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

AGU FALL MEETING
New Orleans, LA & Online Everywhere
13–17 December 2021

MODELING COMPLEX FLUID FLOW IN ROUGH-FRACTURES: A LUBRICATION-BASED APPROACH

Alessandro Lenci[1,2], Yves Méheust[2], Mario Putti[3], Vittorio Di Federico[1]

[1] Università di Bologna, Department of Civil, Chemical, Environmental and Materials Engineering, 40126 Bologna, Italy
[2] Université de Rennes 1, CNRS, Géosciences Rennes UMR 6118, 35042 Rennes, France
[3] Università di Padova, Department of Mathematics, 35131 Padua, Italy

alessandro.lenci@unibo.it

Session: H35R. Non-linearity in Subsurface Flow and Transport: Modeling, Experiments, and Applications

1 FLOW OF SHEAR-THINNING FLUIDS IN GEOLOGICAL FRACTURES

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

- Typically, unconventional and deep geothermal reservoirs present both **low porosity** and **low permeability**
- Operations in gas shale or hot rock require **hydraulic stimulation** to enhance productivity and become cost effective

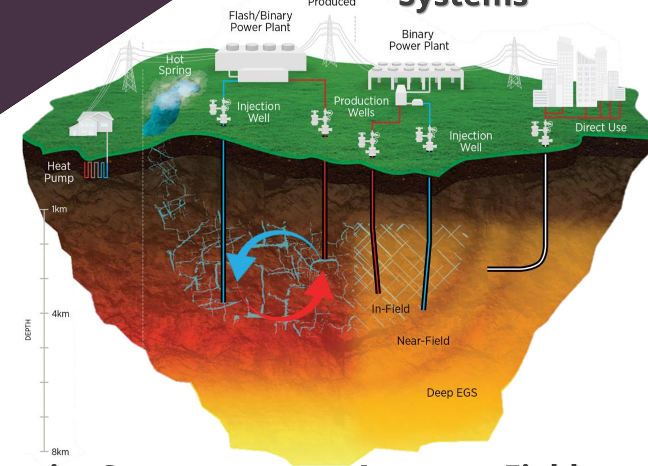
Fluids involved in subsurface industrial activities present a **shear-thinning behaviour** at **continuum scale**, due to their complex microstructure.

- muds
- foams
- water-based suspensions

Subsurface industrial activities:

- Enhanced Oil Recovery (EOL)
- Enhanced Geothermal Systems (EGS)
- Carbon sequestration

Enhanced Geothermal Systems

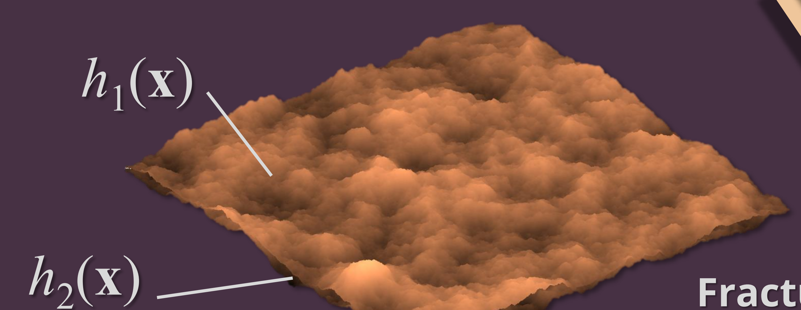


2 NUMERICAL MODELING

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 noise and introducing spatial correlations: multiplying the modulus of the Fourier transform by the modulus of the wave numbers $|k|=(k_{x_1}^2+k_{x_2}^2)^{1/2}$ to the power $-1-H$

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

Fracture Geometry

$\sigma_w/\langle w\rangle$	1.0
$\langle w\rangle$	10^{-3} m
H	0.8
L_c	0.1 m
L	0.4 m

