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Macroscopic regime transition of a non-Newtonian fluid through porous media

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► **To cite this version:**

Frédéric Zami-Pierre, Yohan Davit, Romain De Loubens, Michel Quintard. Macroscopic regime transition of a non-Newtonian fluid through porous media. 6th International Conference on Approximation Methods and Numerical Modelling in Environment and Natural Resources, Jun 2015, Pau, France, France. hal-04444196

HAL Id: hal-04444196

<https://hal.science/hal-04444196>

Submitted on 7 Feb 2024

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To cite this version : Pierre, Frédéric and Davit, Yohan and Loubens, Romain de and Quintard, Michel *Macroscopic regime transition of a non-Newtonian fluid through porous media*. (2015) In: MAMERN'15 : The 6th International Conference on Approximation Methods and Numerical Modelling in Environment and Natural Resources, 1 June 2015 - 5 June 2015 (Pau, France). (Unpublished)

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Non-Newtonian fluids through porous media

F. Pierre

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Macroscopic regime transition of a non-Newtonian fluid through porous media

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Jun 1, 2015

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Introduction

Many applications fields,

- ▶ composites or paper manufacturing,
- ▶ blood flow,
- ▶ polymer injection,
- ▶ and others.

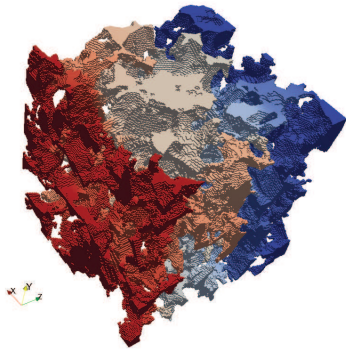


Fig : Pressure field in Clashach sandstone

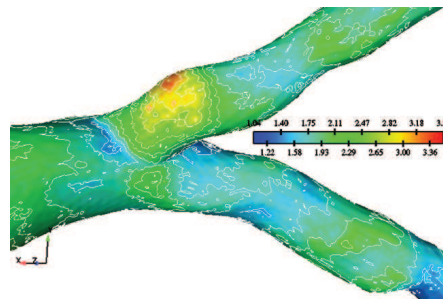


Fig : Soulis2008, blood flow through an arterial tree

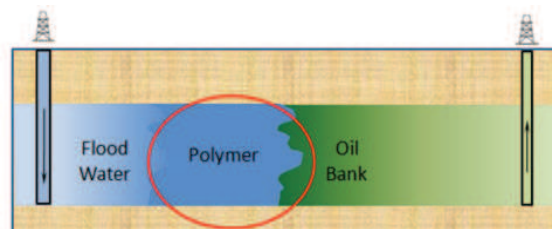


Fig : Use of polymer in EOR

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

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

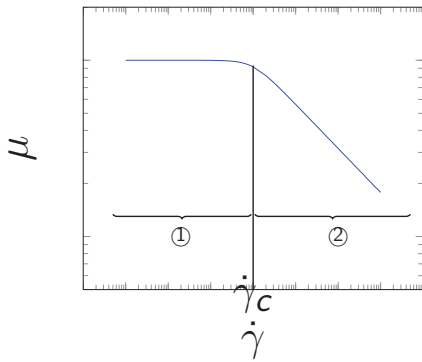


Fig : Non-Newtonian rheology

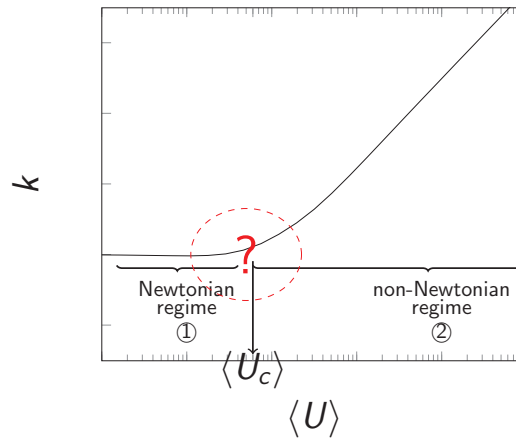


Fig : k versus $\langle U \rangle$

Context

- ▶ Literature: $\dot{\gamma}_{eq} = \alpha \frac{4\langle U \rangle}{\sqrt{8k/\epsilon}}$, with fitting parameter.
- ▶ Reservoir simulators: switch macroscopic law when $\dot{\gamma}_{eq} = \dot{\gamma}_c$.
- ▶ Our Goal: predict and understand the transition, $\langle U_c \rangle$.

