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Scaling of production data obtained from Random Walk Particle Tracking simulations in highly fractured porous media

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HIGHLIGHTS

- A new approach for scaling of traveling time distribution curves for miscible transport in fractured porous media.
- A new scaling rule was proposed as: $P(t)R^{\beta}$ vs. t/R^{α}.
- The exponents (α and β) were correlated to fracture density and fractal characteristics.
- α was strongly correlated to the mass fractal dimension.
- β has strongly dependent on box-dimension and fracture density.

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ABSTRACT

We modeled tracer injection through highly fractured media by Random Walk Particle Tracking simulations, and observed that production curves for different R values (distance between injection and production wells) are similar to each other and can be scaled. Hence, if we define $P(t)$ as a probability of a particle to reach the production well within traveling time t, and plot $P(t)R^{\beta}$ vs. t/R^{α}, we observe that production curves for different values of R overlaid. We identified the dependencies of α and β parameters on fracture network parameters, such as fracture spacing (fracture density) and the fractal characteristics of fracture network.

1. Introduction

Numerical simulation of fluid flow in porous media is commonly practiced in many different engineering disciplines including in oil and gas recovery, groundwater contamination, and waste disposal. These applications involve a detailed description of the underground reservoir and running the simulation on the created detailed model. This can be challenging and time consuming for complex fractured systems because of lack of information and description of details that require high computational time.

Over the last six decades, several different approaches have been proposed to model transport processes of fractured porous media. Classical dual porosity approach was presented by Barenblatt and Zheltov [1] and improved by Warren and Root [2] and Kazemi [3]. Although this approach is useful in modeling matrix–fracture interaction in multiphase flow, complex fracture network system is represented by an orthogonal grid system, which could be an oversimplification. Another

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Nomenclature

D_{bc}	=	box counting fractal dimension
D_f	=	fractal dimension (by construction)
D_m	=	mass fractal dimension
$P(t)$	=	probability of the particle to reach the production well with traveling time t
P_{mp}	=	$P(t_{mp})$ the highest possible probability
R	=	distance between injecting and producing wells
sp	=	spacing between fractures
t_{mp}	=	the most probable traveling time
V_f	=	(volume of fractures in the system)/(total volume of the system). Volume fraction of fractures.
α	=	scaling parameter, exponent, relating R and t_{mp}
β	=	scaling parameter, exponent, relating R and P_{mp}

traditional approach as an alternative to this is to use single porosity models by defining grids for fracture and matrix media separately and assigning equivalent porosity and permeability values to them. This requires very fine grids for the fracture system and conversion of fracture network permeability to a grid value is highly exhaustive process [4–6].

In addition to these "classical" approaches that use continuum modeling based on solving partial differential equations through finite difference approximation, "non-classical" techniques based on stochastic modeling were proposed to solve different types of flow in porous media problems [7–11].

More recently, the Discrete Fracture Network (DFN) approach was proposed. The DFN approach describes each fracture separately so that complexity of fracture network system can be captured to a greater extent [4,12]. For flow simulations, however, applications on the DFN models are very limited and for modeling complex transport processes, the DFN model needs to be converted and upscaled to a grid system to define equivalent reservoir properties [13]. Several attempts were made to improve flow simulation in DFN systems to incorporate matrix flow [12,14]. Hoteit and Firoozabadi [15] and Matthai et al. [16] used DFN systems to model miscible and immiscible flow applying finite volume element approach but they observed that this requires huge computational time as fracture systems require very large volume of finite volumes.

Non-classical approaches were proposed to improve flow simulation on a more realistic representative of fracture networks generated using the DFN approach. Among them, random walk [17–21] and its improved versions, Continuous Time Random Walk [22–27], as well as the particle tracking method [28] have received a great deal of attention to model fluid flow in complex fractured systems due to successful applications of complex transport processes, especially miscible transport [29,30].

For practical purposes, such as hydrocarbon production forecasting, groundwater pollution, or CO_2 sequestration, it is more important to obtain quick results for decision making purposes rather than using exhaustive characterization and modeling approaches listed above. In these cases, other techniques including analog fields [31] or analytical modeling [32] approaches are used.

Another practical solution for quick (but not necessarily precise) results is to apply scaling rules. The idea behind this approach is that the behavior of flow parameters (such as recovery, breakthrough time, and productivity index) depends on the characteristic length of the media (for example, the distance between wells). Once this dependency is described, it can be used for predictions. This approach has applied the percolation theory extensively and effectively [33,34]. The percolation theory describes connectivity of the reservoir as a function of its geological heterogeneities. Coefficients of the function are defined from small scale simulations and used for the bigger scale afterwards [35,36].

Classical percolation theory uses the modeling of regular percolation clusters and because those are well defined systems, it is possible to generate universal scaling constants for such modeling [34,35,37–39].

For the case of highly heterogeneous and complex (for example, fractured) structures, using ordinary percolation clusters may not be easily applicable [40–43]. Two major problems in these types of problems are the quantification of the complex and irregular structure of fracture systems, and the description of the percolation exponents. Recently, fractal theory has been useful in the quantitative description of this complexity [44–48]. One may use the same concept to relate the non-universal percolation (or any other scaling) exponents to fractal characteristics.

In this paper, we represent a scaling technique for modeling fluid flow in naturally fractured reservoirs and investigate how scaling parameters, i.e., exponents, are correlated to fracture network properties, including fractal dimensions.

2. Background and problem description

In an earlier study [30], we suggested a non-classical modeling technique to simulate miscible flow in fractured porous media. Detailed description of the algorithm is provided in the above mentioned paper and here we briefly introduce the main steps of the algorithm:

(1) *Convert discrete fracture network to a classical simulation grid, where fractures are represented by a set of thin highly permeable cells:* for this study, we generated a set of vertical fractures and assigned same permeability to all fractures. An