Investigation of Two-Phase Flow Mechanisms in Porous Media Using Micro-Particle Image Velocimetry

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Multiphase Flow in Porous Media

Example of application: CO$_2$ injection and sequestration

CO$_2$ sequestration into deep saline aquifer and pore-scale CO$_2$ flow in native porous media

Experimental investigations

Core-scale two-phase immiscible drainage experiments

2D Micromodels

- Provide direct visualization of the pore-scale
- Valuable to interpret observations at larger scale

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1 Kim et al. (2013) Aquifer-on-a-Chip: understanding pore-scale salt precipitation dynamics during CO$_2$ sequestration. Lab on a Chip 13, 2508.
3 Buchgraber et al. (2011) A microvisual study of the displacement of viscous oil by polymer solutions. SPE Reservoir Evaluation & Engineering 14, 269280.
Two-phase immiscible flow in micromodels

Viscosity ratio: \( M = \frac{\mu_{nw}}{\mu_w} \)

Capillary number:
\[ Ca = \frac{\mu_{nw} u_{nw}}{(\sigma_{nw-w} \cos \theta)} \]

\( nw \): non-wetting, \( w \): wetting


Micro-dynamics of two-phase flows

- Aim: to investigate the mechanisms of displacement of one fluid by another in micromodels at the pore-scale

- Direct numerical simulations of multiphase flows at the pore scale are still in development and need validation

The Particle Image Velocimetry (PIV) technique, used to obtain instantaneous velocity measurements, appears useful and relatively unexplored to understand and quantify the mechanisms involved at the pore scale

- PIV allows for quantitative comparisons between experimental and numerical data

- Previous studies: complex and expensive optical systems, simplified geometries, PIV measurements have not been validated
Particle Image Velocimetry (PIV)

To measure the displacements of tracer particles seeded in the fluid in a fixed time interval

- The images are divided in a uniform grid of so-called interrogation windows.
- The image patterns in the interrogation windows in the images at \( t \) and \( t+\Delta t \) are compared statistically.
- The procedure is repeated for all interrogation windows resulting in a uniform grid of displacement information.
- The same procedure is repeated for several image pairs and the results are averaged.

Outline

I/ Introduction

II/ Experimental Setup

III/ Single Phase Flow: validation of the micro-PIV measurements in micromodels

IV/ Two-phase Flow: investigation of two-phase flow mechanisms using micro-PIV

V/ Conclusion
Experimental Setup: Micromodels

- Microfabrication of 2D etched-silicon micromodels

Coating

UV exposure

Development

Etching

Cleaning

Glass bonding

Etching depth: 12µm
Micromodel surface: water-wet

The water is seeded with **Carboxylate Modified Latex Microparticles**: 

- 1µm diameter: to follow the flow without disturbing it
- negatively charged, hydrophilic: minimize particle aggregation and binding to the walls
- particle density ≈ water density, to avoid sedimentation.

→ Sequences of images of the flow are recorded
**Image processing**

Original image sequence

- Noise removal
- Correction of light intensity fluctuations
- Calculation of the background image
- Grain detection
- Subtraction of the background and the grains

After image processing: bright particles, dark background and grain detections


**Lindken, R. et al. (2009), Micro-particle image velocimetry (μ-PIV): Recent developments, applications, and guidelines, Lab Chip 9(17) 2551-2567
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PIV measurements in micromodels: validation

In the case of fully saturated micromodels, 2D direct numerical simulations are performed with OpenFOAM.
The numerical results are compared with the data provided by PIV measurements.

**Experiment**

- **Fluid**: water seeded with micro-particles
- **Q**: $1.10^{-4}$ to $1.10^{-3}$ mL/min

**Numerical Simulation**

- **Flow direction**: 45°
- **Periodic boundary conditions**
- **Velocity**: Flow pathways strongly influenced by the pore geometry

**Microchannels**

- **Inlet**
- **Outlet**

**Flow path**: Microchannels
PIV measurements in micromodels: validation

Sandstone pattern: single phase flow

Experiment, zoom
Vector resolution: 2.2µm x 2.2µm grid
Up to 1.2µm x 1.2µm vector grid

Experiments PIV results
Numerical simulation
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Two-phase flow experiment

Fluid properties

Wetting fluid: 65% water, 35% glycerin + UV-dye + particles
Non-wetting fluid: n-heptane
Viscosity ratio: $\mu_{nw}/\mu_w = 0.145$

Micromodel
Sandstone pattern

Drainage experiment

1) Micromodel saturated with the wetting fluid
2) Injection of the non-wetting fluid at $2.5 \times 10^{-3}$ mL/min
3) Acquisition of movies at different locations in the micromodel

Advancing non-wetting phase

Oil pushing dyed water before entering the micromodel
Flow instabilities due to interface migration may induce pressure instabilities that propagate further downstream → perturb the wetting phase before the passage of the interface.

Microdynamics of two-phase flow

μ-PIV results

Displacement along x (Ux) and along y (Uy) of the wetting phase as a function of time for 3 positions in the porous medium

Flow direction

Last image of the sequence

Non-wetting phase arrives in area 1

Non-wetting phase arrives in area 2

Position 1

Position 2

Position 3

50µm

Flow direction

Last image of the sequence
Microdynamics of two-phase flow

Observation and measurement of recirculation intensity

Driven cavity flow due to the shear stress resulting from the non-wetting phase that is still flowing.

→ Are viscous dissipation terms really negligible at larger scale?
→ What are the consequences on multicomponent mass transport?

Microdynamics of two-phase flow
Interface tracking

“Slow motion” of the advancing interface (highlighted in red)

- Further investigations are needed to describe such fast jumps and their consequences
- The micro-PIV setup developed offers new possibilities to characterize the complex microdynamics of the jumps.
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Conclusion

• Single phase flow: good agreement between experiments and numerical simulation

• PIV measurements in micromodels have been validated

• High resolution of velocity vectors: less than 2µmx2µm vector grids

We have now a tool to investigate two-phase flow mechanisms in micromodels

• The micro-PIV measurements during a drainage experiment have already shown interesting and complex behaviors
  • Oscillations of the wetting fluid before the passage of the interface
  • Dissipative recirculations during two-phase flow
Future work

• Particles in both phases

• Parametric study of two-phase immiscible flows in simple geometries, comparison with direct numerical simulations under development

Converging-diverging tube drainage
(numerical simulation, Moataz Abu AlSaud)

Final time = 0.32 seconds

grid: 360 by 120
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Questions?

www.sophieroman.com
PIV measurements in micromodels: validation

Homogeneous pattern: single phase flow at the interface matrix/fracture

In the case of fully saturated micromodels, 2D direct numerical simulations are performed with OpenFOAM (Cyprien Soulaine, SUPRI-B).

The numerical results are compared with the data provided by PIV measurements.

Experiment:
Max(U) fracture / Max(U) matrix ≈ 2.05

Simulation:
Max(U) fracture / Max(U) matrix ≈ 1.99

Flow direction (45°)

Q_{exp}=2.10^{-4}\text{mL/min}

Experiments
PIV results

Numerical simulation
PIV measurements

For a successful µ-PIV experiment**, consider:

- Optical system
- Size and type of tracing particles
- Size of image particle
- Time delay between image pairs
- Number of image pairs
- Size of interrogation windows
