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Non-Newtonian fluids through porous media: micro- and macro-scale properties of power-law fluids

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October 13, 2015

Non-Newtonian
fluids through
porous media

F. Pierre

Introduction

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Rheology
Porous media
Permeability
prediction

Numerical Study

Numerical set up
Numerical results

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- Permeability prediction

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Introduction: How do non-Newtonian effects impact porous media flows ?

The physic is complex,

- ▶ non-linearities,
- ▶ memory effects,
- ▶ adsorption...

Porous media flow is also complex,

- ▶ multi-scale,
- ▶ confinement effects...

Polymer flows in EOR,

- ▶ increase viscosities,
- ▶ reduce instabilities.

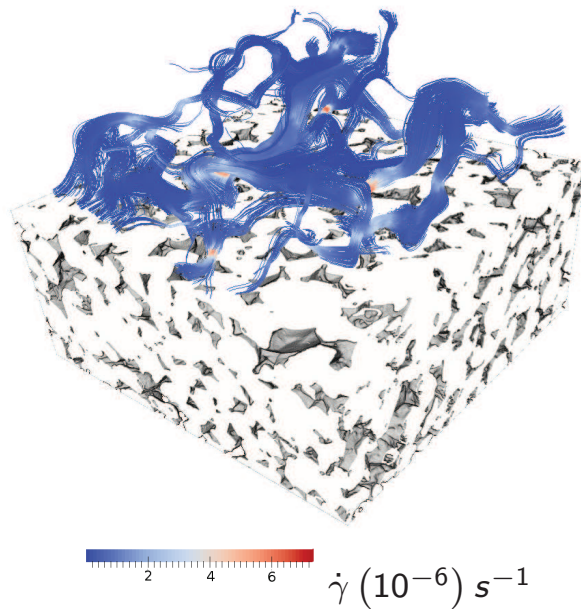


Fig: Power-law fluid flowing through a Bentheimer sandstone

Context

$$\mu = \mu_0 \Rightarrow \langle U \rangle = -\frac{K \cdot \nabla p}{\mu_0} \Rightarrow \langle U \rangle \propto \|\Delta p\| \Rightarrow \textcircled{1}$$

$$\mu = \mu_0 \dot{\gamma}^{n-1} \Rightarrow \langle U \rangle = -\frac{K(\|\langle U \rangle\|) \cdot \nabla p}{\mu_0} \Rightarrow \langle U \rangle \propto \|\Delta p\|^{1/n} \Rightarrow \textcircled{2}$$

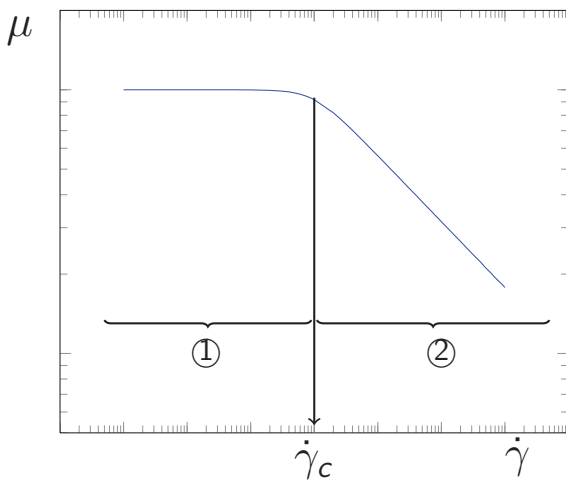


Fig: Non-Newtonian rheology

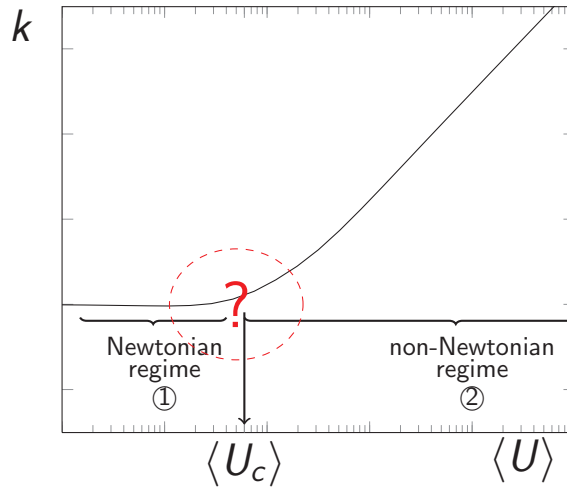


Fig: k versus $\langle U \rangle$

Refs: Auriault et al. 2002; Getachew et al. 1998; Lecourtier et al. 1984; Seright et al. 2011; Sorbie et al. 1991; Zitha et al. 1995

