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# Alma Mater Studiorum Università di Bologna Department of Civil, Chemical, Environmental and Materials Engineering

# A STOCHASTIC ANALYSIS OF THE NON-NEWTONIAN HYDRAULIC BEHAVIOUR OF ROUGH FRACTURES

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### FLOW OF SHEAR-THINNING FLUIDS IN GEOLOGICAL FRACTURES

The hydraulic behavior of geological formations is mainly governed by fractures connectivity and permeability, whose heterogeneity strongly affects flow and transport, with fluid rheology playing an important role often oversimpliefied.

- Typically, unconventional and deep geotermal reservoirs present both low-porosity and low-permeability
- Activities in gas shale or hot rock requires hydraulic stimulation to enhances productivity and become cost effective
- Fluid viscosity is stryctly linked with the activity effectiveness (e.g., proppant transport or stimulation fluid recovery).

Fluids involved in subsurface industrial activities present **Subsurface industrial activities**:



a shear-thinning behaviour at continuum scale, due to their complex make-up.

- muds
- foams
- water-based suspentions



- Enhanced Oil Recovery (EOL) •
- Enhanced Geothermal Systems (EGS)
- Carbon sequestration
- Lost circulation of drilling fluids

## NUMERICAL MODELING

#### 2.1 Synthetic fracture generator

A synthetic aperture field is estimated by mating two isotropic self-affine surfaces  $h_i(\mathbf{x})$ 

 $w(\mathbf{x}) = h_1(\mathbf{x}) - h_2(\mathbf{x}) + \langle w \rangle$ 

A rough surface can be generated as a 2D white noises and introducing spatial correlation: multiplying the modulus of the Fourier transform by the modulus of the wave numbers  $|k| = (k_x^2 + k_v^2)^{1/2}$  to the power -1-*H* 

 $|h(\mathbf{k})| \rightarrow |k|^{-1-H} |h(\mathbf{k})|$ 

#### 2.2 Fluid Rheology: Ellis model

The Ellis model is a three-parameter generalized Newtonian rheology





- \ ' 1 / *Z* /
- low-shear rate viscosity ( $\eta \rightarrow \mu_0$  for  $\dot{\gamma} \rightarrow 0$ )  $\mu_0$
- shear-thinning index n
- $\tau_{1/2}$  characteristic shear stress:  $\eta(\tau_{1/2})=\mu_0/2$

2.3 Generalized Non-linear Reynolds Equation • Lubrication theory holds ( $\nabla w \ll 1$  and Re $\ll 1$ )

$$-\nabla \cdot \left[\frac{w(\mathbf{x})^3}{12\mu_0} + \frac{n}{(2n+1)} \left(\frac{1}{2^{1+n}\mu_0^n \tau_{1/2}^{1-n}}\right)^{\frac{1}{n}} w(\mathbf{x})^{\frac{2n+1}{n}} |\nabla P|^{\frac{1}{n}-1}\right] \nabla P = 0$$

Numerical modeling via finite volume method:

• The non-linear system of equations is solve via **inexact Newton-Krylov** method Variable-fill-in Cholesky preconditioned conjugate gradient → linear problem • A parameters continuation strategy is adopted to handle strongly non-linear cases

### **STOCHASTIC ANALYSIS**



A Monte Carlo Framework is adopted to study the impact of:

- **Pressure gradient**  $(\overline{\nabla P})$  $\rightarrow$  Flow regime
- **Shear-thinning behaviour**  $(n) \rightarrow$  Fluid rheology
- **Fracture dimension** (*L*)  $\rightarrow$  Scale

For each combination of the parameters (12 in total), the flow is solved considering a set of **1000** fracture realizations.

Eventually, ensemble statistics are then analysed for:

Velocity components and magnitude  $(u_{\chi}, u_{\nu}, u)$ **Apparent Transmissivity** (*T* )

### **CONCLUSION AND PERSPECTIVES**

#### 4.2 Perspectives

Flow localization impacts the effectiveness of any subsurface activities

**High velocities** magnitude PDFs  $\rightarrow$  **channeling metrics** Low velocities magnitude PDFs  $\rightarrow$  anomalous transport

Mèheust, Y., Schmittbuhl, J. (2000) Flow enhancement of rough fracture. *Geophys. Res.* Lett., 27(18), 2989-2992. doi: 10.1029/1888gl1008464

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#### **4.1 Conclusion**

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 $T(\langle u \rangle) = \frac{Q \,\mu_0}{\overline{\nabla P}}$ 

*L*=0.1 m

 $L_{c}=0.1 \text{ m}$ 

H=0.8

 $\langle w \rangle = 10^{-3} \,\mathrm{m}$ 

 $\sigma_w/\langle w \rangle = 0.8$ 

XG \_\_\_\_\_

**SO** //---

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 $\langle u \rangle \propto \overline{\nabla P^n}$ 

 $T/T_0$ 

 $\langle u \rangle \propto \nabla l$ 

Velocity components displays narrow PDFs with nearly exponential decay

- High  $\overline{\nabla P}$  and low *n* incresase shear-thinning behaviour, favouring flow localization
- Qols PDFs of the smaller fracture length present higher dispersion •
  - Shear-thinning behaviour enhances fracture transmissivity, leading to non-darcian flow regime  $\langle u \rangle \propto \overline{\nabla P^n}$