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HS8.1.6 - Fluid dynamics, solute transport and biogeochemical reactions in porous media – new advances towards mechanistic understanding

A simplified model to evaluate the effect of fluid rheology on non-Newtonian flow in variable aperture fractures

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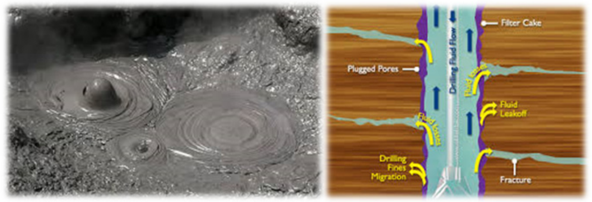
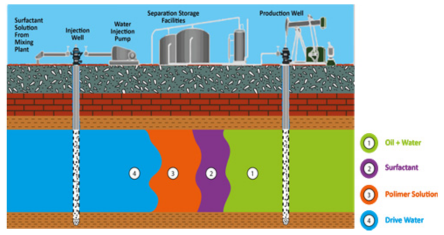
1. Applications in reservoir engineering of non Newtonian fluids

Modeling of non-Newtonian flow in fractured media is essential in hydraulic fracturing operations, largely used for optimal exploitation of oil, gas and thermal reservoirs. Complex fluids interact with pre-existing rock fractures also during drilling operations, enhanced oil recovery, environmental remediation, and other natural phenomena such as magma and sand intrusions, and mud volcanoes.



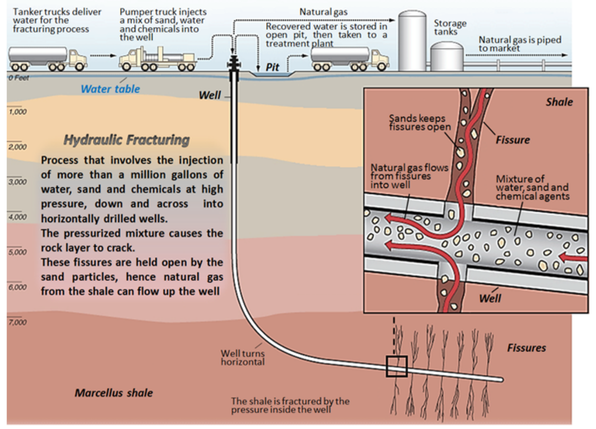
Mining Engineering: drilling muds (suspensions of solid particles), pollutants with complex rheology



Exploitation of oil/gas reservoirs: polymer solutions

Fracturing fluids

98% fresh water and sand, with chemical additives comprising 2% or less of the fluid.
Shear – thinning (pseudoplastic) fluid are usually adopted.



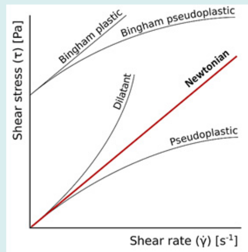
Hydraulic fracturing

Largely used for optimal exploitation of oil, gas and thermal reservoirs. It produces fractures in the rock formation that stimulate the flow of natural gas or oil, increasing the volumes that can be recovered. Fractures are created by pumping large quantities of fluids at high pressure down a wellbore and into the target rock formation.
Once the injection process is completed, the internal pressure of the rock formation causes fluid to return to the surface through the wellbore. This fluid is known as both "flowback" and "produced water" and may contain the injected chemicals plus naturally occurring materials such as brines, metals, radionuclides, and hydrocarbons.

A first step in the modeling effort is a detailed understanding of flow in a single fracture, as the fracture aperture is typically spatially variable. The equivalent flow aperture for non-Newtonian fluids of power-law nature in single, variable aperture fractures has been obtained in the past both for deterministic and stochastic variations.

2. Flow of truncated power – law fluid in fractures

Non – Newtonian fluids

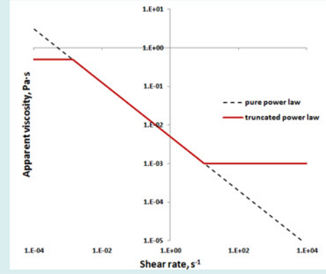


Non linear relationship between shear stress and shear rate

$$\tau = m\left|\dot{\gamma}\right|^{n-1}\dot{\gamma} = \mu_{app}\dot{\gamma} \quad \text{(Ostwald De Waele)}$$

m = consistency index [$ML^{-1}T^{n-2}$];
n = rheological index
- n < 1 pseudoplastic
- n = 1 Newtonian ($\mu_{app} \rightarrow \mu$)
- n > 1 dilatant