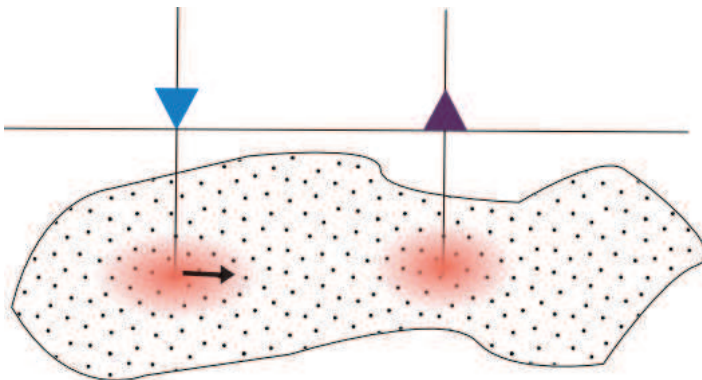


Fig : Predict $\langle U_c \rangle \Rightarrow R_c$?

Rheology

- ▶ Time-independent fluids, no Bingham, Sochi2011. 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,

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

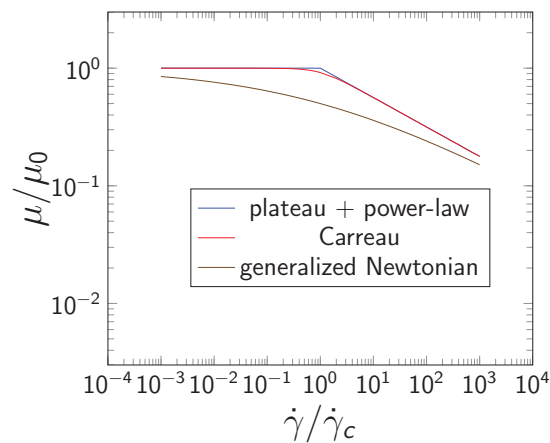










Fig : Different rheological model

Porous Medium

Keywords: universal, wide panel, pore to throat ratio (PTR).

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

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

$\frac{PTR}{k_0}$

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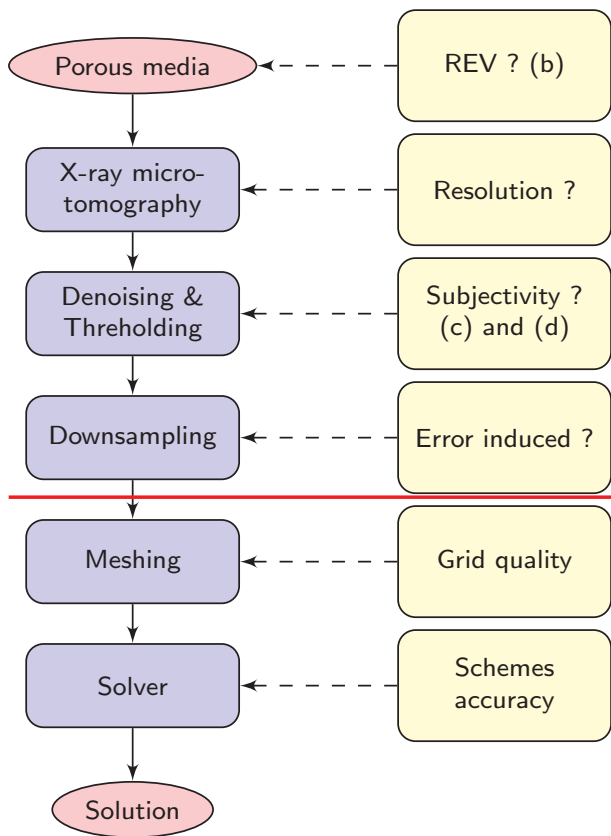
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Model

