Image Analysis to Improve Data Acquisition During Micromodel Experiments

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Outline

• Scientific Context

• Experimental Setup

• Improving the Visualization of Pore-Scale Mechanisms in Micromodels:
  • Two-Phase Immiscible Flows
    • Particle Velocimetry Analysis of Immiscible Two-Phase Flow in Micromodels
    • Tracking of a Fluid-Fluid Interface in Real-Time
  • Quantification of Calcite Dissolution in Micromodels

• Conclusion and Future Work
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CO₂ injection and sequestration

1. Drainage, imbibition and trapping mechanism
   - Aqueous speciation, brine pH is lowered,
   - Transport of acid to the mineral surface.

2. Interphase mass transfer, sCO₂/brine dissolution

3. Minerals dissolution, wettability alteration

4. Mineral precipitation

5. CO₂ sequestration into deep saline aquifer and pore-scale CO₂ flow in native porous media

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2. Steefel et al. (2013), *Pore Scale Processes Associated with Subsurface CO₂ Injection and Sequestration* Reviews in Mineralogy and Geochemistry, 77, 259-303
Multiphase Flow in Porous Media

Experimental investigations

2D Micromodels

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

Two-phase immiscible drainage experiments
Dissolution in fractured carbonate experiments

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2 Elkhoury et al. (2013), *Dissolution and deformation in fractured carbonates caused by flow of CO2-rich brine under reservoir conditions*, Int. J. Greenh. Gas Control
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Etched Silicon-Micromodels

- Microfabrication of 2D etched-silicon micromodels

### Experimental Setup

- Etching depth: 12-30µm
- Micromodel surface: water-wet

- Etched patterns
  - Rock-replica: sandstone 1:1 representation of pore sizes
  - Capillaries with different pore shapes

- Micromodel after anoding bonding of coverplate
Experimental Setup

Fluids:
- Water, water/glycerin mix
- N-heptane, silicone oil
- Acid: HCl (0-2%)

→ Sequences of images of the flow are recorded
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Sequences of images and image processing

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.

Original image sequence
Single phase flow

After image processing: bright particles, dark background and grains

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.


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The **Particle Image Velocimetry** (PIV) technique has been validated and optimized to measure velocity field in micromodels:

→ Better understanding of flow mechanisms
→ Quantitative comparisons between experimental and numerical data

- 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

*Roman et al. (2015), *Particle velocimetry analysis of immiscible two-phase flow in micromodels*, Advances in Water Resources*
Microdynamics of two-phase flow

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


Microdynamics of two-phase flow

Heptane Displacing Water (M=2.4, Ca≈10^-6)*

Range of parameters representative of a CO₂/brine system in subsurface aquifer conditions

Flow instabilities

*Roman et al. (2015), Particle velocimetry analysis of immiscible two-phase flow in micromodels, Advances in Water Resources
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?

*Roman et al. (2015), Particle velocimetry analysis of immiscible two-phase flow in micromodels, Advances in Water Resources

Microdynamics of two-phase flow

• The micro-PIV measurements during a drainage experiment have shown interesting and complex behaviors

  • Oscillations of the wetting fluid before the passage of the interface
  • Dissipative recirculations during two-phase flow

• Current goals:

  • Need of a better understanding of these mechanisms
  • Tracking displacement fronts
  • Quantification of re-circulations
  • Parametric study of two-phase immiscible flows in simple geometries, comparison with direct numerical simulations under development
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• Conclusion and Future Work
Image processing: detection of interface displacement

Experiments in simplified geometries
- Control of experimental parameters
- Varying one parameter at a time
- Comparison with numerical simulations

Heptane displacing water
$\mu_o/\mu_w = 0.37$

100µm

Pauline Louazel’s experiments

100µm

39.5µm/sec

Displacement (µm)

0 20 40 60 80 100 120

0.5 1 1.5 2 2.5 3

time (s)

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Image processing: detection of interface displacement

Experiments in simplified geometries

- Control of experimental parameters
- Varying one parameter at a time
- Comparison with numerical simulations

Heptane displacing water
\[ \mu_o / \mu_w = 0.37 \]
\[ D_{\text{pore}} / D_{\text{throat}} = 100/40 \]
Pore-pore = 400µm

