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# Modeling the effects of fracture interference using a spectral gas reservoir simulator

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A R T I C L E I N F O

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A B S T R A C T

Economic success in the Cana Woodford shale play in Western Oklahoma has been largely due to field development using vertically fractured long horizontal laterals. In progressing from the field delineation phase, where sections are held by single well, to the field development phase, where multiple new wells are added to a previously produced section, many of the pre-existing “parent” wells suffer significant reduction in productivity as a result of interference from fracturing operations in the neighboring “infill” wells. We hypothesized that the change in the parent well's productivity was due to changes in fracture conductivity and/or changes in effective fracture length. In order to investigate the validity of our hypothesis, we developed a novel high-resolution spectral gas reservoir simulator to determine whether we could mimic the observed production behavior in the field. In particular, we wanted a simulator that would be immune to spatial truncation errors associated with finite difference schemes, and which would allow us to clearly examine interaction between nanodarcy reservoir matrix and high permeability narrow fractures; in addition, we needed the ability to alter fracture permeability with time to simulate the hypothesized effects of fracture interference. This paper details development of the spectral simulator and demonstrates that changes in fracture conductivity and length due to the interference event can account for observed productivity changes. We qualitatively compare simulator data to observed field data and show that changes in well productivity due to fracture interference can be explained by alteration of fracture half length and/or fracture conductivity.

## 1. Introduction

The effects of fracture interference on production data in the Cana Woodford shale play in Western Oklahoma have been documented in Ajani and Kelkar (2012), where pre-existing parent wells showed significant losses in productivity due to fracture interference from infill wells. Following that work, a multitude of papers were presented to try to understand and quantify the effects of fracture interference in shale plays; Yu et al. (2016) provided an excellent review on the literature available up to 2016. They noted that “the impact of spatial changes in fracture conductivity, number of connecting fractures, and complex fracture geometry on the pressure response of well interference have not been systematically modeled in previous studies”. They presented a semi-analytical segmented fracture model for simulating fracture “hits” and showed good agreement between their model and a numerical simulator, but did not compare their model to actual field data.

Tang et al. (2017) presented a 3D coupled compositional reservoir simulator and multi-segment wellbore model to simulate the performance of parent and infill wells under the impact of fracture interference. They showed that fracture interference could result in increases or decreases in the impacted parent well's productivity. A productivity increase results from an infill well whose completions enlarge the stimulated reservoir volume (SRV) of the parent well, whereas a productivity decrease results from the infill well sharing some of the parent well's SRV. Qualitatively, their “negative impact” production results resemble impacted parent production data observed in the Cana Woodford play.

In this work, we introduce another high-resolution tool to the effort of simulating and trying to understand the mechanisms affecting production in hydraulically fractured horizontal wells in shale plays: spectral reservoir simulation. Application of Spectral methods to the approximate solution of partial differential equations is a well-established technique in the field of numerical analysis; see, for example, Trefethen (2000), Boyd (2001), Press et al. (2007) and Kopriva (2009). However, as applied to flow in porous media, there are very few references to the method; (in fact, Riaz and Meiburg (2003) is the only application that we have been able to find.) Unlike finite difference methods, where spatial derivative operators are replaced by algebraic finite difference approximations,

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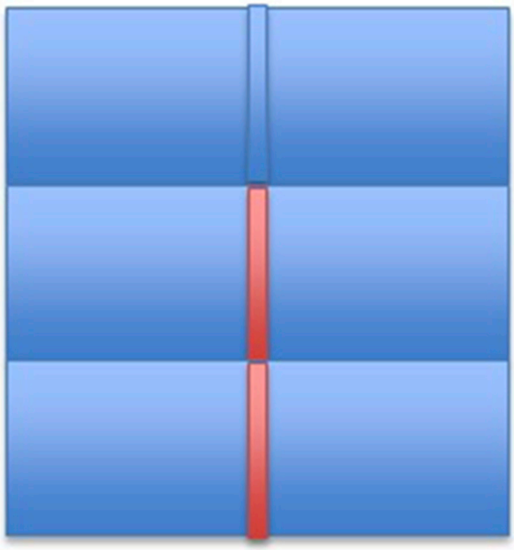

**Fig. 1.** Schematic of reservoir consisting of nine regions.

spectral methods approximate the global solution to the problem as a truncated series of analytical functions, most typically Fourier or Chebyshev series. The analytical spatial solution approximations can then be differentiated exactly for substitution into the governing flow equations and boundary conditions.

Whereas finite difference approximations to spatial derivatives always incur truncation errors that decrease with the grid size to some power, (squared for second order spatial derivatives) (Abou-Kassem et al., 2001), spectral approximations are exponentially convergent: spatial approximation errors decrease exponentially with increases in the number of terms in the approximating analytical series. In practice, this means that we can achieve spatial accuracies that far exceed finite difference accuracies on a given domain with as few as 20–35 terms in the approximating series. This allows us to examine fracture-matrix interaction during reservoir production in detail, and aids in the understanding of interference mechanisms. In the following sections, we provide a detailed description of the 2D spectral gas reservoir simulator used in this work. We apply it to simulate the hypothetical effects of fracture interference, and qualitatively compare the obtained results to actual observed field data.

