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Slightly compressible gas slip flow in a fracture: macroscopic model and simulations

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Abstract

Gas flow in fractures is of interest in many fields ranging from hydrocarbon gas recovery from fractured reservoirs (Berkowitz, 2002) to sealing between clamped rough surfaces (Vallet *et al.*, 2009). The present work is focused on gas flow in a single fracture in the creeping, slightly compressible and slip regime. An equivalent of the Reynolds equation is first derived from the complete 3D Stokes problem governing the flow in the fracture. In a second step, a macroscopic model, describing the flow at the scale of a Representative Elementary Surface (RES), is derived by upscaling the Reynolds equation. Numerical solutions for the prediction of the fracture transmissivity appearing in the macroscopic model are illustrated on model fractures. Finally, the determination of the global transmissivity of a heterogeneous fracture characterized by a field of local anisotropic transmissivities is presented.

Keywords: Fracture; Gas flow; Upscaling; Boundary element method

1 Reynolds equation and upscaling

The steady creeping and slightly compressible gas slip flow in a rigid fracture of variable aperture h can be described by the classical mass and momentum (Stokes) equation along with a first order (Navier) slip condition at the fracture surfaces. When the slope of surfaces' roughness is everywhere small compared to 1, this 3D problem can be reduced to a 2D one, namely a Reynolds model, operating at the roughness scale for which the point transmissivity is $\frac{h^3}{12\mu} \left(1 + 6\frac{\xi\lambda}{h}\right)$ (see Zaouter *et al.* (2018) for the details and notations). As discussed below, a macroscopic model, valid at the scale of a RES, is of interest in practice. It can be obtained by upscaling the Reynolds problem operating at the roughness scale using the volume averaging technique. This yields (Zaouter *et al.*, 2018)

$$\nabla \cdot \langle \mathbf{q} \rangle = 0 \quad (1a)$$

$$\langle \mathbf{q} \rangle = -\langle \rho \rangle^\beta \frac{\mathbf{K}}{\mu} \cdot \nabla \langle p \rangle^\beta \quad (1b)$$

$$\langle \rho \rangle^\beta = \varphi(\langle p \rangle^\beta) \quad (1c)$$

where \mathbf{K} is the macroscopic transmissivity tensor defined as $\mathbf{K} = \langle k(\mathbf{1} + \nabla b) \rangle / 12$ with $k = h^3 + 6\xi\lambda h^2$ and \mathbf{b} is solution of a closure problem. The prediction of \mathbf{K} for a sinusoidal fracture is reported versus the Knudsen number in Fig. 1a together with a comparison with the corresponding analytical result showing the relevance of the macroscopic model.

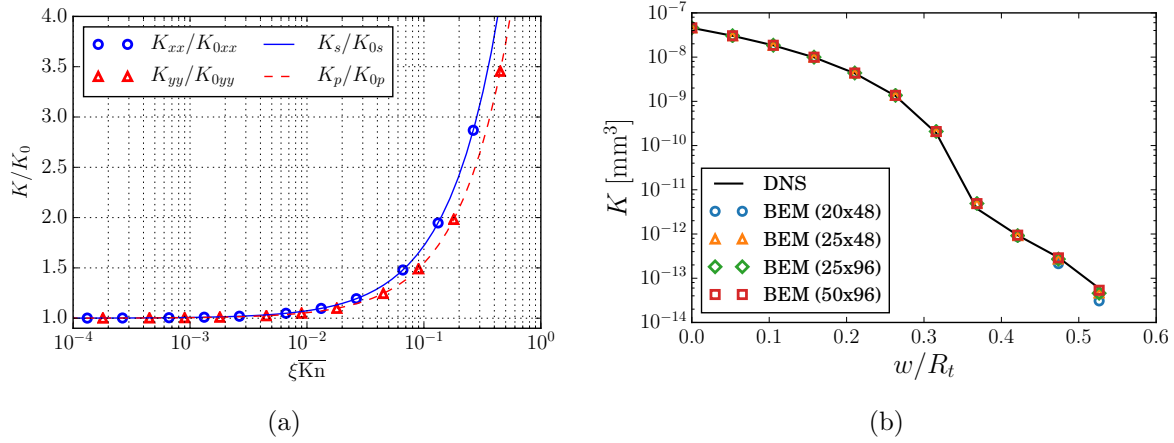


Figure 1: a) Ratio of the apparent slip-corrected to intrinsic transmissivity K_{ij}/K_{0ij} as a function of $\xi \overline{Kn}$ for a sinusoidal fracture. Symbols are the prediction from upscaling and lines are the analytical solutions. b) Global transmissivity, K , of a spiral-groove fracture in the direction transverse to the groove as a function of the dimensionless squeezing displacement, w/R_t , obtained from DNS and the subdomain approach (BEM) with four tessellations.

2 Global transmissivity prediction

In practice, the Reynolds problem involving the point transmissivity field may be solved with a Direct Numerical Simulation (DNS) approach on the entire fracture to the cost, however, of tremendous computational resources due to the contrast of length scales between the roughness and the fracture size. An alternative is to adopt a subdomain approach, based on a tessellation. Each tile is affected a local anisotropic transmissivity tensor \mathbf{K} obtained from the closure problem mentioned above. The prediction of the global fracture transmissivity can hence be obtained from the solution of Eqs. (1) on each tile along with pressure and normal flux continuity at the boundary between two adjacent tiles. Note that the local transmissivity tensor, \mathbf{K} , features a heterogeneous anisotropic field with a dependence on the local pressure due to the dependence of λ on $\langle p \rangle^\beta$.

An integral formulation associated to a boundary element method is employed to solve this heterogeneous diffusion-like problem using two successive transformations (rotation and dilatation) on each tile. An example of the global transmissivity (denoted K) obtained on a spiral groove surface pressed against a flat rigid surface in the direction orthogonal to the groove is represented in Fig. 1b versus the squeezing displacement w/R_t . Comparison of the results obtained from the DNS and subdomain approach using four different tessellations shows an excellent agreement, confirming the validity of the later method.

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