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Flow of polymer solutions through porous media

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June 8, 2016
Overview

Introduction

Context
  Rheology
  Porous Media
  Permeability prediction

Numerical Study
  Numerical set up
  Numerical results

Modelling

Conclusions

Perspectives
Scope of work

- EOR context:
  → adverse mobility ratio waterflood,
  → hydrodynamic instabilities,
  → use of polymer.

- Physics is complex...

- Lack of micro-scale observations
  → real mechanisms remain unclear.

- Porous media flow is also complex, e.g, multi-scale, confinement effects.

Zami-Pierre et al., Transition in the flow of power-law fluids through isotropic porous media, Physical Review Letters, *publication under review* (2016)
\[ \mu = \mu_0 \implies \langle U \rangle = -\frac{K \cdot \nabla p}{\mu_0} \implies \langle U \rangle \propto \| \Delta p \| \implies (1) \]

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

**Fig:** Non-Newtonian rheology

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

Refs: [Sorbie and Huang, 1991; Getachew et al., 1998; Sorbie and Huang, 1991; Zitha et al., 1995; Lecourtier and Chauveteau, 1984]
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Context

- Literature: \( \dot{\gamma}_{eq} = 4\alpha \frac{\langle U \rangle / \phi}{\sqrt{8k / \phi}} \), [Chauveteau, 1982].

Two semi-empirical parameters:

- \( R_{eq} = \sqrt{8k / \phi} \), comes from an 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.

- Our goal: simulate the flow a non-Newtonian fluid over a wide panel of porous media. Can we predict and understand the transition velocity, \( \langle U_c \rangle \)?
Rheology

EOR polymer solutions: shear-thinning, no yield, assume time-independent. Common models are,

- **plateau + power-law**,

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

(1)

- Carreau,
- generalized Newtonian.

Refs: [Bird and Carreau, 1968; Savins, 1969; Collyer, 1973]
Porous Media

2D Arrays media and 3D Packing, Bentheimer and Clashach media.

Fig: Investigated porous media.

Keywords: wide panel, complex 3D structure, isotropic, pore size distribution (PSD), local mesh refinement.
Permeability prediction

(a) Workflow

Fig: Permeability prediction issues
Numerical set up

- Equations: \( 0 = -\nabla p + \nabla \cdot [\nu(\dot{\gamma})(\nabla U + \nabla U^T)] \), \( \nabla \cdot \mathbf{U} = 0 \).
- FVM with OpenFOAM, 2\(^{nd}\) order schemes, and the SIMPLE algorithm [Patankar, 1980].
- Permeameter, no-slip conditions.
- Grid convergence study, \( \sim 100 \) millions cells, \( 10^5 \) hours of CPU time, use of HPC.

\[ \frac{h}{h_0} \]

\[ e(\langle U \rangle \text{ in } \%) \]

Using 1 cell = 1 voxel \( \rightarrow \) factor 2 in final permeability prediction.
**Numerical results: at the micro-scale**

![Graphs showing PDFs of dimensionless velocities](image)

(a) PDF of $U^*_z$
- $\bigcirc$ A2 $n = 1.00$
- $\triangle$ B2 $n = 1.00$
- $\square$ C2 $n = 1.00$
- $\diamond$ P1 $n = 1.00$
- $\bigcirc$ A2 $n = 0.75$
- $\triangle$ B2 $n = 0.75$
- $\square$ C2 $n = 0.75$
- $\diamond$ P1 $n = 0.75$

(b) PDF of $U^*_y$

**Fig:** PDF of longitudinal and transverse dimensionless velocity ($U^* = U/\langle U \rangle$) for a Newtonian and a non-Newtonian flow.