## 2. Model development

Our objective is to accurately model flow from ultra-low permeability reservoir matrix to high permeability, very narrow, long fractures. For this work, we assume that the fractures are completely penetrating, and we model the 2D areal region of interest, e.g., the reservoir and half fracture, as a set of rectangular regions, each of which can exchange fluids with its immediate neighbors; (see Fig. 1). In the figure, the large blocks bounding the left and right of the areal region are reservoir matrix blocks with permeabilities in the nanodarcy range. Some of the narrow blocks at the center of the area (the lower two center blocks in this case) are fractures with permeabilities in the hundreds of millidarcy range, whereas others (the top middle block in this case) could have matrix properties, with permeabilities in the nanodarcy range. If a specified pressure (or rate) function were applied at the lower face of the lower center block, the production behavior of the system would be conceptually similar to production through a perforation from a reservoir area containing half of a single vertical fracture. Complex reservoir-fracture geometries could be synthesized by interfacing any number of "matrix" or "fracture" blocks; the only restriction is that common borders of connected regions must have the same length.

In this paper, we focus on simple 2-D geometries, but 3-D reservoir/fracture geometries could be built in a similar manner by stacking rectangular parallelepiped reservoir regions together. In the simple model above, the outer "matrix" blocks may have dimensions of tens of feet by tens of feet, whereas the "fracture" blocks could have dimensions of hundredths of feet by tens of feet.

### 2.1. Flow equations

The flow equation for any constituent region "$m$" in the reservoir, with corner coordinates $(x_{m,lo}, y_{m,lo})$, $\left(x_{m,hi}, y_{m,lo}\right)$, $(x_{m,hi}, y_{m,hi})$ and $(x_{m,lo}, y_{m,hi})$, is

$$C_1\left(\frac{\partial}{\partial x}\left(\rho_g\frac{k_{m,x}}{\mu_g}\frac{\partial p_m}{\partial x}\right)+\frac{\partial}{\partial y}\left(\rho_g\frac{k_{m,y}}{\mu_g}\frac{\partial p_m}{\partial y}\right)\right)=\phi_m\frac{\partial \rho_g}{\partial t} \tag{1}$$

where the symbols are defined in the Nomenclature; the units in Eq. (1) are lbm/d. If region "$m$" has a neighbor at its left, right, top or bottom, the boundary conditions at the common boundary are continuity of pressure and flux if the two regions are in hydraulic communication; thus, if region "$l$" is region "$m$'s" left neighbor, these conditions would be

$$p_l(x_{l,hi}, y, t) = p_m(x_{m,lo}, y, t) \text{ for } y_{m,lo} < y < y_{m,hi} \tag{2}$$

and

$$\left(\frac{k_{l,x}}{\mu_g}\frac{\partial p_l}{\partial x}\right)_{x_{l,hi}} = \left(\frac{k_{m,x}}{\mu_g}\frac{\partial p_m}{\partial x}\right)_{x_{m,lo}} \quad \text{for } y_{m,lo} < y < y_{m,hi} \tag{3}$$

If there were no left neighbor, (or no hydraulic communication between the neighbors), the boundary could be sealed, at specified rate or at specified pressure, i.e.,

$$\left(\frac{k_{m,x}}{\mu_g}\frac{\partial p_m}{\partial x}\right)_{x_{m,lo}} = 0 \text{ for } y_{m,lo} < y < y_{m,hi}; \tag{4}$$

$$\int_{y_{m,lo}}^{y_{m,hi}}\left(\frac{k_{m,x}\rho_g}{\mu_g}\frac{\partial p_m}{\partial x}\right)_{x_{m,lo}} dy = \frac{1000q(t)\rho_{g,sc}}{C_1 h} \tag{5}$$

where $q(t)$ is the specified rate in Mscf/d, and $\rho_{g,sc}$ is the density of the reservoir gas at standard conditions (lbm/ft$^3$); or

$$p_m(x_{m,lo}, y, t) = f(t) \text{ for } y_{m,lo} < y < y_{m,hi} \tag{6}$$

respectively. In particular, boundary conditions corresponding to Eqs. (4)–(6) would apply at the external boundaries of the simulated composite reservoir.

### 2.2. Spectral approximation

We assume that in each region, the pressure distribution can be approximated by truncated Chebyshev series; i.e., for region "$m$", we assume that the pressure distribution is given by

$$p_m(x,y,t)\approx\sum_{j=0}^{N_{x,m}}\sum_{k=0}^{N_{y,m}}c_{P,m,k,j}(t)T_j\left(\frac{(2x-x_{m,hi}-x_{m,lo})}{x_{m,hi}-x_{m,lo}}\right)T_k\left(\frac{(2y-y_{m,hi}-y_{m,lo})}{y_{m,hi}-y_{m,lo}}\right) \tag{7}$$

where $T_j(x)$ is the Chebyshev polynomial of the first kind of order $j$ (Press et al., 2007) or

$$T_j(x) = \cos\left(j\cos^{-1}(x)\right) \tag{8}$$

and $c_{P,m,k,j}(t)$ is a set of $(N_{x,m}+1)\times(N_{y,m}+1)$ coefficients that depend only on time. The number of terms in the truncated Chebyshev series for