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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

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Context

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Porous media  
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# Overview

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- Permeability prediction

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## Modelling macro-scale the phenomena

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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.

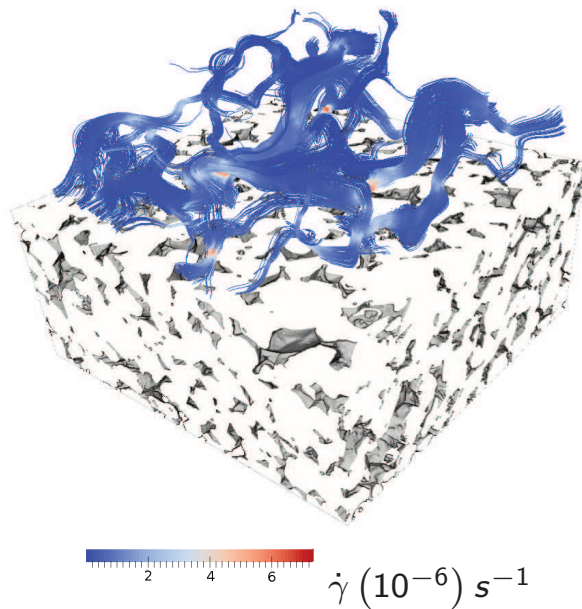


Fig: Power-law fluid flowing through a Bentheimer sandtone

# Context

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

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

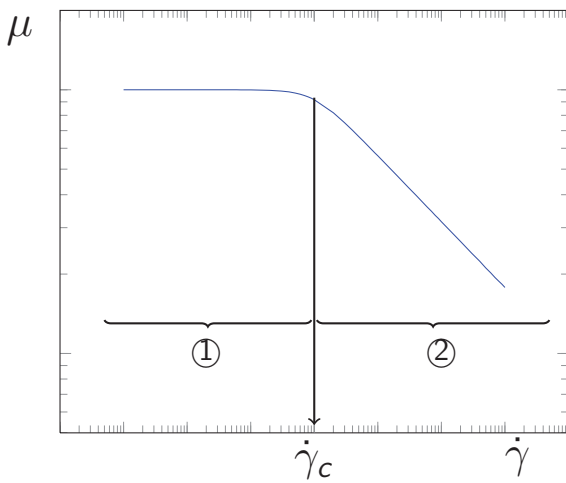


Fig: Non-Newtonian rheology

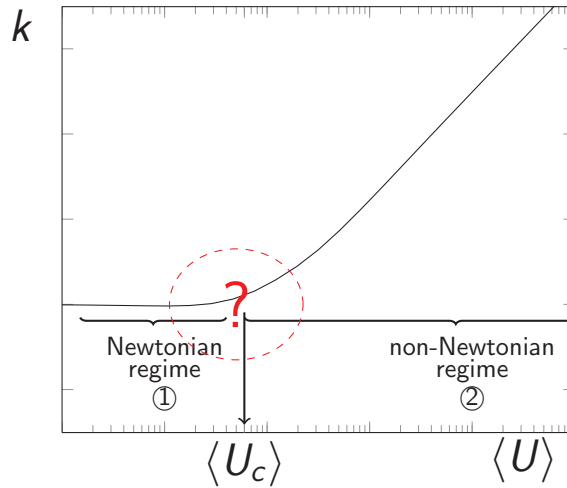


Fig:  $k$  versus  $\langle U \rangle$

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?
  - ▶  $\alpha$ : 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

