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Fracture Aperture in Flow Models: to Average, or not to Average?

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Summary

Fracture networks are heterogeneous systems creating anisotropic flow patterns, though field-scale flow models of fractured reservoirs use up-scaling of the fracture network to effective properties to model flow. We study the impact of upscaling aperture from a realistic aperture model, where aperture is defined by a stress-aperture relation that considers aperture variations within single fractures, to an arithmetically averaged distribution. This analysis is done through calculation of the equivalent permeability tensor of a discrete fracture and matrix flow model, taking into account different contrasts between fracture and matrix permeability. Results show that a strong equivalent permeability anisotropy emerges for a low matrix permeability, and that accurate representation of fracture aperture is as important as the fracture topology, particularly when the fracture matrix permeability ratio is large. The orientation of the permeability tensor varies with varying rock matrix permeability, reflecting anisotropy of the permeability that is impossible to extract from the fracture patterns itself. The results also highlight that utilizing a constant aperture for the fracture network may not reproduce the true anisotropy of the permeability. Utilizing an equivalent aperture in flow simulations introduces errors in both the direction and magnitude of principal permeabilities and the equivalent permeability anisotropy.

Introduction

To date, the complexity of fractured porous media still precludes the direct incorporation of small-scale features into field-scale modelling. Coarse-scale models are commonly utilised for history matching and prediction employing different up-scaling schemes for the simulation of large-scale fluid flow (e.g. Matthai and Nick 2009). The main difficulty appears when fine-scale processes have a major impact on the large-scale patterns of flow (Berkowitz, 2002). It is essential to understand the emergent behaviour of small-scale features that need to be considered on the field-scale. The equivalent permeability of fractured porous media and its degree of anisotropy can be estimated for the coarse-scale simulations utilizing fine-scale discrete fracture networks.

The discrete fracture network required for reservoir simulations can be obtained from subsurface well and seismic data (e.g. Aabø et al., 2017) and outcropping analog data (Bisdom et al., 2016a). It is however barely possible to extract fracture aperture information directly from these sources. Fracture apertures are commonly assumed constant (e.g. Hardebol et al., 2015) otherwise they can be calculated based on scaling relationships or through geomechanical modelling (Bisdom et al., 2016b). It may be possible to find an equivalent aperture for semi-parallel fracture sets (Nick et al., 2011). Taking into account the heterogeneous aperture distributions, Bisdom et al., (2016c) showed that fracture aperture - varying with ambient stress, and fracture and rock properties, among others - has a significant impact on the equivalent permeability.

Here we demonstrate how variable apertures impact the equivalent permeability of fractured porous media and its degree of anisotropy. We achieve this by combining a geomechanical model with a flow model. The first provides aperture distributions and the second simulates flow for different conditions. We compute the equivalent aperture size of the analysed fracture pattern and the ensued equivalent permeability of the system. We further aim to discuss whether or not a single equivalent aperture size can be used in the flow simulations of fractured porous media.

Method

We use the workflow presented in Bisdom et al., (2017) for obtaining flow-based equivalent permeability tensors from outcropping fracture networks by taking into account the impact of stress on aperture and flow. Figure 1 shows an example of a 2D fracture network. The network covers an area of 150 by 142 m and contains 1082 digitised fractures in a highly-connected arrangement. For the geomechanical model a maximum horizontal stress σ_1 (30 MPa) is applied in the y-direction which results in a σ_3 of 10 MPa in the x-direction, for a Poisson's ratio of 0.3. The resulting local normal and shear stresses from the geomechanical FE model are used to obtain stress-dependent apertures. Similar to Durlofsky (1991), the full equivalent permeability tensor is computed by solving the steady state continuity equation for flow in different directions using a far-field pressure gradient applied in both horizontal directions of the rectangular 2-D fracture model. As a result the maximum and minimum principal permeability values (k_{max}, k_{min}) and the principal direction (θ) can be calculated.

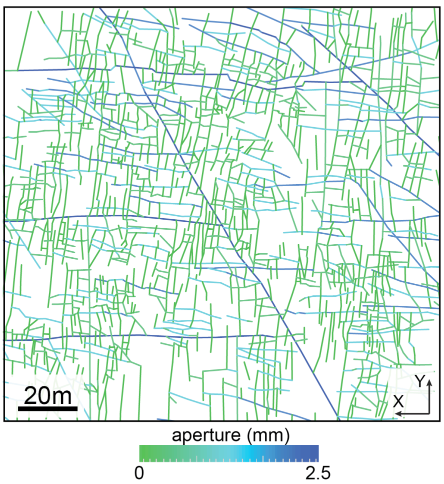

Figure 1 *Fracture network obtained from an outcropping carbonate pavement with an aperture distribution obtained from the geomechanical simulation (Bisdom et al., 2017).*

One could also use constant aperture values for all fractures. Two constant values for fracture aperture in an entire model are: the weighted segment length average, $a_{avg} = \sum_i^n a_i l_i / \sum_i^n l_i$, and the equivalent aperture, $a_{eq} = (\sum_i^n a_i^2 l_i / \sum_i^n l_i)^{0.5}$, based on the fact that the permeability of individual fracture segments is calculated through $k_{fi} = a_i^2/12$. Here l_i is the length of fracture element $i \in [1,n]$ with aperture size equal to a_i.