Context

- ▶ Literature: $\dot{\gamma}_{eq} = \alpha \frac{4(\langle U \rangle / \phi)}{\sqrt{8k/\phi}}$, Chauveteau 1982.
Two misunderstood parameters;
 - ▶ $R_{eq} = \sqrt{8k/\phi}$, comes from analogy with a single pipe. Is it still valid in complex multi-scale porous media?
 - ▶ α : fitting parameter coming from core-flood experiments. Many hidden physical phenomena (adsorption, time-dependant effects, mass transport)...
- ▶ Our Goal: Model only the simplest phenomenon (using plateau + power-law fluid). Can we predict and understand the transition, $\langle U_c \rangle$?

Rheology

- ▶ Time-independent fluids, no yield stress. Common models are,

- ▶ plateau + power-law,

$$\mu = \begin{cases} \mu_0 & \text{if } \dot{\gamma} < \dot{\gamma}_c, \\ \mu_0 \left(\frac{\dot{\gamma}}{\dot{\gamma}_c}\right)^{n-1} & \text{else,} \end{cases} \quad (1)$$

- ▶ Carreau,
- ▶ generalized Newtonian.

- ▶ Choice of plateau + power-law (and tried others).
- ▶ This leads at a macro scale to,

$$\langle U \rangle \propto \begin{cases} \|\Delta p\| \\ \|\Delta p\|^{1/n} \end{cases} \quad (2)$$

Refs: Bird et al. 1968; Collyer 1973; Savins 1969

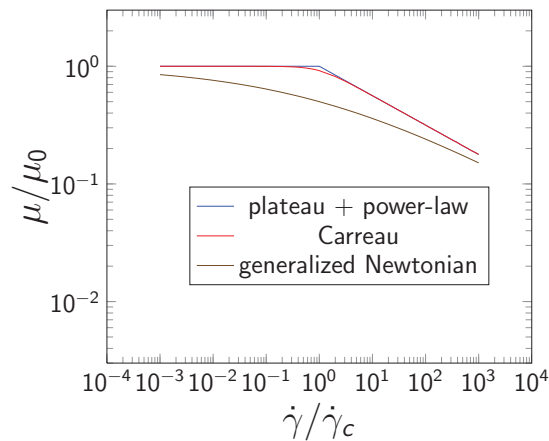










Fig: A few rheological model

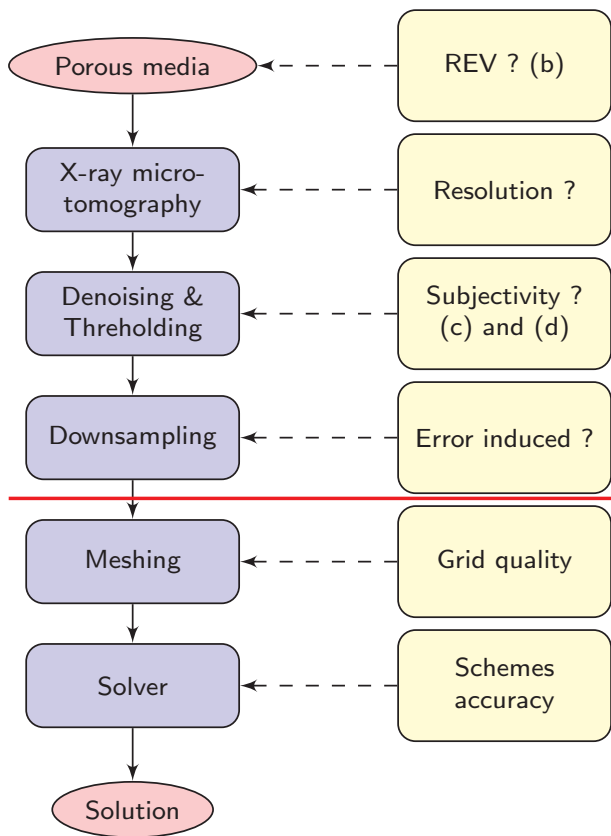
Porous Media

Keywords: wide panel, isotopic, pore size distribution (PSD).