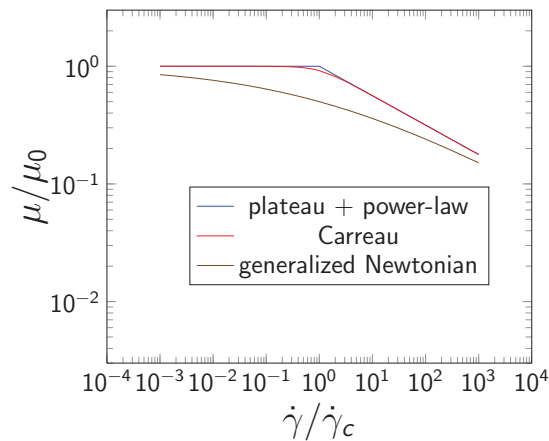










Fig: A few rheological model



# 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)

Non-Newtonian fluids through porous media

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Porous media  
Permeability prediction

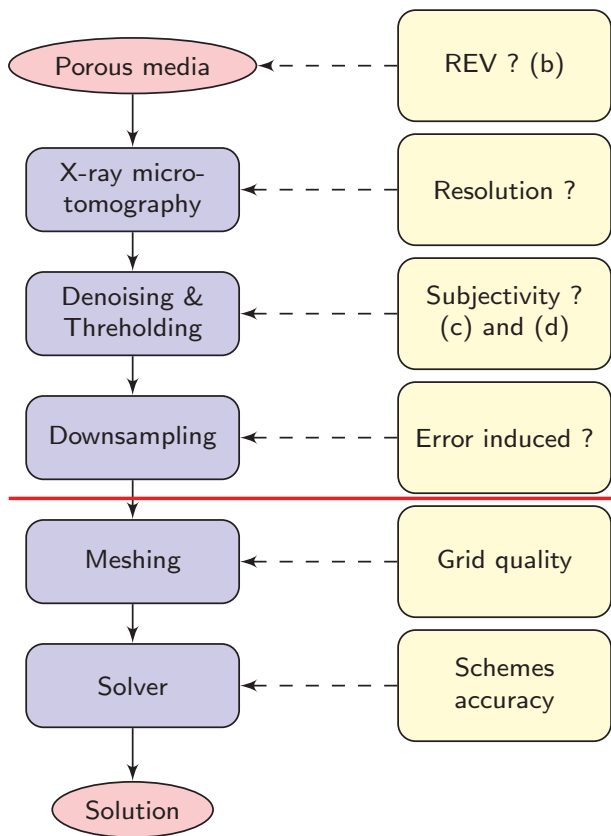
Numerical Study

Numerical set up  
Numerical results

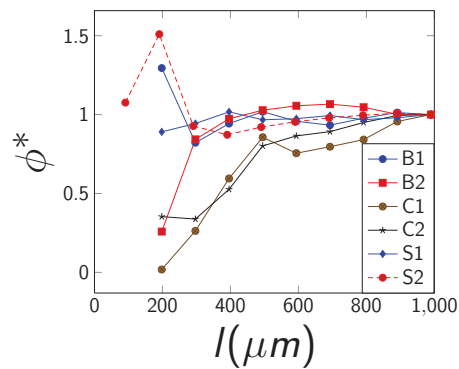
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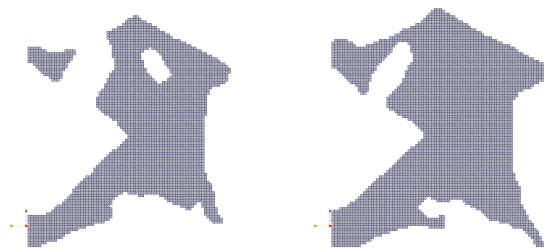
# Permeability prediction



(a) Workflow



(b)  $\phi^*$  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, 2<sup>nd</sup> order schemes.
- ▶ Permeameter, no-slip conditions.
- ▶ Grid convergence study, 80 millions meshes, 10<sup>5</sup> hours of CPU time, use of HPC.