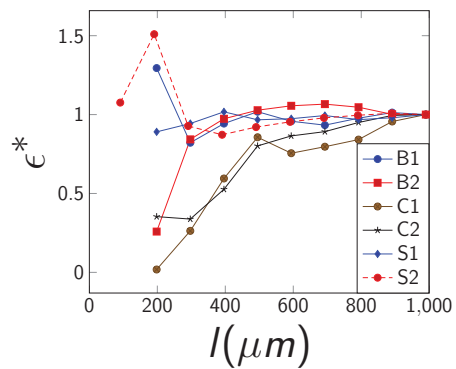
Transition's model
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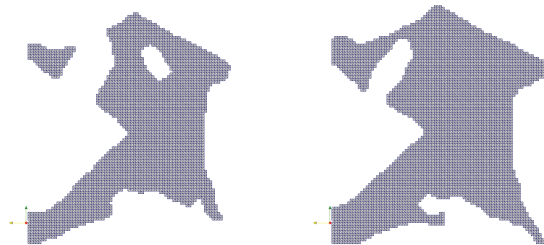
Permeability prediction



(a) Workflow



(b) ϵ^* 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.
- ▶ no-slip conditions, walls.
- ▶ Grid convergence study, 80 millions meshes, 80000 hours of CPU time, use of HPC.