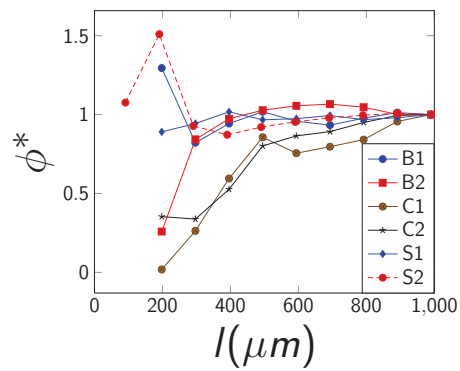
	1		2	
2D Array name : A		$\phi = 0.72$ $k_0 = 1.1 \cdot 10^4$		$\phi = 0.75$ $k_0 = 1.3 \cdot 10^4$
3D Packing name : P		$\phi = 0.35$ $k_0 = 33$		$\phi = 0.44$ $k_0 = 46$
3D Bentheimer name : B		$\phi = 0.18$ $k_0 = 1.92$		$\phi = 0.17$ $k_0 = 0.82$
3D Clashach name : C		$\phi = 0.13$ $k_0 = 0.27$		$\phi = 0.14$ $k_0 = 0.48$

Tab: Porous medium investigated (k_0 in Darcy unit, ■ for liquid)

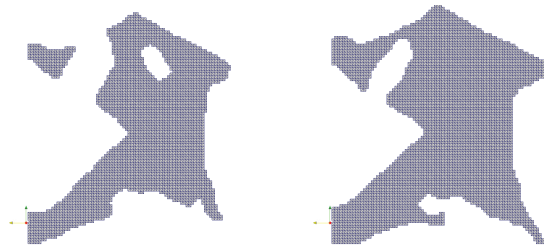
Permeability prediction



(a) Workflow



(b) ϕ^* versus cube length



(c) Thresholding 1 (d) Thresholding 2

Fig: Permeability prediction issues

Numerical set up

- ▶ Equations: $0 = -\nabla p + \nabla \cdot [\nu(\dot{\gamma})(\nabla \mathbf{U} + \nabla \mathbf{U}^T)], \nabla \cdot \mathbf{U} = 0$.
- ▶ FVM with OpenFOAM, 2nd order schemes.
- ▶ Permeameter, no-slip conditions.
- ▶ Grid convergence study, 80 millions meshes, 10⁵ hours of CPU time, use of HPC.

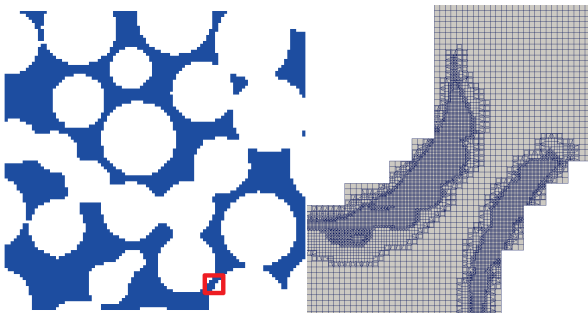


Fig: P1 grid

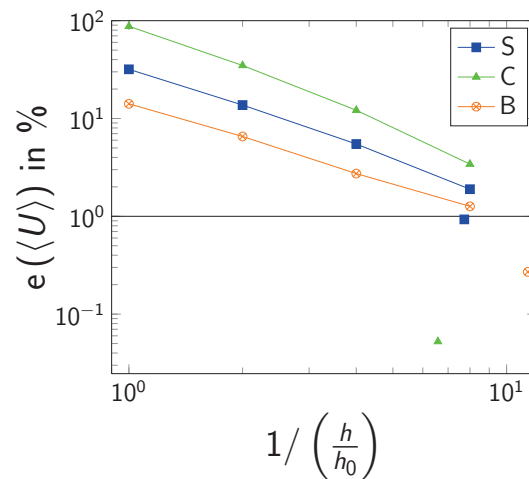


Fig: Grid convergence study

Numerical results - Two regimes

- Relevant dimensionless non-Newtonian number, $\mathcal{U}^* = \frac{\langle U \rangle}{\langle U_c \rangle}$.

