Journal of Petroleum Science and Engineering ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Impact of multi-set fracture pattern on the effective permeability of fractured porous media

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ARTICLE INFO

Article history:
Received 30 November 2012
Accepted 14 October 2013

Keywords:
permeability
multi-sets
numerical
fracture
anisotropy

ABSTRACT

In fractured porous media, a significant contribution to flow is made through fracture–matrix networks. These networks create flow channels which play an important role in overall fluid transport. Previous fracture simulation studies were mostly done with stochastic patterns. In contrast, the analysis of geomechanically generated discrete fracture data sets that closely render naturally occurring systems, whilst account for flow through matrix and fractures simultaneously was presented in this study. The used propagation algorithm provides similar results to physical experiments. The impact of multiple superposed fracture sets within geological formations, created by multiple deformation events, on the effective permeability has been analysed. A 2D fracture-matrix medium was simulated and effective permeability computed using a finite element based method. Specifically, the impact of certain detailed fracture characteristics, such as density, mean length, spacing, connectivity and matrix permeability on the flow was measured. Results indicated the increase of effective permeability in multiple-sets of fracture sets. Fractures superimposed at different angles to the main set, parallel to the flow, increase connectivity between main flowlines and neighbouring fracture clusters. Thus, an increase in connectivity leads to higher effective permeability of media and increased probability of percolation. Permeability anisotropy was also analysed in this study. An expression for the characterisation of anisotropic effective permeability was proposed and simulated permeability was compared to analytical predictions.

1. Introduction

Studying fractures can help us understand their influence on fluid transport in differentially fractured geological formations (Shen et al., 2008). They have been shown to have a great impact on the porous media's overall effective permeability (Bogdanov et al., 2007). Numerical models are effective tools for the simulation and investigation of such structures. Utilizing robust numerical models for flow simulation and realistic geometric representation of the fractured media we aim to enhance flow prediction capability and render naturally occurring systems.

There are various modelling approaches used to simulate flow through fractured formations. The Equivalent Porous Medium, (EPM), (Barenblatt et al., 1960; Pruess et al., 1986) is a single continuum porous medium model, where permeability is a sum of fracture and porous medium permeability. Dual Continua Models, such as DCDM (Barenblatt et al., 1960; Warren and Root, 1963) contemplate connected fractures and disconnected matrix models. These have restrictive assumptions such as no-flow in rock matrix, interconnected fractures, and averaged grid block fracture and matrix properties. Another approach is the Discrete Fracture Network, (DFN), (Witherspoon et al., 1980; Dershowitz and Einstein, 1988), in which the porous medium is not represented, and all flow is transmitted through fractures. Network-based effective permeability models are efficient, but often less accurate (Bogdanov et al., 2007). These are best suited for low permeability media (Long et al., 1985), such as intact crystalline rock, intact shales and halite, where permeability may reach 10^{-8} mD (Ingebritsen and Sanford, 1998). In contrast, for flow where matrix has a significant contribution, both flow through fractures and matrix must be accounted for. A model that captures this behaviour is the Discrete Fracture and Matrix model (DFM), in which the flow is simulated through the matrix and fractures simultaneously (Matthai et al., 2007; Paluszny and Matthai, 2010). Effective permeability is a crucial conductivity parameter (Ingebritsen and Sanford, 1998), which measures the ability of medium to transmit fluids. It is an internal physical property not dependant on macroscopic boundary conditions and is statistically homogeneous in large scales (Renard and Marsily, 1997). It is measured analytically, numerically, and by correlating it with different physical properties, e.g. porosity. Heterogeneity may occur on many scales, leading to extreme permeability fluctuations, thus, in many cases the permeability is not accurate (King, 1989). For numerical studies it is essential to include

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http://dx.doi.org/10.1016/j.petrol.2013.10.022

Nomenclature

A	area cross section
a	aperture size
α	anisotropy angle
d	dimensionless fracture density in porous media
k	permeability
k_{eff}	effective permeability
k_f	fracture permeability
k_m	matrix permeability
K_{IC}	material toughness
K	hydraulic conductivity
L	length of the flow region
l	mean fracture length
l_i	i fracture length
l_o	side length of a square measuring region
L_r	total length of fractures i in region
P	pressure
$P(u)$, $P(d)$	fluid pressure gradients, upstream and downstream
q	influx
R_k	effective permeability ratio, dimensionless
s	spacing
μ	viscosity
θ	superimposition angle of fracture sets