2.2 Fluid Rheology: Ellis model

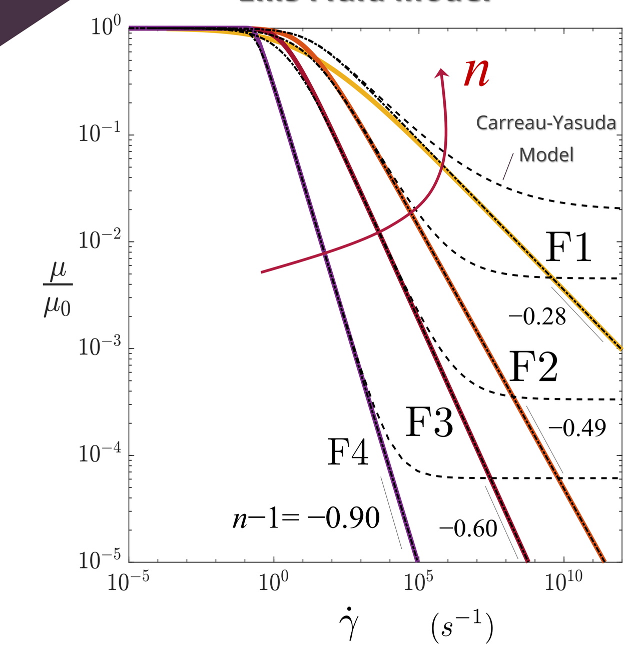
The Ellis rheology is a **three-parameter model**

$$\eta=\frac{\mu_0}{1+\left(\frac{\tau_{xz}}{\tau_{1/2}}\right)^{\frac{1}{n}-1}}$$

- μ_0 low-shear rate viscosity ($\eta\rightarrow\mu_0$ for $\dot\gamma\rightarrow0$)
- n shear-thinning index
- $\tau_{1/2}$ characteristic shear stress: $\eta(\tau_{1/2})=\mu_0/2$

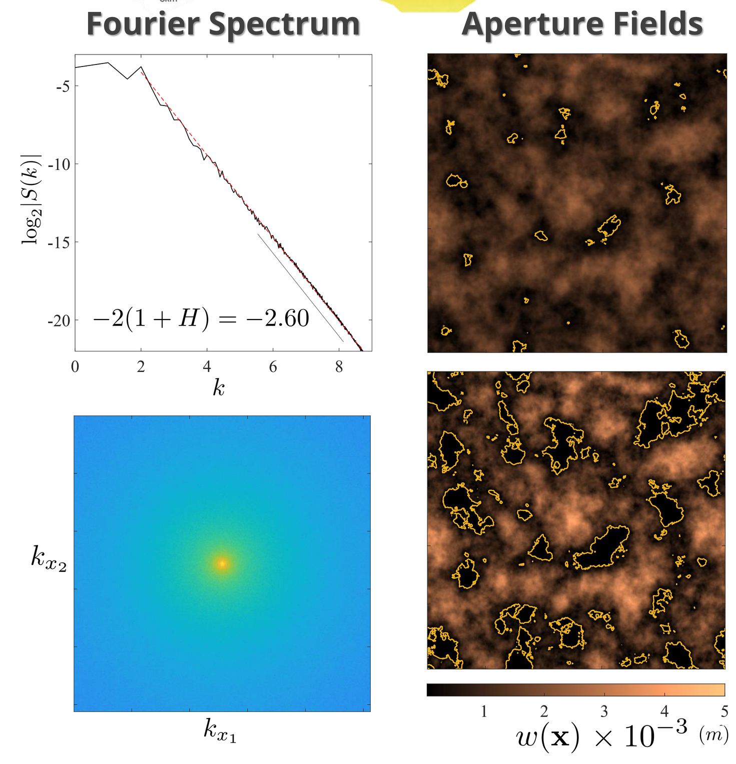
	Fluids	n (-)	μ_0 (Pa·s)	$\tau_{1/2}$ (Pa)
F1	CMC at 0.3 wt%	0.72	0.05	4.07
F2	CMC at 0.5 wt%	0.51	0.22	2.50
F3	CMC at 1.0 wt%	0.40	2.99	5.14
F4	VES	0.10	49.00	1.07