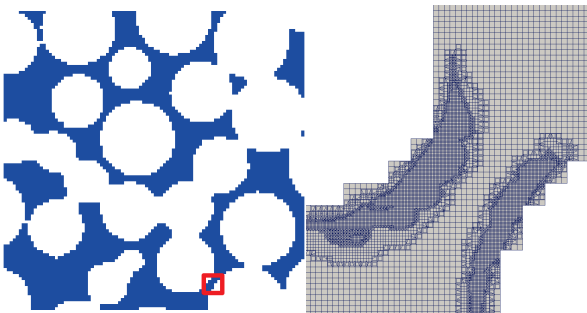


Fig: P1 grid

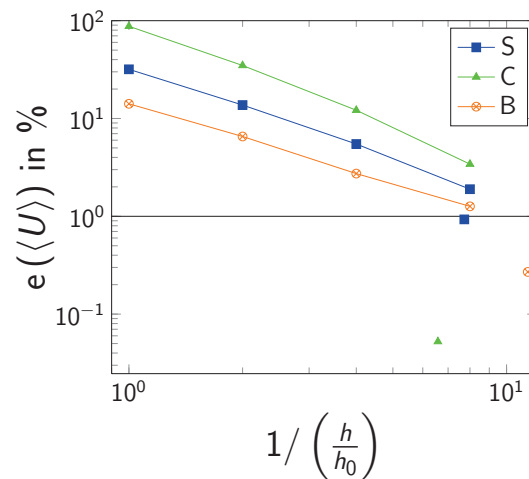
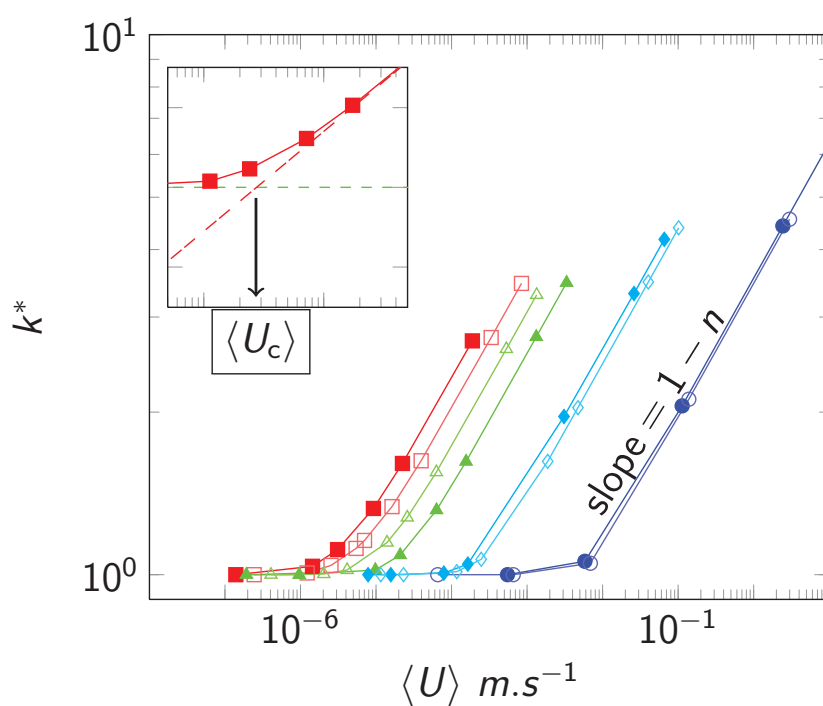