Subscripts

c	fracture centreline
f	fracture wall
eff	effective
f	fracture
m	matrix
t	total

heterogeneities in the computation of flow conductivity. Conventional simulators often neglect to incorporate fractures as discrete entities, leading to inadequate results (Philip et al., 2005). For instance, to obtain a reasonable production history match, gridblock permeability is often increased (Philip et al., 2005). In some cases, it was found that flow in simulated models was less than that found in a natural fractured network, where naturally occurring fracture patterns are arranged in a way that improves connectivity and hence permeability (Odling and Webman, 1991). Some simulated models of fracture sets were developed with a degree of similarity to those obtained experimentally (Renshaw and Pollard, 1994). It was shown that connectivity is of a primary importance to flow (Bogdanov et al., 2007). Previously, simulation algorithms were extremely time-consuming and demanded much computational power (Wawrzynek and Ingraffea, 1989). However, with technological advancement geomechanical modelling of complicated fracture patterns has now become a viable tool (Ingraffea and Saouma, 1985). It is demanding to measure the effective permeability of a model with a high level of geological realism that incorporates geomechanical properties, such as density and spatial fracture distribution. Paluszny and Matthai (2010) presented a 2D numerical model that measures effective permeability through a geomechanically generated network taking into account flow through the matrix and fractures, and examines the effect of the level of detail in fracture representation on the accuracy of effective permeability measurements.

Previous studies were done for single set fracture patterns only, which assume a sole episode of deformation (Paluszny and Matthai, 2010). However, in nature rock masses are often subjected to multiple stress and strain regimes throughout their burial history, resulting in the superposition of a multiple fracture sets. These patterns are common in geological formations (Rives et al., 1994; Cosgrove, 2005; Odling and Roden, 1997; Mandl, 1999; Grechka and Tsvankin, 2003). The study of the nature of fractures and their geometry is critical as bulk properties of fractured media, such as permeability for example, are determined by fracturing, rather than by intrinsic rock properties (Cosgrove, 2005). Thus, multi-sets with superimposition angles should render naturally occurring structures more precisely than the randomly oriented datasets.

The purpose of this paper is to measure the effective permeability of multi-sets, with respect to levels of geomechanical realism: curving, aperture distribution and connectivity. A comparative 2D study between the effective permeability of rock masses containing single-set and multi-set fracture patterns is presented. Single-set fracture patterns are developed geomechanically and subsequently superimposed. This is performed numerically, using finite element based method established from: a fracture criterion, a propagation criterion, and propagation angle (Paluszny and Matthai, 2009).

This paper is organized as follows. Section 2 describes the methodology, computation of effective permeability, methods of fracture growth, generation of multi-set fracture patterns and experimental setup. Section 3 compares and analyses the results of single-set and multi-set fracture pattern model. Conclusion of results is provided in Section 4.

2. Material and methods

2.1. Flow model and equations

We measure effective permeability by applying a pressure gradient to the model and computing fluid pressure field. We consider steady-state single-phase fluid flow, which obeys volume conservation law

$$\nabla q = 0 \tag{1}$$

where q (m/s) is the filtration velocity or Darcy flux:

$$q = -\frac{k}{\mu}\nabla P \tag{2}$$

where P (Pa) and μ (Pa s) are the fluid pressure and dynamic viscosity respectively, and k is the permeability of the rock. The equation is discretized using finite element method, where each element of discretized domain has permeability related to it. We define a constant matrix permeability k_m, for fractures we define an equivalent porous medium fracture permeability k_f, by applying a parallel plate approximation. We apply effective permeability boundary conditions to calculate total model throughput q. For given fluid flow we approximate k_{eff} as

$$k_{eff} = \frac{q\mu L}{A(P(u) - P(d))} \tag{3}$$

where L (m) is length of model in the direction of flow, A (m^2) is the area of a cross section perpendicular to the flow, $P(u)$ and $P(d)$ are upstream and downstream pressures (Pa) respectively. Here, effective permeability, k_{eff}, is the permeability of the fractured porous medium as it accounts for the flow through matrix and fractures simultaneously. Fluid pressure is solved for using the finite element method, $P(u)$ and $P(d)$ are integrated over the boundaries of the model. Fig. 1a shows that we apply a fluid pressure gradient as boundary condition. The effective permeability is expressed in dimensionless term, R_k