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

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Overview

Introduction

Context

Keys concept
  Rheology
  Porous medium
  Permeability prediction

Numerical Results
  Numerical set up
  Numerical results

Model
  Transition’s model
  Full model

Conclusions
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
**Context**

\[ \mu = \mu_0 \quad \Rightarrow \quad \langle U \rangle = -\frac{K \cdot \nabla p}{\mu_0} \quad \Rightarrow \quad \langle U \rangle \propto \| \Delta p \| \quad \Rightarrow \quad (1) \]

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

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 $\langle U_c \rangle \Rightarrow R_c$?
Time-independent fluids, no Bingham, Sochi2011. Common models are,
- plateau + power-law,
\[ \mu = \begin{cases} \mu_0 & \text{if } \dot{\gamma} < \dot{\gamma}_c, \\ \mu_0 \left( \frac{\dot{\gamma}}{\dot{\gamma}_c} \right)^{n-1} & \text{else,} \end{cases} \]
\[ (1) \]
- Carreau,
- generalized Newtonian.

Choice of plateau + power-law (and tried others).

This leads at a macro scale to,
\[ \langle U \rangle \propto \begin{cases} \| \Delta p \| \\ \| \Delta p \|^{1/n} \end{cases} \]
\[ (2) \]
## Porous Medium

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

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<thead>
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<th>Porous Medium</th>
<th>ε</th>
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<th>PTR</th>
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</table>

Tab: Porous medium investigated (k₀ in Darcy unit, ■ for liquid)
Permeability prediction

(a) Workflow

Fig: Permeability prediction issues
Numerical set up

- Equations: \( 0 = -\nabla p + \nabla \cdot [\nu(\dot{\gamma})(\nabla U + (\nabla U)^T)] \), \( \nabla \cdot U = 0 \).
- 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, $N$,:

$$N = \frac{\langle U \rangle}{\langle U_c \rangle}.$$  \hspace{1cm} (3)

![Graph showing dimensionless permeability $k^* = k/k_0$ versus $\langle U \rangle$. Here $n = 0.75$ and $\dot{\gamma}_{lim} = 1 \text{s}^{-1}$. 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 $\ell_{eff}$.
- Use of $\epsilon$.

**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

\[ \langle U \rangle = 0.1\,cm.D^{-1} \]
\[ \langle U \rangle = 8\,cm.D^{-1} \]
\[ \langle U \rangle = 1\,cm.D^{-1} \]
\[ \langle U \rangle = 22\,cm.D^{-1} \]

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).
Non-Newtonian fluids through porous media

F. Pierre

Introduction

Context

Keys concept

Rheology

Porous medium

Permeability prediction

Numerical Results

Numerical set up

Numerical results

Model

Transition’s model

Full model

Conclusions

Numerical results - Microscopic Phenomenology

- Identify a critical pore throat volume with PDF.

<table>
<thead>
<tr>
<th>Media</th>
<th>$\epsilon$</th>
<th>$k_0$</th>
<th>$V_{PT}$</th>
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<tbody>
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<td>A1</td>
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<tr>
<td>C2</td>
<td>0.14</td>
<td>0.48</td>
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</tbody>
</table>

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

Fig : PDF of $\dot{\gamma}^*$ at $N = 1$ for media C1.
Legend : $+$ for $\dot{\gamma}_c = 10^0 \, s^{-1}$, $\times$ for $\dot{\gamma}_c = 10^1 \, s^{-1}$, $-$ for $\dot{\gamma}_c = 10^2 \, s^{-1}$
Transition’s model

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

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: $\sqrt{8k_0/\varepsilon}$, $\sqrt{32k_0/\varepsilon}$, $\sqrt{k_0/\varepsilon}$, $\sqrt{k_0}$.
- 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:

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

Introduction

Context

Keys concept

Rheology

Porous medium

Permeability prediction

Numerical Results

Numerical set up

Numerical results

Model

Transition’s model

Full model

Conclusions

Fig : Dimensionless permeability $k^* = k / k_0$ versus $\langle U \rangle$. Here $n = 0.75$ and $\dot{\gamma}_{lim} = 1 s^{-1}$. $A_1$, $A_2$, $B_1$, $B_2$, $C_1$, $C_2$, $S_1$
Non-Newtonian fluids through porous media

F. Pierre

Introduction

Context

Keys concept

Rheology

Porous medium

Permeability prediction

Numerical Results

Numerical set up

Numerical results

Model

Transition’s model

Full model

Conclusions

Full model

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

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

\[
K^* = (1 - f(\mathcal{N}))K_0 + f(\mathcal{N})K(\parallel \langle U \rangle \parallel).
\]

(5)

\[
\text{Fig : } k^* \text{ versus } \mathcal{N}. \quad \bullet \text{ A1, } \bigcirc \text{ A2, } \bigtriangleup \text{ B1, } \triangle \text{ B2, } \square \text{ C1, } \blacksquare \text{ C2, } \bigtriangledown \text{ S1, } \bigtriangledown \text{ S2, } \text{ Model Eq.5}
\]
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 $\ell_{\text{eff}}$.
- 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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Thanks you for your attention. Any question is welcomed :)
References

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