Fig: Grid convergence study

## Numerical results - Two regimes

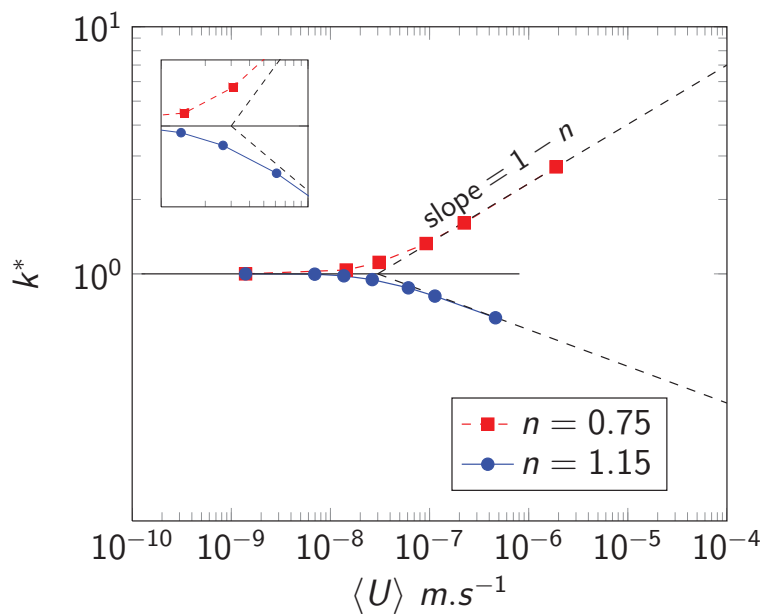
- Relevant dimensionless non-Newtonian number,  $\mathcal{U}^* = \frac{\langle U \rangle}{\langle U_c \rangle}$ .



**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  $\ell_{eff}$ .
- ▶ Use of  $\phi$ .

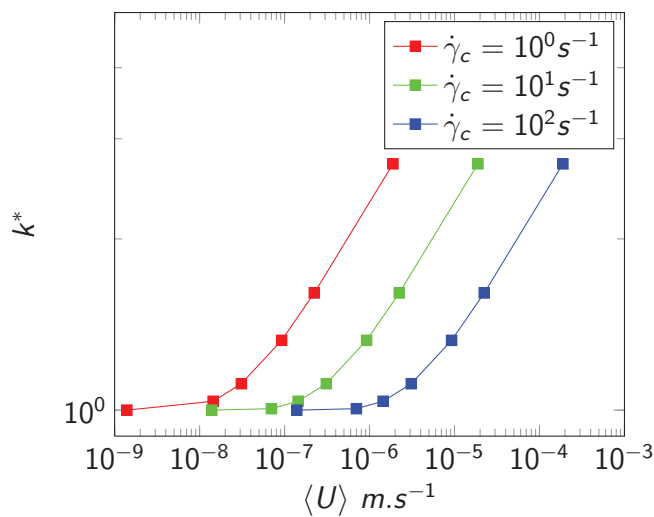


Fig: Dimensionless permeability  $k^* = k/k_0$  versus  $\langle U \rangle$  for the C1 case. Rheological parameters : fixing  $n$  and varying  $\dot{\gamma}_c$ .