Rheological truncated power – law model



$$\mu_{app} = \begin{cases} \mu_0 & \text{if } \dot{\gamma} < \dot{\gamma}_1 \\ m\dot{\gamma}^{n-1} & \text{if } \dot{\gamma}_1 < \dot{\gamma} < \dot{\gamma}_2 \\ \mu_\infty & \text{if } \dot{\gamma} > \dot{\gamma}_2 \end{cases}$$

$$\dot{\gamma}_1 = \left(m/\mu_0\right)^{1/(1-n)}$$

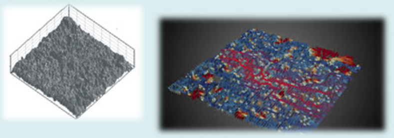
$$\dot{\gamma}_2 = \left(m/\mu_\infty\right)^{1/(1-n)}$$

A relevant issue in non-Newtonian fracture flow is the rheological nature of the fluid. The constitutive model routinely used for hydro-fracturing modeling is the simple, two-parameter power-law. Yet this model does not characterize real fluids at low and high shear rates, as it implies, for shear-thinning fluids, an apparent viscosity which becomes unbounded for zero shear rate and tends to zero for infinite shear rate. On the contrary, the four-parameter Carreau constitutive equation includes asymptotic values of the apparent viscosity at those limits; in turn, the Carreau rheological equation is well approximated by the more tractable truncated power-law model (Lavrov, 2015). Results for flow of such fluids between parallel walls are already available.

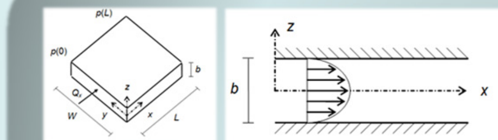
Flow in a variable aperture fracture

Real fractures

The fracture aperture (b) is usually taken to vary as a 2 - D, spatially homogeneous and correlated random field, with a **probability density function *f(b)*.**



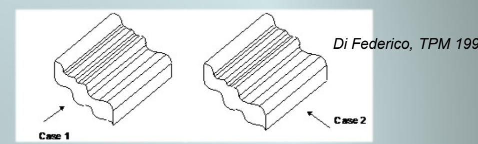
1) Parallel plates scheme



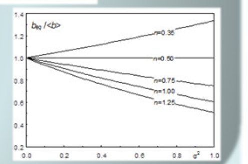
$$f(b) = \frac{1}{b\sigma\sqrt{2\pi}}\exp\left[-\frac{\left(\ln b - \ln b_g\right)^2}{2\sigma^2}\right]$$

b_g = <b> exp (- σ^2/2) = geometric mean
<b> = arithmetic mean, σ^2 = variance of lnb

2) Simplified model: geometric average of results from two 1 – D cases



Impact of rheological index and opening variability on equivalent aperture



3. Estimate of flowrate and discussion

- Aperture with spatial variability: case 1
- A lognormal distribution is adopted for the aperture field, with probability density function *f(b)*.
- The fracture model is discretized into *N* neighboring channels, each having equal width and constant aperture b_i (aperture). Depending on the local aperture value, three flow regimes are possible within the fracture (I = low shear rate regime, II = intermediate shear rate regime, and III = high shear rate regime).

Total flowrate in the *x* direction:

$$Q_x = \sum_{i=1}^{N_I} q_I(b_i)W_{Ii} + \sum_{i=1}^{N_{II}} q_{II}(b_i)W_{IIIi} + \sum_{i=1}^{N_{III}} q_{III}(b_i)W_{IIIi}$$

Factors P_j

$$P_I = \frac{1}{2}\left[1 + erf\left(\frac{1}{\sqrt{2}\sigma}\left(\ln\frac{b_1}{<b>} + \frac{\sigma^2}{2}\right)\right)\right];$$

$$P_{II} = \frac{1}{2}\left[erf\left(\frac{1}{\sqrt{2}\sigma}\left(\ln\frac{b_2}{<b>} + \frac{\sigma^2}{2}\right)\right) - erf\left(\frac{1}{\sqrt{2}\sigma}\left(\ln\frac{b_1}{<b>} + \frac{\sigma^2}{2}\right)\right)\right]$$

$$P_{III} = \frac{1}{2}\left[1 - erf\left(\frac{1}{\sqrt{2}\sigma}\left(\ln\frac{b_2}{<b>} + \frac{\sigma^2}{2}\right)\right)\right]$$