**Keywords:** correlation to geometrical features, different distribution (max velocities, co- and counter-current flow), exponential decay for P1, isotropy, weak impact of nonlinear effects.
**Numerical results: at the macro-scale**

![Graph showing the relationship between apparent dimensionless permeability and intrinsic average velocity](image)

**Fig**: Apparent dimensionless permeability $k^* = k/k_0$ vs. the intrinsic average velocity $\langle U \rangle_{FL}$

**Keywords**: Newtonian and non-Newtonian regime, only $\phi_{PT}$ needed to be non-Newtonian, define a critical velocity $\langle U_c \rangle_{FL}$
Transition’s model: a remarkable finding

- Our goal: predict $\langle U_c \rangle_{FL} = \dot{\gamma}_c \ell_{eff}$. 
- Goal: predict $\ell_{eff}$.

Model for $\ell_{eff}$:
- We have tried: $\sqrt{8k_0/\phi}$, $\sqrt{32k_0/\phi}$, $\sqrt{k_0/\phi}$ (with $k_0$ obtained from DNS).
- Use of Kozeny-Carman formulation and equivalent diameter, [du Plessis and Roos, 1994; Kozeny, 1927; Sadowski, 1963].
- Use of volume or surface of the medium ($V_{part}$, $V_{medium}$, $S_{part}$) [Ozahi et al., 2008].

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

$$\langle U_c \rangle_{FL} = \dot{\gamma}_c \sqrt{k_0}. \quad (2)$$
Transition’s model: a remarkable finding

![Graph showing data]

**Fig:** Apparent dimensionless permeability $k^* = k/k_0$ against (a): the average velocity $\langle U \rangle_{FL}$ and (b): the dimensionless velocity $U^* = \langle U \rangle_{FL} / (\dot{\gamma}_c \sqrt{k_0})$.

Keywords: Newtonian and non-Newtonian regime, only $\phi_{PT}$ needed to be non-Newtonian, define a critical velocity, predict simple $\langle U_c \rangle_{FL}$ as $\dot{\gamma}_c \sqrt{k_0}$ works!
Let’s get back to micro-scale results...

\[ \langle U \rangle = 0.1 \, cm.D^{-1} \]

\[ \langle U \rangle = 1 \, cm.D^{-1} \sim \langle U_c \rangle \]

\[ \langle U \rangle = 8 \, cm.D^{-1} \]

\[ \langle U \rangle = 22 \, cm.D^{-1} \]

\[ \mu / \mu_0 \]

Fig : Viscosity fields at different flow regime for C1 case.

Keywords: domain extension, sources (surfaces and PT), critical region \( \phi_{PT} \).
The macro-scale behaviour is sensitive to $\phi_{PT}$.

The viscous dissipation mainly occurs in $\phi_{PT}$.

$\beta = \frac{\langle U_c \rangle_{PT}}{\langle U_c \rangle_{FL}}$

$\sqrt{k_0} \approx \frac{\phi_{FL}}{\sqrt{\phi_{PT}}} \frac{\ell_{PT}}{\beta}$

$\langle U_c \rangle_{FL} = \gamma_c \ell_{eff}$

$\langle U_c \rangle_{FL} \propto \dot{\gamma}_c$

$\langle U_c \rangle_{FL} = \gamma_c \ell_{eff}$

$\langle U_c \rangle_{FL} \perp n$

$\ell_{eff} \approx \sqrt{k_0}$

Keywords: small sub domain $\phi_{PT}$, viscous dissipation, non-Newtonian transition.
Partial Conclusions

- Studying cut-off phenomena due to non-Newtonian fluid through isotropic porous media.

- Nonlinear effects weakly impact the flow statistics (PDF).

- A small subdomain $\phi_{PT}$ controls the macro-scale behaviour. It controls both the viscous dissipation and the non-Newtonian transition.

- Simple theory provides analytical formulation for the transition velocity.

- Explain why $l_{eff} \simeq \sqrt{k_0}$. Used in many porous media applications (core-flood experiments, Bingham fluids, inertial regime) $\rightarrow$ meaningful length (topology+flow), universal role?
Perspectives

Previous work based on a simple view of polymer flow, i.e., generalized N.S. A simplified view leads to split the porous medium domain into 3 areas:

- bulk phase, p-phase (→ Justify continuum approach?),
- excluded zones (where macro-molecules do not enter), e-phase,
- boundary zones (specific arrangements), b-phase.