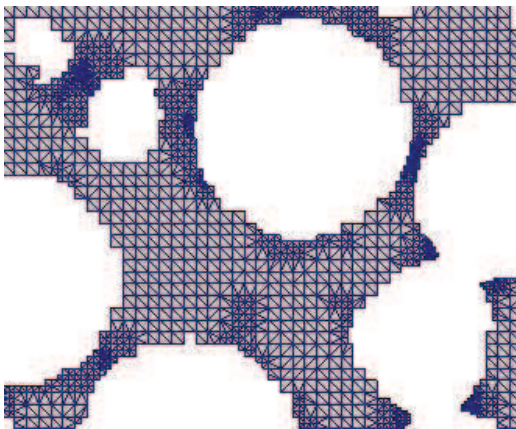


Fig : Slice of grid over over S1

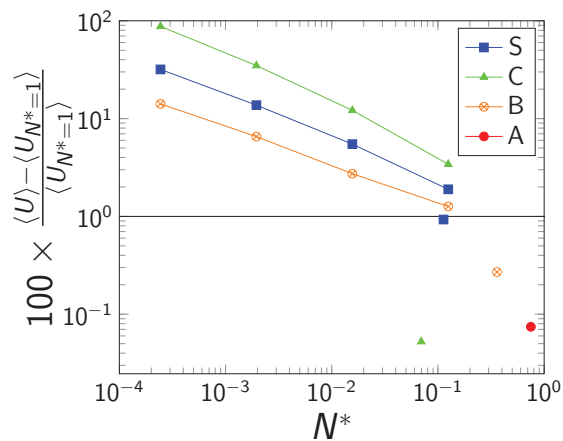


Fig : Grid convergence study

Numerical results - Two regimes

To quantify the transition, we define an dimensionless number, \mathcal{N} ,

$$\mathcal{N} = \frac{\langle U \rangle}{\langle U_c \rangle}. \quad (3)$$

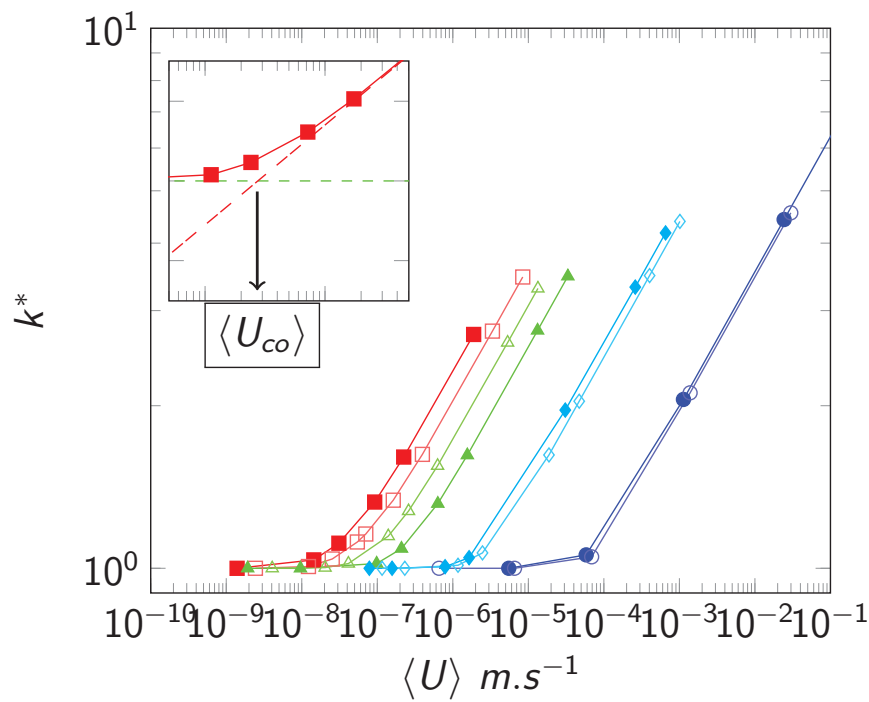


Fig : Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$. Here $n = 0.75$ and $\dot{\gamma}_{lim} = 1s^{-1}$. —●— A1, —○— A2, —▲— B1, —△— B2, —■— C1, —□— C2, —◆— S1

Numerical results - Varying n

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

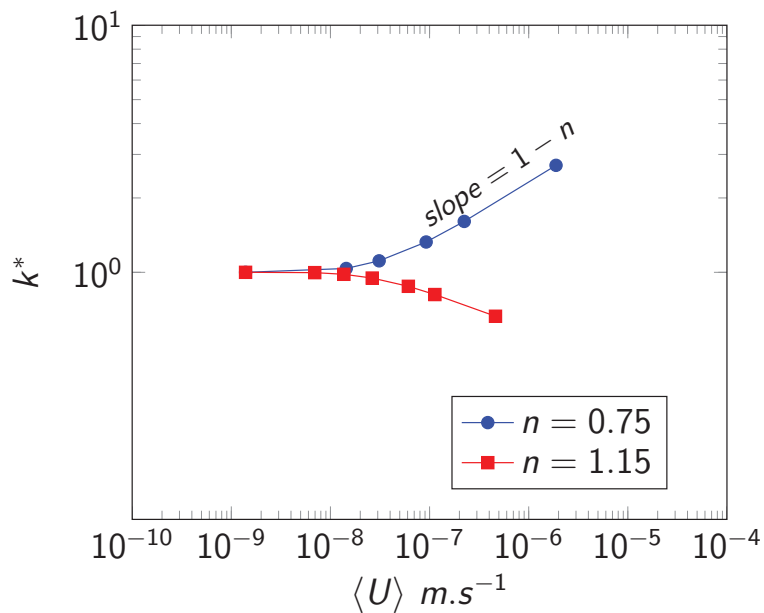


Fig : Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$ for the C1 case. Rheological parameters : fixing $\dot{\gamma}_c$ and varying n .