## Numerical results - Microscopic Phenomenology

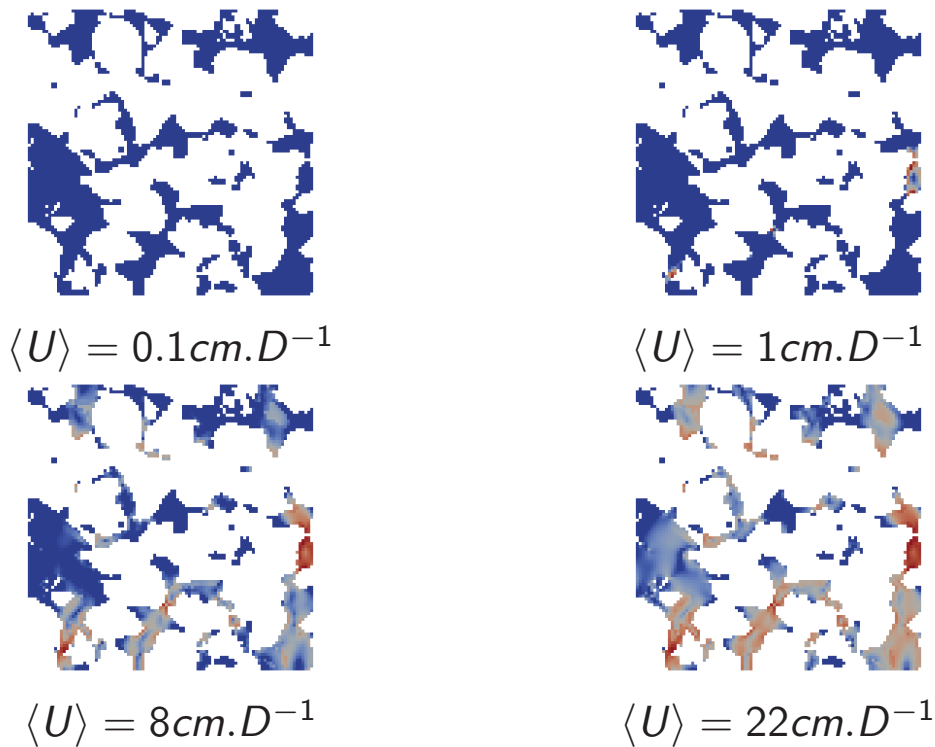


Fig: Viscosity fields at different  $\langle U \rangle$  for C1 case.

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	$k_0$	$\phi$	$\phi_{PT}$
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)

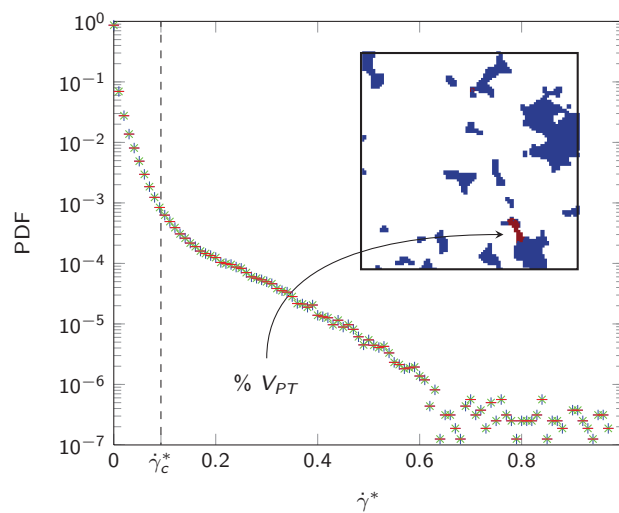


Fig: PDF of  $\hat{\gamma}^*$  at  $\mathcal{U}^* = 1$  for media C1.  
 Legend : + for  $\dot{\gamma}_c = 10^0 s^{-1}$ , x for  $\dot{\gamma}_c = 10^1 s^{-1}$ ,  
 - for  $\dot{\gamma}_c = 10^2 s^{-1}$



## Transition's model

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

Model for  $\ell_{eff}$  :

- ▶ 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?