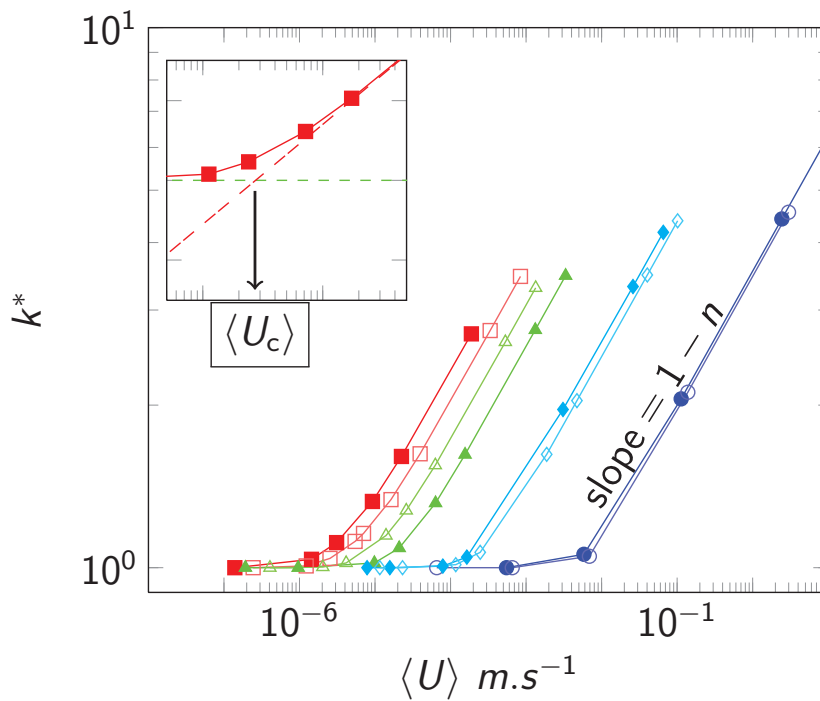


Fig: Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$. Rheology: $n = 0.75$ and $\dot{\gamma}_{lim} = 1s^{-1}$.
Medium: ● A1, ○ A2, ▲ B1, △ B2, ■ C1, □ C2, ◆ P1, ◇ P2

Numerical results - Varying n

Varying n : $k \propto \|\langle U \rangle\|^{1-n}$ is equivalent to $\langle U \rangle \propto \|\Delta p\|^{1/n}$.

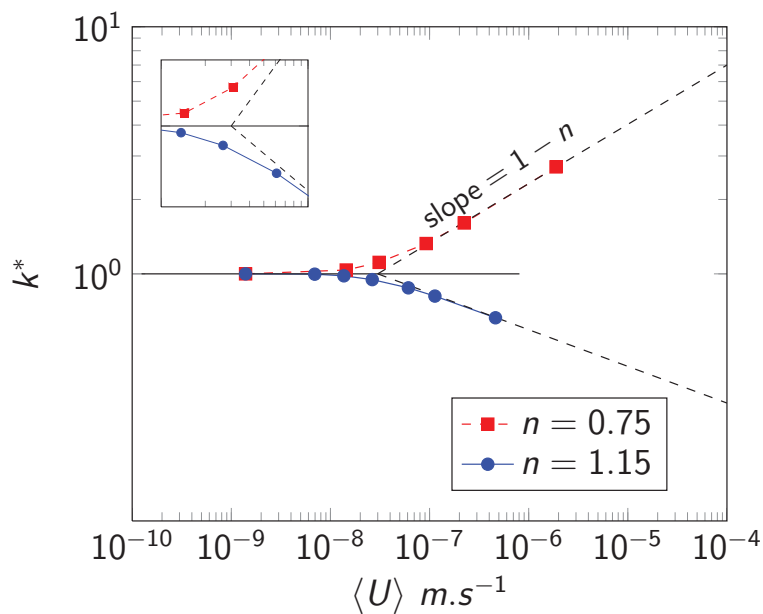


Fig: Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$ for the C1 case. Rheological parameters : fixing $\dot{\gamma}_c$ and varying n .

Numerical results - Varying $\dot{\gamma}_c$

Varying $\dot{\gamma}_c$: $\langle U_c \rangle \propto \dot{\gamma}_c$. This leads to, $\langle U_c \rangle = \phi \times \dot{\gamma}_c \ell_{eff}$.

- ▶ Rheology: embedded in $\dot{\gamma}_c$.
- ▶ Topology: embedded in ℓ_{eff} .
- ▶ Use of ϕ .