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

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

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

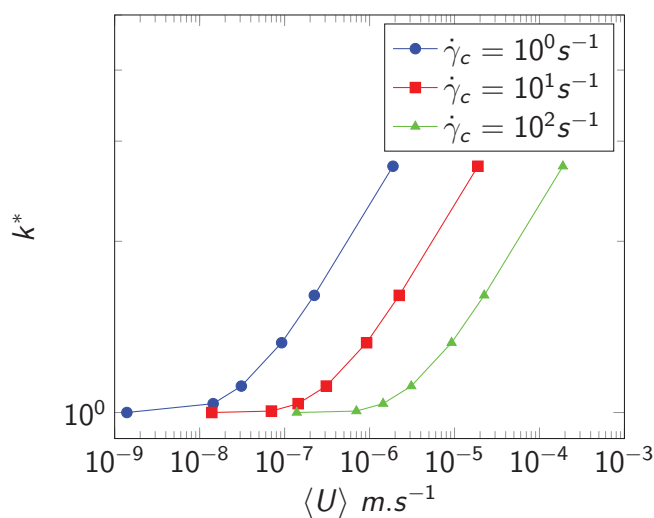


Fig : Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$ for the C1 case. Rheological parameters : fixing n and varying $\dot{\gamma}_c$.

Numerical results - Microscopic Phenomenology

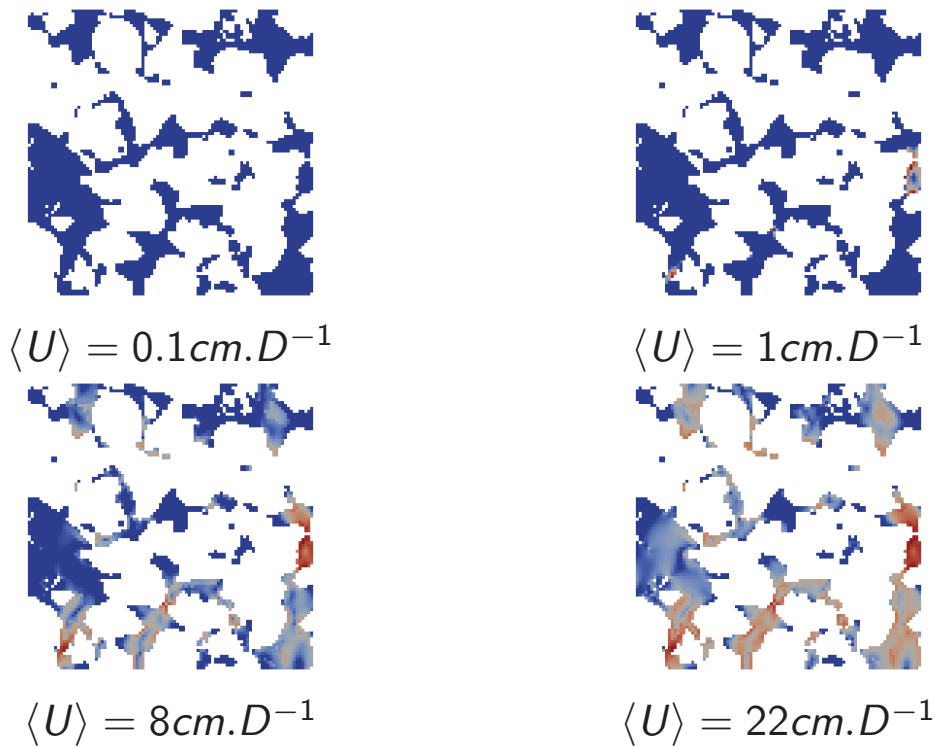


Fig : Viscosity fields at different $\langle U \rangle$ for C1 case.

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

Numerical results - Microscopic Phenomenology

- Identify a critical pore throat volume with PDF.

