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Full Length Article

Shape factor for dual-permeability fractured reservoir simulation: Effect of non-uniform flow in 2D fracture network

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ABSTRACT

The flow properties of naturally fractured reservoirs are dominated by flow through the fractures. In a previous study we showed that even a well-connected fracture network behaves like a much sparser network when the aperture distribution is broad enough: i.e., most fractures can be eliminated while leaving a sub-network with virtually the same permeability as the original fracture network. In this study, we focus on the influence of eliminating unimportant fractures which carry little flow on the inferred characteristic matrix-block size. We model a two-dimensional fractured reservoir in which the fractures are well-connected. The fractures obey a power-law length distribution, as observed in natural fracture networks. For the aperture distribution, because information from the subsurface is limited, we test a number of cases: log-normal distributions (from narrow to broad), and power-law distributions (from narrow to broad). The matrix blocks in fractured reservoirs are of varying sizes and shapes; we adopt the characteristic radius and the characteristic length to represent the characteristic matrix-block size. We show how the characteristic matrix-block sizes increase from the original fracture network to the dominant sub-network. This suggests that the matrix-block size, or shape factor, used in dual-porosity/dual-permeability waterflood or enhanced oil recovery (EOR) simulations or in homogenization should be based not on the entire fracture population but on the sub-network that carries almost all of the injected fluid (water or EOR agent).

1. Introduction

Naturally fractured reservoirs contain a significant amount of hydrocarbon reserves worldwide [1], However, the oil recovery from these reservoirs has been rather low. The low level of oil recovery indicates that more accurate reservoir characterisation and flow simulation is needed.

Reservoir simulation is one of the most practical methods of studying flow problems in porous media. For fractured reservoir simulation, the dual-porosity/dual-permeability concept and the discrete fracture model are two typical methods [2]. In the dual-porosity/dual-permeability approach, the fracture and matrix systems are treated as separate domains; interconnected fractures serve as fluid flow paths between injection and production wells, while the matrix acts only as fluid storage, and these two domains are connected with an exchange term [3–5]. In a dual-permeability model, fluid flow can also take place between matrix grid blocks, unlike from the dual-porosity model [6,7]. In order to simulate the realistic fracture geometry and account explicitly for the effect of individual fractures on fluid flow, discrete-fracture models have been developed [8–14]. Compared to the dual-porosity/dual-permeability models, discrete-fracture models represent a fracture network more explicitly and make the simulation more realistic. But discrete fracture models are typically difficult to solve numerically. Thus, although dual-porosity/dual-permeability models are much simplified characterizations of naturally fractured reservoirs, they are still the most widely used methods for field-scale fractured-reservoir simulation, as they address the dual-porosity nature of fractured reservoirs and are computationally cheaper. To generate a dual-porosity/dual-permeability model, it is necessary to define average properties for each grid cell, such as porosity, permeability and matrix-fracture interaction parameters (typical fracture spacing or shape factor) [15]. Therefore, the discrete fracture network considered to generate the dual-porosity model parameters is crucial. Using homogenization, one can treat matrix-fracture exchange more accurately than in dual porosity/dual permeability simulations [16], but, again, one needs a characteristic matrix-block size.

As we presented in a previous study [17], even in a well-connected fracture network, there is a dominant sub-network

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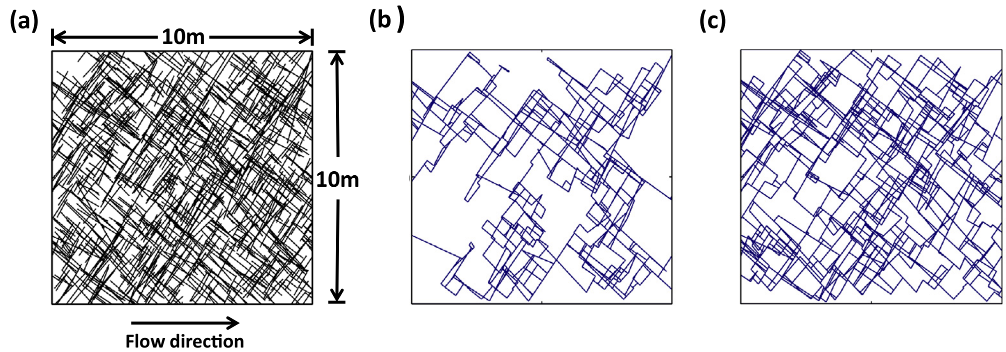

Fig. 1. (a) One realization of the fracture network examined in this study. The size of the fractured region is 10 m × 10 m × 0.01 m. The left and right boundaries are each at fixed hydraulic head; the difference in hydraulic head is 1 m. Water flows from left to right; the top and bottom edges are no-flow boundaries. (b) Dominant sub-network for one realization with a power-law aperture distribution with $\alpha = 1.001$. (c) Dominant sub-network for one realization with a power-law aperture distribution with $\alpha = 2$.

which carries almost all the flow, but it is much more sparse than the original network (Fig. 1). The flow-path length of the dominant sub-network can be as little as roughly 30% of that of the corresponding original fracture network in the most extreme case. This suggests that in secondary production, the water injected flows mainly along a small portion of the fracture network. In contrast, in primary production even relatively small fractures can be an efficient path for oil to flow to a production well.