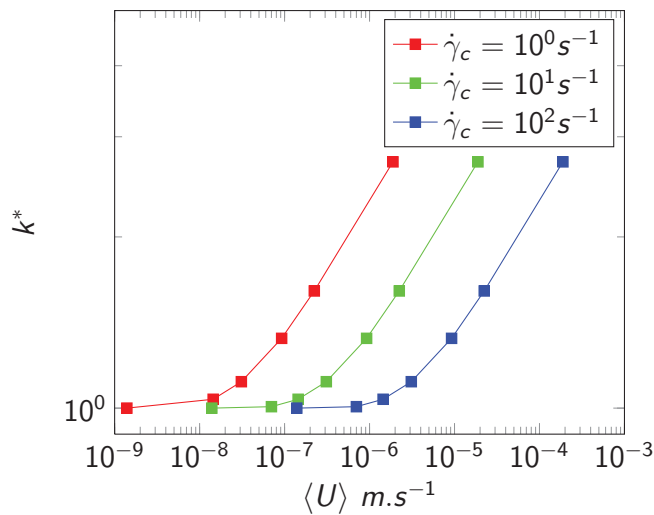


Fig: Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$ for the C1 case. Rheological parameters : fixing n and varying $\dot{\gamma}_c$.

Numerical results - Microscopic Phenomenology

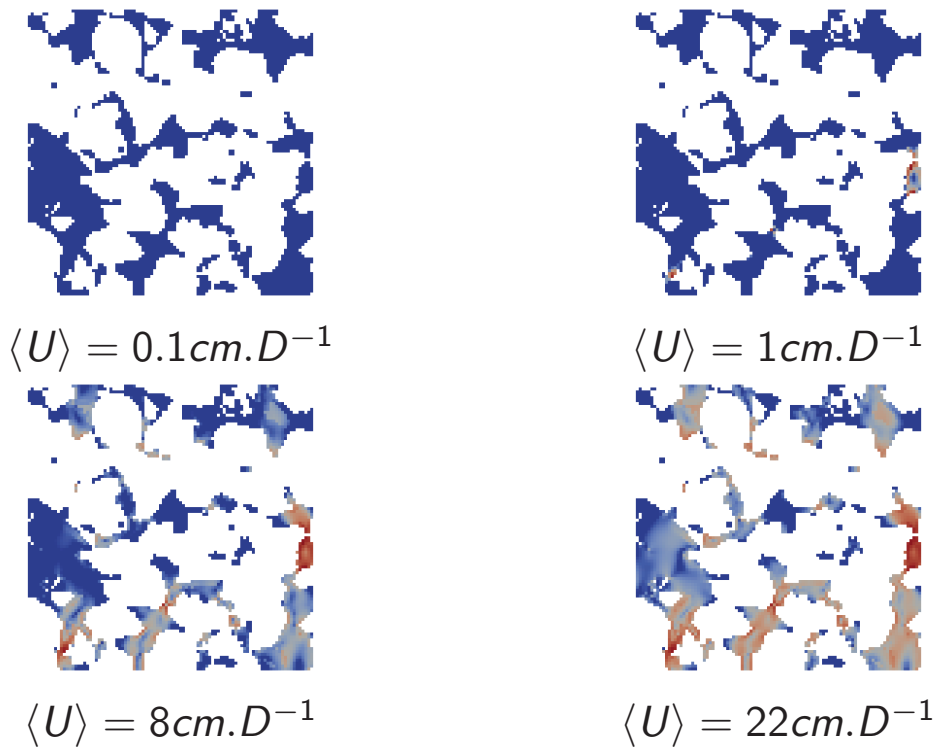


Fig: Viscosity fields at different $\langle U \rangle$ for C1 case.

The non-Newtonian phenomena start in the pore throats and then extend in the larger pore (lower shear rate).

Numerical results - Microscopic Phenomenology

- Identify a critical pore throat volume with PDF.

Media	k_0	ϕ	ϕ_{PT}
A1	$1.1 \cdot 10^4$	0.72	0.175
A2	$1.3 \cdot 10^4$	0.75	0.252
P1	33	0.35	0.085
P2	46	0.44	0.10
B1	1.92	0.18	0.025
B2	0.82	0.17	0.022
C1	0.27	0.13	0.010
C2	0.48	0.14	0.014

Tab: Medium description (k_0 in Darcy unit)