Media	ϵ	k_0	V_{PT}
A1	0.72	$1.1 \cdot 10^4$	8
A2	0.75	$1.3 \cdot 10^4$	11
S1	0.35	33	2.9
S2	0.44	46	5.2
B1	0.18	1.92	1.8
B2	0.17	0.82	1.6
C1	0.13	0.27	0.4
C2	0.14	0.48	0.5

Tab : Medium description (k_0 in Darcy unit, and V_{PT} in % of volume)

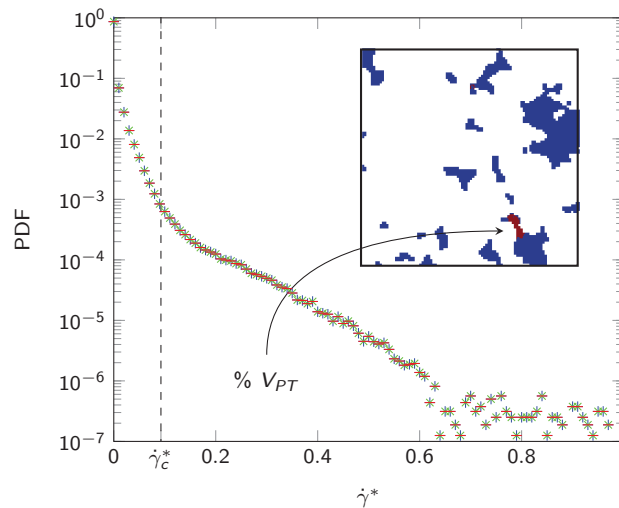


Fig : PDF of $\dot{\gamma}^*$ at $\mathcal{N} = 1$ for media C1.

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 $\langle U_c \rangle = \epsilon \times \dot{\gamma}_c \ell_{eff}$.
- ▶ Equivalent to: predict ℓ_{eff} .
- ▶ Validation by comparison between $\langle U_c \rangle$ and $\langle U_{co} \rangle$.

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: $\sqrt{8k_0/\epsilon}$, $\sqrt{32k_0/\epsilon}$, $\sqrt{k_0/\epsilon}$, $\sqrt{k_0}$.
- ▶ Use of Kozeny-Carman formulation and equivalent diameter, DuPlessis1994, Kozeny1927, Sadowski1963.
- ▶ Use of volume or surface of the medium (V_{part} , V_{medium} , S_{part}), Li2011, Ozahi2008.

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

$$\langle U_c \rangle = \epsilon \times \dot{\gamma}_c \sqrt{k_0}. \quad (4)$$

Full model

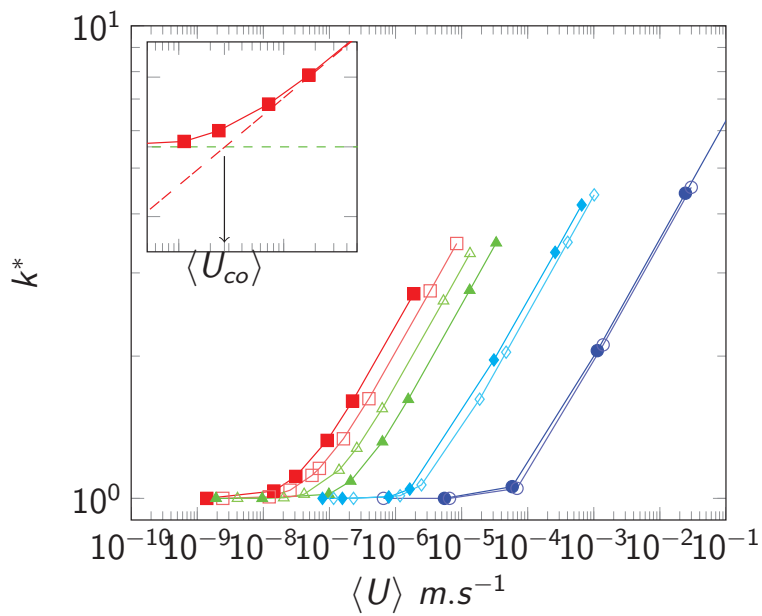


Fig : Dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$. Here $n = 0.75$ and $\dot{\gamma}_{lim} = 1s^{-1}$. —●— A1, —○— A2, —▲— B1, —△— B2, —■— C1, —□— C2, —◆— S1

