fractures are explicitly represented as continuous equation with instantaneous source functions, having sufficient flexibility to account for various fracture geometries, regular or irregular. Based on the model, different physical properties could be assigned for individual fractures. Furthermore, case studies are performed to detect the transient response for complex fracture network and quantify the effect of key fracture parameters on transient pressure response. A field-scale example was provided to demonstrate the potential that the approach could be expanded to complex networks. The corresponding pressure-field maps were also generated to facilitate our interpretation into transient response behavior. The generalized framework model would provide the fundamental guidance for production performance analysis and optimization.

2. Model description

The emphasis of this study is put on the effect of fracture geometry on transient response, so single phase black-oil is used for reservoir fluid. As shown in Fig. 1a, taking one fracturing stage of horizontal well from Barnett shale for example, according to the nonuniform of proppant distribution, the fractures are grouped into high conductivity fractures in which proppant concentrate and low conductivity fractures containing less propped (unpropped).

Fig. 1b depicts that the fracture network can be divided into a series of planar fractures, and some illustrations are list as follows:

(1) There are N_f fracture panels, and these panels are connected by N_υ interconnections;
(2) N_f fracture panels are further discretized into N_p fracture segments;
(3) Interconnections between fractures and wellbore are denoted as red solid points, and interconnections between fracture and fracture are denoted as black solid points;
(4) Each fracture is represented by linear-source function with multiple source terms, corresponding to the location of intersection.

In addition, other necessary assumptions are illustrated next:

(5) The reservoir is isotropic, homogeneous and infinite slab strata with thickness h, porosity φ, permeability k_m, and compressibility c_t;
(6) Horizontal well is intercepted by a fracture network containing N_f fractures with a full-length $L_{f,n}$, conductivity $k_{fn}w_{fn}$, angle θ_n with x-axis, and the located position (x_{ofn}, y_{ofn}), $n = 1 \ldots N_f$;
(7) The fractures are assumed to fully penetrate the reservoir thickness;
(8) All fluid is extracted from reservoirs through the interconnections between fractures and wellbore;
(9) The flux mass from the reservoir to unfractured horizontal segment is not considered, and the production rate is provided by a set of fractures;
(10) No pressure loss inside horizontal wellbore is assumed, and the radial-convergence effect of flow towards the wellbore within the transverse fractures is ignored.

Besides, two coordinate systems are established with regard to reservoir flow of 2D coordinate x-y and fracture flow of 1D coordinate x_n.

3. Mathematical model

3.1. Coupled reservoir-fracture flow model

In most cases, the fracture is not parallel to the x-axis and we define the angle between the fracture and the x-axis as θ shown in Fig. 2.

3.1.1. Reservoir flow model

After incorporating mass conservation equation, the single-phase fluid flow in the reservoir system can be described as the following pressure governing equation

$$\left(\frac{k_m}{\mu}\frac{\partial^2 p_m}{\partial x^2} + \frac{k_m}{\mu}\frac{\partial^2 p_m}{\partial y^2}\right) + S_f(x, y, t) = \varphi_m c_t \frac{\partial p_m}{\partial t} \tag{1}$$

where p_m is the reservoir pressure, t is the time variable, φ_m is reservoir porosity, k_m is the reservoir permeability, and μ is fluid viscosity. The reservoir flow model is subject to initial and boundary conditions as p_m $(x,y,t = 0) = p_i$, and p_m $(x = \infty, y = \infty, t) = p_i$. $S_f(t)$ is the sink function caused by N_f fracture, and is given as follows:

$$S_f(x, y, t) = \frac{\mu B}{k_m h}\sum_{m=1}^{N_f}\int_0^t \int_{x_{ofm}}^{x_{ofm}+L_{fm}} q_{fm}(u, t - \tau)\begin{bmatrix}\delta_m(x - x_{ofm} - u\cos\theta_m, \tau)\\ \delta_m(y - y_{ofm} - u\sin\theta_m, \tau)\end{bmatrix} du d\tau \tag{2}$$

where h is the formation thickness, B is volume factor, q_{fm} is the flux distribution of m-th fracture, L_{fm} is the length of m-th fracture, the fracture tip is located at (x_{ofm}, $y = y_{ofm}$), included angle between fracture panel and x-coordinate is θ_m, and δ_m is the instantaneous point function of m-th fracture on spatial point u and temporal point τ. Detailed assumptions and solution derivation process of this differential