Ellis Fluid Model



Fourier Spectrum

Aperture Fields



2.3 Generalized Non-linear Reynolds Equation

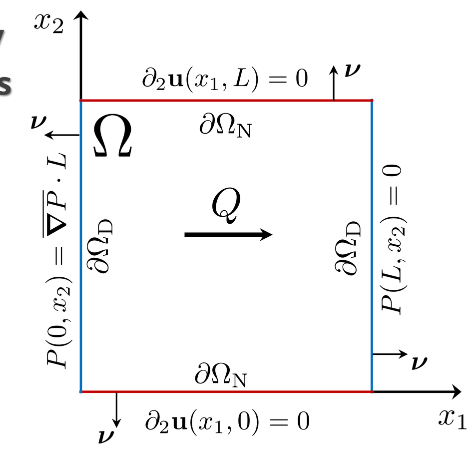
- **Lubrication theory** holds ($\nabla w\ll1$ and Re$\ll1$)

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

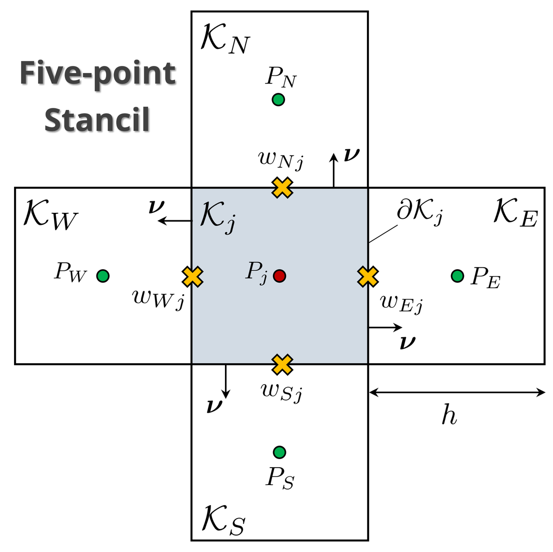
Numerical modeling via finite volume method:

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

Boundary Conditions

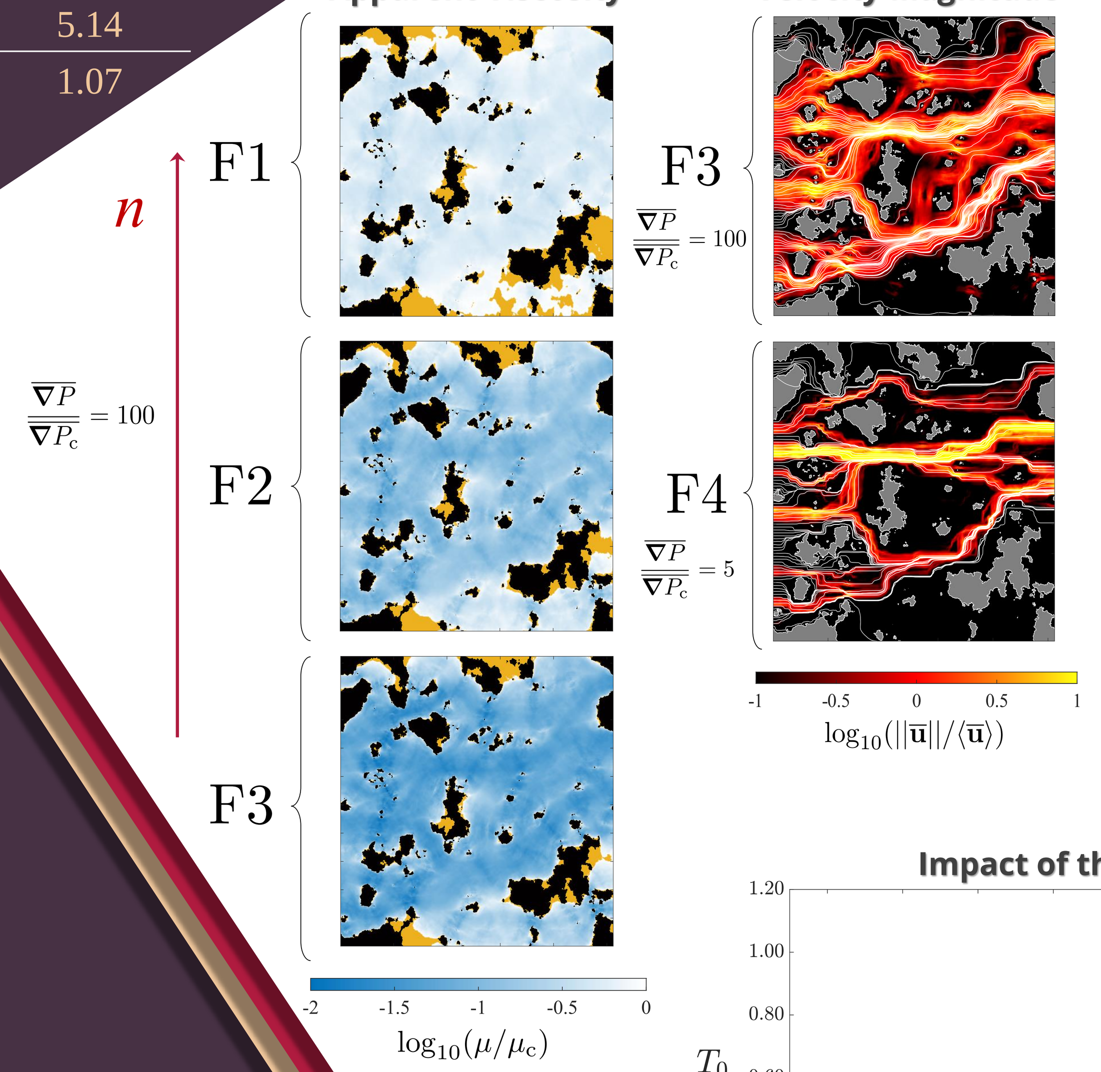


Five-point Stencil

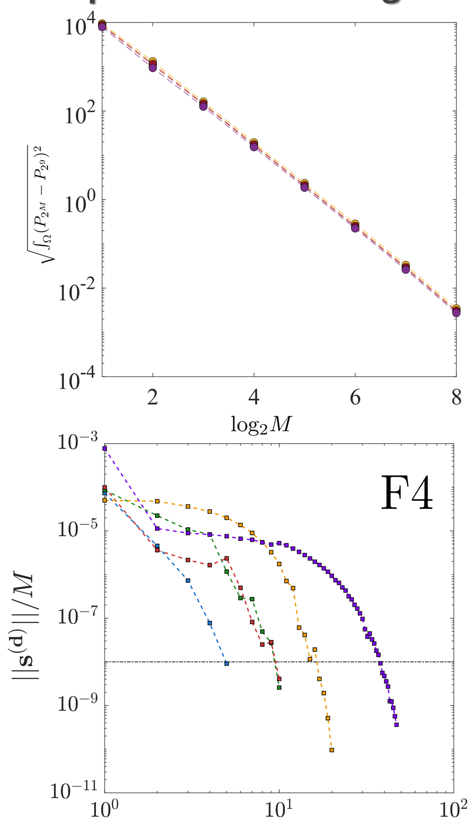


3 RESULTS

Apparent Viscosity · Velocity Magnitude



Experimental Convergence



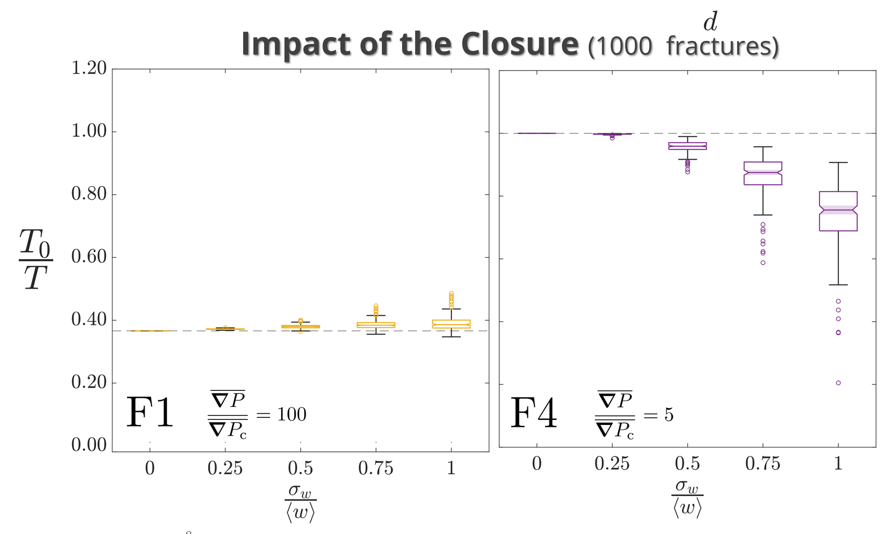
3.1 Experimental Convergence

- Starting from a 2x2 aperture field (level mesh 0), we estimate the error at different mesh levels. The **convergence of this sequence of errors** together with the **scheme consistency** implies the **convergence to the true solution** of the problem.
- The adopted strategy aims at **reducing the pre-asymptotic phase of the Newton method**, thus engaging efficient quadratic convergence as quickly as possible.

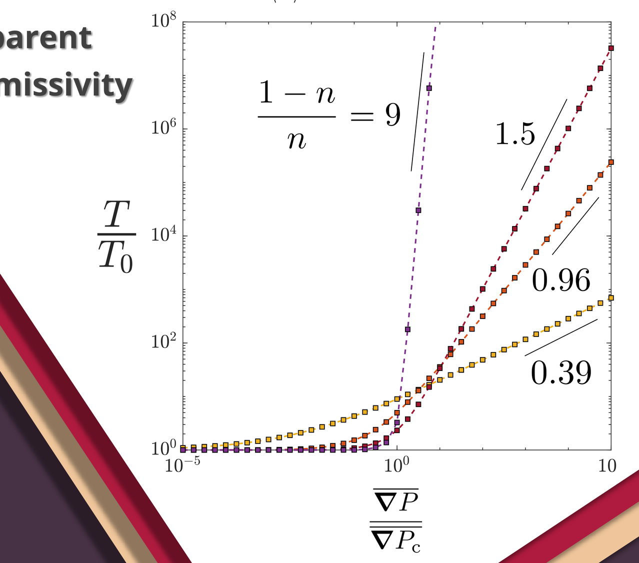
3.2 Impact of Rheology

- The fluid shear-thinning behaviour **promote flow localization**, with parts of the fractures characterized by high velocities (channels) and others where the flow is almost stagnant.
- **Flow mainly occurs in channels of low apparent viscosity and high velocity**, resulting from flow localization.
- **Shear-thinning behaviour reduces the impact of the closure**, increasing the apparent transmissivity.

Impact of the Closure (1000 fractures)



Apparent Transmissivity



4 CONCLUSIONS AND FUTURE PERSPECTIVES

4.1 Conclusions

- Transmissivity attenuation due to fracture closure is mitigated by the shear-thinning rheology.
- High $\overline{\nabla P}$ and low n increases shear-thinning behaviour, favouring flow localization
- The smaller the fracture length, the higher the dispersions of the velocities
- Shear-thinning behaviour enhances fracture transmissivity, leading to non-darcian flow regime for sufficiently high pressure gradients

4.2 Future Perspectives

- Comparison with full **3-D CFD simulations** to investigate the **limits of the lubrication approximation.**
- Implement a **transport solver** to study the **impact of the shear-thinning rheology on breakthrough curves.**

Méheust, Y., Schmittbuhl, J. (2000) Flow enhancement of rough fracture. *Geophys. Res. Lett.*, 27(18), 2989-2992. doi: 10.1029/1888gl100464

Lenci, A., Méheust, Y., Putti, M., Di Federico, V. (2021) Monte Carlo Simulations of Shear-thinning Flow in Geological Fractures, *Water Resour. Res.* (preprint)

GEOSCIENCES Rennes
Università degli Studi di Padova
Alma Mater Studiorum Università di Bologna