Full model

- ▶ Relevant dimensionless non-Newtonian number, $\mathcal{N} = \frac{\langle U \rangle}{\langle U_c \rangle} = \frac{\langle U \rangle}{\epsilon \times \dot{\gamma}_c \sqrt{k_0}}$.
- ▶ Proof of model validation.
- ▶ Analytical model,

$$\langle U \rangle = -\frac{K^* \cdot \nabla p}{\mu_0},$$

$$K^* = (1 - f(\mathcal{N}))K_0 + f(\mathcal{N})K(\|\langle U \rangle\|). \quad (5)$$

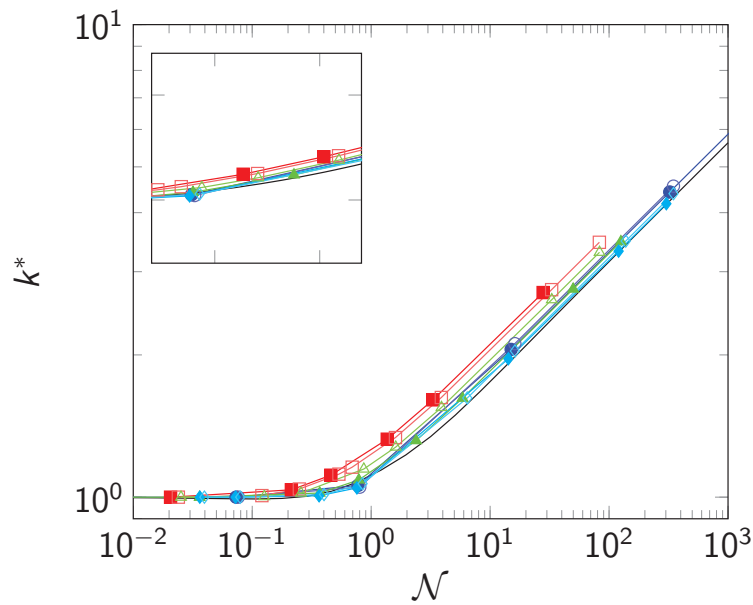
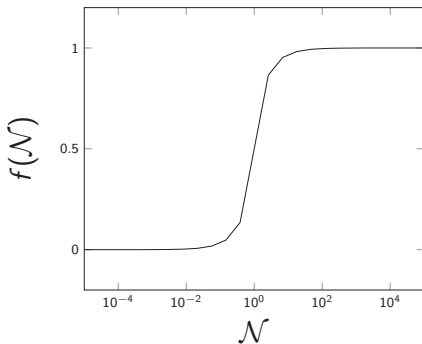


Fig : k^* versus \mathcal{N} . —●— A1, —○— A2, —▲— B1, —△— B2, —■— C1, —□— C2, —◆— S1, —◇— S2, ——— Model Eq.5

Conclusions & Applications

- ▶ Studying the transition of a non-Newtonian fluid through porous media.
- ▶ Model this transition using rheological and topological parameters, $\dot{\gamma}_c$ and ℓ_{eff} .
- ▶ Definition of a dimensionless non-Newtonian number \mathcal{N} , which characterizes the regime.

Many applications can be seen,

- ▶ Regime verification in core-flood experiments,
- ▶ Estimation of critical distances characterizing the regime transition in petroleum and environmental engineering.

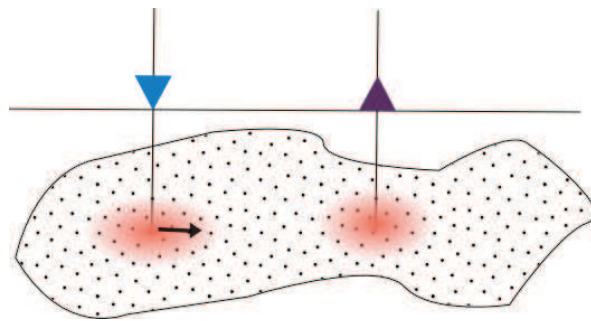


Fig : We find $R_c = 50m$

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

This work was supported by Total.

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

References

../../../../Dropbox/DropBox_These_polymer/Biblio/myBibli.bib

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