Factors I_j

$$I_I = \frac{<b>^3}{2}\exp\left(3\sigma^2\right)\left[1 + erf\left(\frac{1}{\sqrt{2}\sigma}\left(\ln\frac{b_1}{<b>} - \frac{5\sigma^2}{2}\right)\right)\right]$$

$$I_{II} = \frac{<b>^{(2n+1)/n}}{2}\exp\left(\frac{(2n+1)(n+1)}{2n^2}\sigma^2\right)\left[erf\left(\frac{1}{\sqrt{2}\sigma}\left(\ln\frac{b_2}{<b>} - \frac{(3n+2)\sigma^2}{2n}\right)\right) - erf\left(\frac{1}{\sqrt{2}\sigma}\left(\ln\frac{b_1}{<b>} - \frac{(3n+2)\sigma^2}{2n}\right)\right)\right]$$

$$I_{III} = \frac{<b>^3}{2}\exp\left(3\sigma^2\right)\left[1 - erf\left(\frac{1}{\sqrt{2}\sigma}\left(\ln\frac{b_2}{<b>} - \frac{5\sigma^2}{2}\right)\right)\right]$$

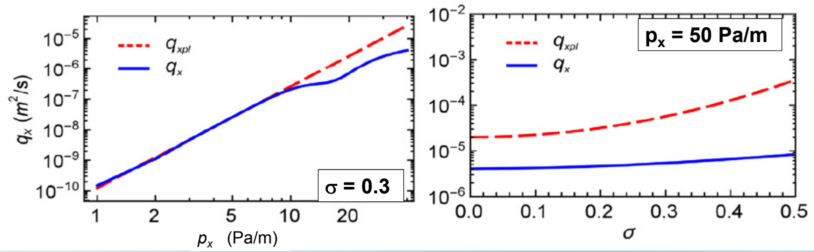
- The number of channels in each regime is N_I, N_{II}, N_{III}, respectively, and the total width of the channels in each regime is W_I, W_{II}, W_{III} ($N = N_I + N_{II} + N_{III}$, $W = W_I + W_{II} + W_{III}$)
- The i-th channel in each regime j (j = 1,2,3) has width $W_{ji} = W_j/N_j$.

$$\mathbf{N_j \rightarrow \infty}: \quad q_x = \frac{Q_x}{W} = P_I I_I \frac{p_x}{12\mu_0} + P_{II}\left[P_{II}\frac{2(1-n)m^{3/(1-n)}}{3(2n+1)\mu_0^{(2n+1)/(1-n)}p_x^2} + \frac{n}{2n+1}I_{II}\left(\frac{p_x}{2^{n+1}m}\right)^{1/n}\right] +$$

$$+ P_{III}\left[I_{III}\frac{p_x}{12\mu_\infty} - P_{III}\frac{2(1-n)m^{3/(1-n)}}{3(2n+1)p_x^2}\left(\frac{1}{\mu_\infty^{(2n+1)/(1-n)}} - \frac{1}{\mu_0^{(2n+1)/(1-n)}}\right)\right]$$

The expression of the flowrate q_x is compared with that of a pure power-law (*pl*) fluid of parameters *m* and *n*:

$$q_{xpl} = \frac{n}{2n+1}\left(\frac{p_x}{2^{n+1}m}\right)^{1/n} <b>^{(2n+1)/n}\exp\left(\frac{(2n+1)(n+1)\sigma^2}{2n^2}\right) \quad \mathbf{2}$$

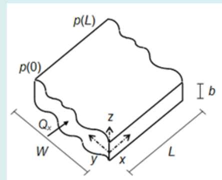


Adoption of the pure power law model leads to a significant overestimation of the flowrate with respect to the more realistic truncated rheological model

The nonlinear rheological behaviour and the aperture spatial variability jointly have a significant impact on flow rates and spatial distribution (channeling effects); this in turn influences reactive transport (adsorption) and chemical reactions.

Case 1

flow parallel to constant aperture channels, i.e. transverse to aperture variation



The pressure gradient is transverse to the aperture variability

$$p_x = \left(p(0) - p(L)\right)/L$$

The fracture model is discretized into *N* neighboring channels, each having equal width and constant aperture b_i

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