Fig: Sketch of polymer repartition at the pore-scale.

- Adoption of a continuum approach? → Several conceptual difficulties…
Two major mechanisms [Chauveteau, 1984; De Gennes, 1981]:

- Sorption [Hatzikiriakos, 2012].
- Repulsion [Sorbie and Huang, 1991].

⇒ Need of practical micro-scale observations to quantify slip [Chenneviere et al., 2016]

- Approach (a): MDS [Rouse Jr, 1953; Joshi et al., 2000; Cuenca and Bodiguel, 2013].

- Approach (b): Meso-scale model [Wood et al., 2004].

- Approach (c) and (d): effective surface concept [Achdou et al., 1998; Introïni et al., 2011].

Fig: Various models for describing transport near a solid wall.
This work was performed using HPC resources from CALMIP (Grant 2015-11).

This work was supported by Total.

Thank you for your attention. Any question is welcome!

PS: I am looking for a job next year :)
Is it new?

Is $\ell_{\text{eff}} = \sqrt{k_0}$ so surprising and new?

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

(3)

Thanks to core-flood experiments, we can calculate the pre-factor,

<table>
<thead>
<tr>
<th>Reference</th>
<th>Medium</th>
<th>$\frac{1}{\sqrt{2\phi \alpha}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Lecourtier and Chauveteau, 1984]</td>
<td>P1</td>
<td>0.71</td>
</tr>
<tr>
<td>[Chauveteau, 1982]</td>
<td>P1</td>
<td>0.87</td>
</tr>
<tr>
<td>[Chauveteau, 1984]</td>
<td>C</td>
<td>0.52</td>
</tr>
<tr>
<td>[Fletcher et al., 1991]</td>
<td>C</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Tab: Comparison with data found in literature

This would mean that without complex physical phenomena, $\ell_{\text{eff}} = \sqrt{k_0}$ is a good estimation for the $\ell_{\text{eff}}$. **Plus**, we added a model that explains by a simple approach why this length works.
Independence with $n$?

**Fig**: Critical velocity $\langle U_c \rangle_{FL} \ (\mu m.s^{-1})$ as a function of $\dot{\gamma}_c \ (s^{-1})$ for medium C1 and different values of $n$. 

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Transition’s model: a derivation

\[ \langle U_c \rangle_{FL} \propto \dot{\gamma}_c \]

\[ \langle U_c \rangle_{FL} \perp n \]

The macro-scale behaviour is sensitive to the PT volume

\[ \langle U_c \rangle_{PT} = \dot{\gamma}_c \ell_{PT} \]

\[ \beta = \frac{\langle U_c \rangle_{PT}}{\langle U_c \rangle_{FL}} > 1 \]

\[ \langle U_c \rangle_{FL} = \dot{\gamma}_c \ell_{PT} / \beta \]

With \( \mathcal{E} = 2\mu e \):

\[ e, k_0 = \frac{\mu_0 \langle U \rangle^2}{\langle \mathcal{E} \rangle}, \]

\[ k_0 = \frac{\langle U \rangle^2}{\langle \dot{\gamma}^2 \rangle} \]

\[ \frac{\phi_{FL}}{\sqrt{\phi_{PT}}} \simeq 1 \]

\[ \ell_{eff} \simeq \sqrt{k_0} \]

\[ \langle \dot{\gamma}^2 \rangle \simeq \phi_{PT} \langle \dot{\gamma}^2 \rangle_{PT} \]

\[ = \phi_{PT} \frac{\langle U \rangle^2_{PT}}{\ell_{PT}^2} \]

Keywords: small sub domain \( \phi_{PT} \), viscous dissipation, non-Newtonian transition.
Numerical results: at the micro-scale

Fig : PDF of dimensionless shear rate for all media (Newtonian and non-Newtonian) flow.

Keywords: geometrical differences & nonlinearities induced by the flow, translating to non-Newtonian regime, pore-throat (PT).


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Physics Education, 8(5):333.


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