This paper is organized as follows: we first introduce the numerical model and research process. Next, we analyse the sizes of the matrix blocks formed by the entire fracture network and the corresponding dominant sub-network. Finally, we point out the implications of this distinction for the dual-porosity/dual-permeability reservoir simulation.

2. Models

Since this is a follow-up study to our previous research [17], the models used here are the same as the ones adopted before (Fig. 1). Here we only introduce the models briefly; more details can be found in the previous work. Fracture networks are generated in a 10 m × 10 m × 0.01 m region using the commercial fractured-reservoir simulator FracMan™ [18]. Two fracture sets which are nearly orthogonal to each other are assumed, with almost equal numbers of fractures in the two sets. Each fracture, with a rectangular shape, is located following the Enhanced Baecher Model and is perpendicular to the plane which follows the flow direction and penetrates the top and bottom boundaries of the region. Because of the uncertainties in data and the influence of cut-offs in measurements, fracture-trace lengths have been described by exponential, log-normal or power-law distributions in previous studies [19–21]. Commonly, a power-law distribution is assumed by many researchers to be the correct model for fracture length [22–25], with exponent α ranging from 1.5 to 3.5. In this study, the fracture length follows the power-law distribution ($f(x)$):

$$f(x) = \frac{\alpha - 1}{x_{min}}\left(\frac{x_{min}}{x}\right)^{\alpha} \tag{1}$$

where α is the power-law exponent, x is the fracture length and x_{min} the lower bound on x, which we take to be 0.2 m. In order to make sure that there are no extremely short or long fractures, and in particular that opposite sides of our region of interest cannot be connected by a single fracture, we choose $\alpha = 2$ and truncate the length distribution on the upper end at 6 m. Since even the smallest fracture length (0.2 m) is much larger than the thickness of the region of interest (0.01 m), the 3D model can be seen as a 2D fracture network.

For fracture apertures, two kinds of distribution which have been proposed in previous studies are adopted: power-law [26–31] and log-normal [32–37]. In each kind of distribution, to include the entire range of feasible cases (from narrow to broad aperture distribution), different parameter values (α for a power-law aperture distribution and σ for a log-normal aperture distribution) are examined. The aperture is randomly assigned to each fracture.

The power-law distribution can also be defined as:

$$f(x) = x^{-\alpha} \tag{2}$$

If the power-law aperture distribution is described by Eq. (2), the studies cited above found that the value of the exponent α in nature is 1, 1.1, 1.8, 2.2, or 2.8. In this study, the power-law aperture distribution is defined by Eq. (1) as well as the fracture length distribution, where x stands for aperture instead of length. Eq. (1) differs from Eq. (2), in that it includes a minimum cut-off value, and α should be larger than 1. To include the entire range of feasible cases (from narrow to broad aperture distribution), here we examine α in the range from 1.001 to 6. In each case, the fracture aperture is limited to the interval between 0.01 mm and 10 mm. The aperture range can vary greatly in different formations; it also depends on the resolution and the size of the region studied. According to the field data collected from the Ship Rock volcanic plug in NW New Mexico [38] and Culpeper Quarry and Florence Lake [39], the aperture range [0.01 mm, 10 mm] adopted here is realistic, at least at some locations in natural.

The log-normal distribution is specified by the following probability density function:

$$f(x) = \frac{1}{x\log_{10}(\sigma)\sqrt{2\pi}}\exp\left\{-\frac{1}{2}\left(\frac{\log_{10}(x) - \mu}{\sigma}\right)^2\right\} \tag{3}$$

where μ and σ are the mean and the standard deviation in the log-10 space. The truncated log-normal distribution has two additional parameters: a minimum and a maximum value of aperture. Field studies and hydraulic tests found values of σ from 0.1 to 0.3, 0.23, and 0.47 [32,35,40]. To test the widest range of feasible values, we test values of σ from 0.1 to 0.6. More details can be found in our previous study [17]. In order to focus on the influence of fracture aperture distributions on the dominant sub-network, except for the aperture distribution, all the other parameter distributions remain the same for all the cases tested in this study, including the fracture length, the orientation, etc.

We assume that a fracture can be approximated as the slit between a pair of smooth, parallel plates; thus the aperture of each fracture is uniform. Steady state flow through the fractured region is considered (Fig. 1a). In this paper, we consider that fracture permeability is much greater than matrix permeability, which is