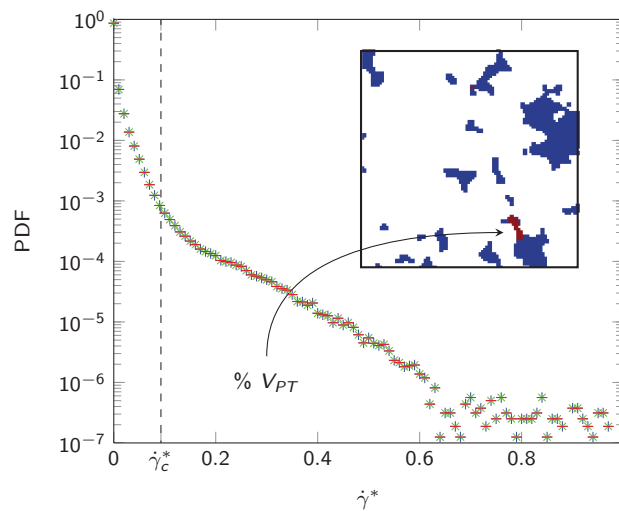


Fig: PDF of $\hat{\gamma}^*$ at $\mathcal{U}^* = 1$ for media C1.
 Legend : + for $\dot{\gamma}_c = 10^0 s^{-1}$, x for $\dot{\gamma}_c = 10^1 s^{-1}$,
 - for $\dot{\gamma}_c = 10^2 s^{-1}$

Transition's model

- ▶ Our goal: predict $\langle U_c \rangle = \phi \times \dot{\gamma}_c \ell_{eff}$.
- ▶ Equivalent to: predict ℓ_{eff} .
- ▶ Validation by comparison between the model and $\langle U_c \rangle$ calculation (cross-over method).

Model for ℓ_{eff} :

- ▶ Use of $\sqrt{k_0}$. For Newtonian fluids, $\sqrt{k_0}$ is a pure topological parameter (even if PDE are needed). We have tried: $\sqrt{8k_0/\phi}$, $\sqrt{32k_0/\phi}$, $\sqrt{k_0/\phi}$, $\sqrt{k_0}$.
- ▶ Use of Kozeny-Carman formulation and equivalent diameter, Kozeny 1927; Plessis et al. 1994; Sadowski 1963.
- ▶ Use of volume or surface of the medium (V_{part} , V_{medium} , S_{part}), Li et al. 2011; Ozahi et al. 2008.

Best results using simply $\ell_{eff} = \sqrt{k_0}$. Leading to:

$$\langle U_c \rangle = \phi \dot{\gamma}_c \sqrt{k_0}. \quad (3)$$

Transition's model

Is $l_{eff} = \sqrt{k_0}$ so surprising?

$$\dot{\gamma}_{eq} = \alpha \frac{4(\langle U \rangle / \phi)}{\sqrt{8k_0 / \phi}} \iff \langle U_c \rangle = \frac{1}{\sqrt{2\phi\alpha}} \times \phi \dot{\gamma}_c \sqrt{k_0} \quad (4)$$

This would mean that without complex physical phenomena, $l_{eff} = \sqrt{k_0}$ is a good estimation for the l_{eff} .

Reference	Medium	$\frac{1}{\sqrt{2\phi\alpha}}$
Lecourtier et al. 1984	P1	0.71
Chauveteau 1982	P1	0.87
Chauveteau 1982	C	0.52
Fletcher et al. 1991	C	0.46