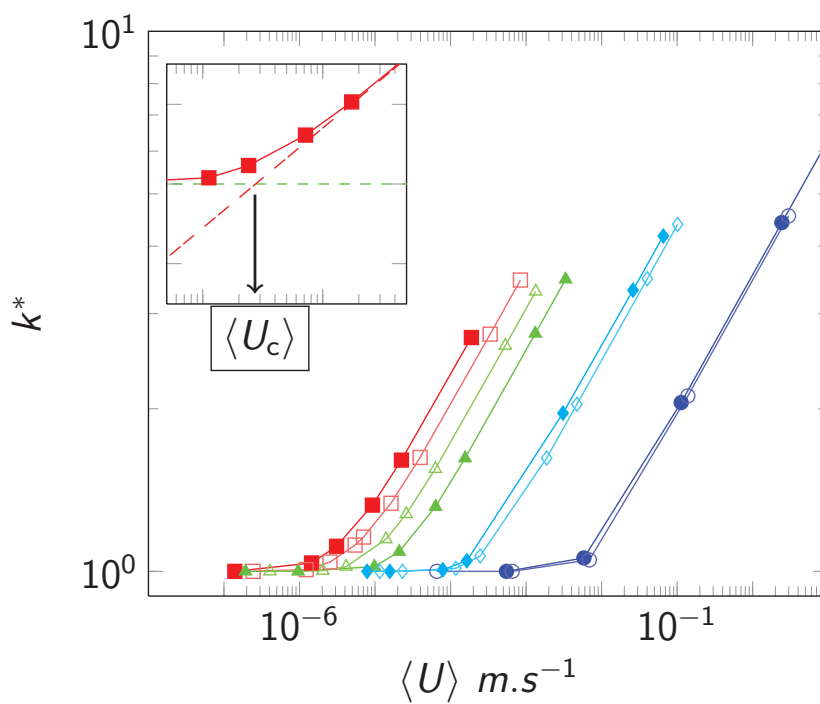
$$\dot{\gamma}_{eq} = \alpha \frac{4(\langle U \rangle / \phi)}{\sqrt{8k_0 / \phi}} \iff \langle U_c \rangle = \frac{1}{\sqrt{2\phi\alpha}} \times \phi \dot{\gamma}_c \sqrt{k_0} \quad (4)$$

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,  $\mathcal{U}^* = \frac{\langle U \rangle}{\langle U_c \rangle} = \frac{\langle U \rangle}{\phi \times \dot{\gamma}_c \sqrt{k_0}}$

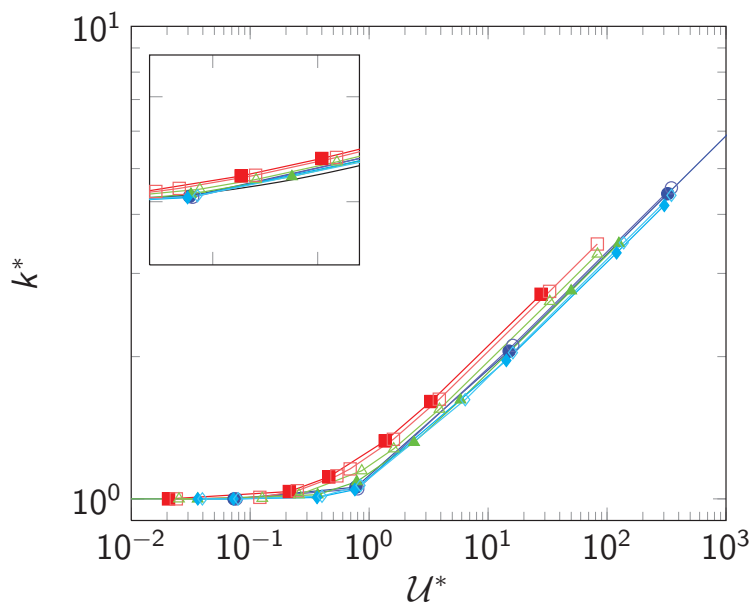


Fig:  $k^*$  versus  $\mathcal{U}^*$ . ● A1, ○ A2, ▲ B1, △ B2, ■ C1, □ C2, ◆ P1, ◇ P2

## 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  $\ell_{eff}$ .
- ▶ 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.

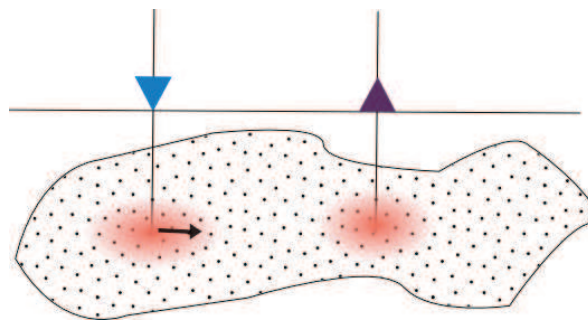


Fig:  $\langle U_c \rangle \iff R_c = 50m$

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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 :)