Results

The fracture set shown in Figure 1 is employed to calculate the permeability tensor. We use the variable aperture values obtained from the geomechanical simulation as input for the flow simulations. The flow simulations are also conducted for the fracture model with the constant aperture size. The constant aperture sizes obtained are 0.5 and 0.685 mm for a_{avg} and a_{eq}, respectively. Figure 2 shows ellipses illustrating the model equivalent permeability tensors for the fracture model with variable aperture and constant aperture size. It is evident that the weighted arithmetic average can not reproduce any features emerged from the flow calculation using the variable aperture data while the model with the equivalent aperture is able to give similar maximum permeability value.

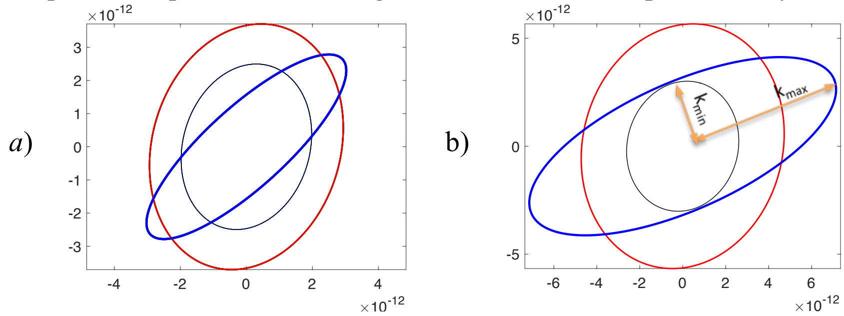

***Figure 2** Ellipses illustrate model equivalent permeability tensor using the variable aperture* (blue ellipse) *and constant apertures a_{avg}* (black ellipse) *and a_{eq}* (red ellipse) *for the matrix permeability of a) 10^{-16} m^2 and b) 10^{-12} m^2.*

We conduct simulations with matrix permeabilities (k_m) ranging from 0.1mD to 1000D. Model properties are fixed, allowing the fracture-matrix flux ratio to vary. Figure 3-a compares the magnitude and direction of principal permeabilities for the model with variable and constant aperture. As shown also in Figure 2, the model with the equivalent aperture can reproduce, for most cases, the maximum permeabilities but it fails to estimate correctly k_{min} and the direction of principal permeabilities. By varying the matrix permeability, tensor orientation varies reflecting anisotropy of the permeability that is impossible to extract from the fracture patterns itself. The results also

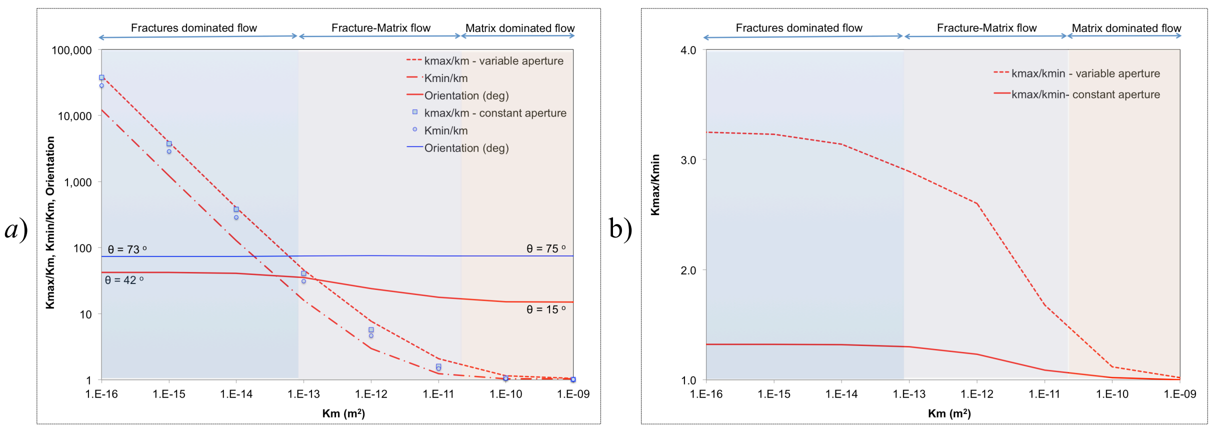

***Figure 3** a) Orientation of the maximum permeability tensor (solid lines) and permeability ratios (red dashed lines and blue markers) as a function of matrix permeability, comparing models with constant apertures (blue) to those with varying apertures (red); b) Comparison of the permeability contrast (K_{max}/K_{min}) for models with a variable aperture and a constant averaged aperture.*

highlight that utilizing a constant aperture for the fracture network may not reproduce the true anisotropy of the permeability (Figure 3-b). For the cases with the matrix permeability smaller than 10^{-12} m^2 (1 D) the equivalent permeability anisotropy is controlled by the aperture distribution and that cannot be inferred only from the fracture network geometry.

Conclusions

In this work, we combine a geomechanical model that produces a realistic (i.e. heterogeneous with variations along a single fracture) aperture distribution with a flow model to analyse the impact of aperture on the equivalent permeability. The key findings of this study are as follows:

- A strong equivalent permeability anisotropy emerges for low matrix permeabilities.
- Accurate representation of fracture aperture is as important as the fracture topology, particularly when the fracture matrix permeability ratio is large.
- Permeability tensor orientation varies, by varying the rock matrix permeability, reflecting anisotropy of the permeability that is impossible to extract from the fracture patterns itself.
- A constant aperture for the fracture network may not reproduce the true permeability anisotropy.
- Utilizing an equivalent aperture in flow simulations introduces errors in both the direction and magnitude of principal permeabilities and the equivalent permeability anisotropy.

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