Tab: Comparison with data found in literature

Full model

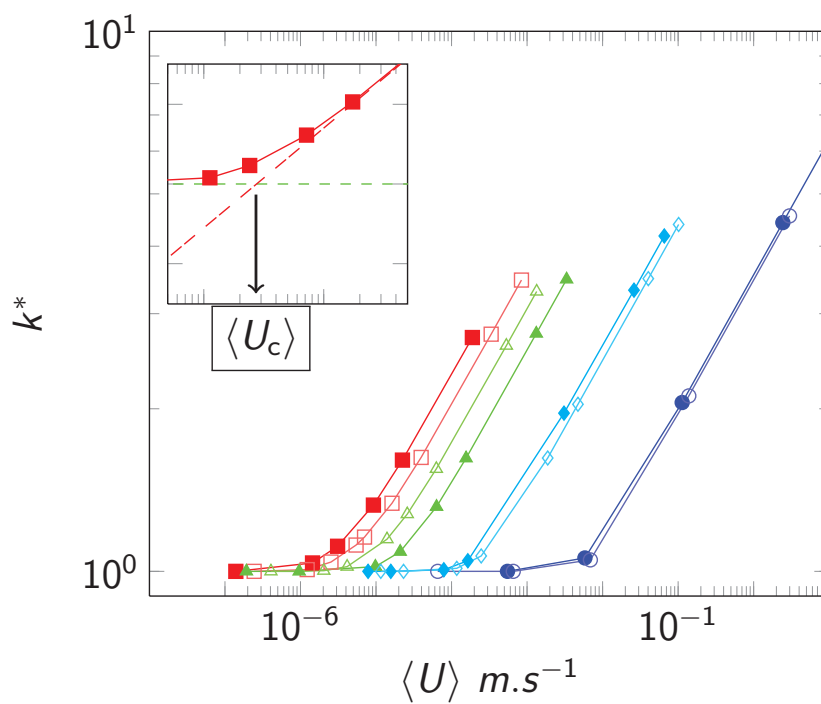


Fig: Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$. Rheology: $n = 0.75$ and $\dot{\gamma}_{lim} = 1s^{-1}$.
Medium: —●— A1, —○— A2, —▲— B1, —△— B2, —■— C1, —□— C2, —◆— P1, —◇— P2

Full model

- ▶ Relevant dimensionless non-Newtonian number, $\mathcal{U}^* = \frac{\langle U \rangle}{\langle U_c \rangle} = \frac{\langle U \rangle}{\phi \times \dot{\gamma}_c \sqrt{k_0}}$

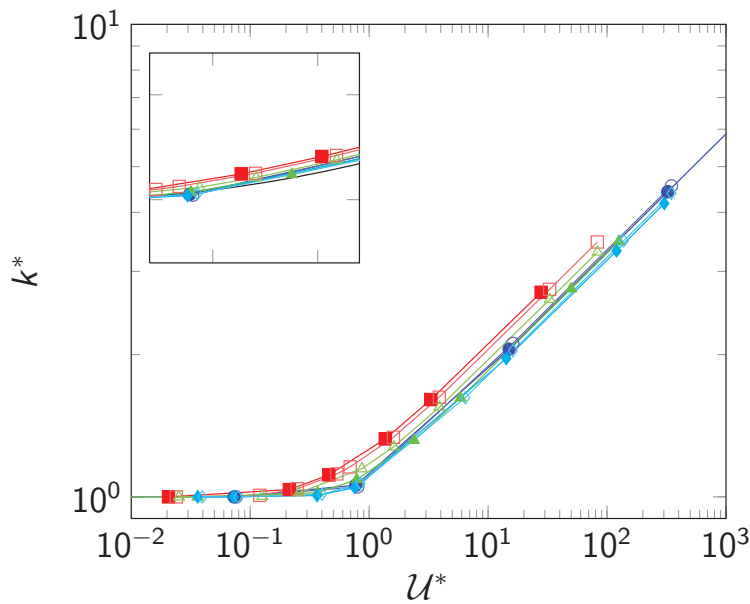


Fig: k^* versus \mathcal{U}^* . —●— A1, —○— A2, —▲— B1, —△— B2, —■— C1, —□— C2, —◆— P1, —◇— P2

Conclusions & Applications

- ▶ Studying cut-off phenomena due to non-Newtonian fluid through porous media.
- ▶ Model the transition using rheological and topological parameters, $\dot{\gamma}_c$ and ℓ_{eff} .
- ▶ Definition of a dimensionless non-Newtonian number \mathcal{U}^* , which characterizes the regime.

Potential applications,

- ▶ use in core-flood experiments,
- ▶ estimation of critical distances characterizing the regime transition in petroleum and environmental engineering.

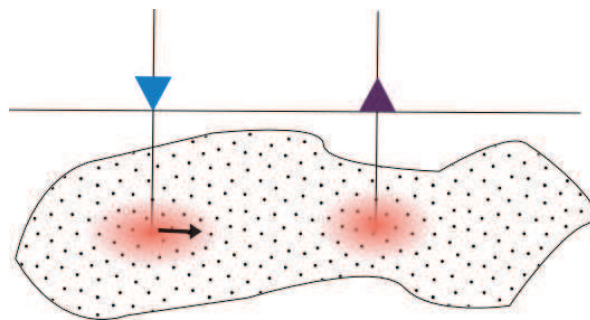


Fig: $\langle U_c \rangle \iff R_c = 50m$

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This work was performed using HPC resources from CALMIP (Grant 2015-11).

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Thanks you for your attention. Any question is welcomed :)