Tracking displacement front

Pauline Louazel’s experiments
Image processing: detection of interface displacement

Experiments in simplified geometries
- Control of experimental parameters
- Varying one parameter at a time
- Comparison with numerical simulations

Heptane displacing water
$\mu_o / \mu_w = 0.37$
$D_{pore}/D_{throat} = 100/20$
Pore-pore = 100µm

Pauline Louazet’s experiments
Detection of interface and $\mu$-PIV

Experiments in simplified geometries
- Control of experimental parameters
- Varying one parameter at a time
- Comparison with numerical simulations

Heptane displacing water seeded with microparticles
$\mu_o/\mu_w = 0.37$
$D_{pore}/D_{throat} = 1.7$
Detection of interface and µ-PIV

Before interface arrival

t=0.012sec

d=0.33sec

t=0.33sec
Microdynamics of two-phase flow: conclusion

- Experiments in simplified micromodels have been designed
- The validated and optimized µ-PIV dramatically improves understanding of multiphase flow
- Image processing tools have been developed to characterize two-phase flows

**Future work:**
- Extension of µ-PIV measurements to the oil phase
  
  *Melamine particles in silicone oil*

- Comparison with numerical simulations

*Converging-diverging tube drainage, Moataz Abu AlSaud*
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Calcite Dissolution in Micromodels

Song et al. experiments*

- The solid dissolves not only in liquid but also in gas
- Formation of droplets of gas

Calcite Dissolution in Micromodels

Experimental setup

- PDMS microchannel
- Calcite Crystal

Acid injection
Calcite Dissolution in Micromodels

Measurement of calcite area, number, size, distribution of bubbles by image processing

Before the passage of the acid front

5.7 sec after the passage of the acid front

1.5 mm

Flow direction

203 sec after the passage of the acid front

744 sec after the passage of the acid front

52 sec after the passage of the acid front

845 sec after the passage of the acid front
Calcite Dissolution in Micromodels

0-300sec

300-860sec

Movies >> X15
Calcite Dissolution in Micromodels: conclusion

Conclusion:

- Calcite dissolution can now be quantified at the pore-scale
- An image processing workflow has been developed to:
  - Measure the calcite area in real-time
  - Measure the size of each gas bubble in real-time

Future work:

- Analyze the data for a large range of experimental parameters
- Compare with numerical simulations that are in development

Red = solid
Blue = fluid
White = gas/liquid interface
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• Conclusion and Future Work
Conclusion and future work

- Experiments in simplified micromodels have been designed.
- The validated and optimized μ-PIV dramatically improves understanding of multiphase flow.
- Image processing tools have been developed to characterize two-phase flows and dissolution mechanisms.

→ Provide data to verify and complete the existing pore level models.

→ Improve large scale models.

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Thank you for your attention!

Questions?

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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

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Velocity profile before interface arrives
Slide 13&14
Terminal velocity

Creeping flow
(Re<<1)

\[ V_t = \frac{gd^2}{18\mu} (\rho_s - \rho) \]

Terminal velocity for creeping flow
Displacement of the interface, $h$

Velocity of the interface

Time (sec)

Model of Moebius & Or, 2012
Extend μ-PIV measures to oil phase

Melamine Resin particles*

- Density: 1.51g/cm³
- Hydrophilic surface
- High stability in organic solvents, no swelling or shrinking upon contact with organic solvents
- Long-term stability in dispersions, no additives or stabilizers required
- Powders of dried particles can be redispersed in any dispersing agent without agglomeration

Dispersion in Heptane:
- Density: 0.68g/cm³
- Viscosity: 0.38cP

Settling velocity, 20µm depth capillary, creeping flow:
> 1µm/sec

Dispersion in Silicone oil:
- Density: 0.96g/cm³
- Viscosity: 96cP

Settling velocity, 20µm depth capillary, creeping flow:
< 0.01µm/sec

*Timgren at al. (2008), Application of the PIV technique to measurements around and inside a forming drop in a liquid–liquid system, Experiments in Fluids

Future work
Flow direction
Settling velocity
Extent μ-PIV measures to oil phase

Melamine particles in silicone oil

- Too diluted for μ-PIV
- Particles stuck to tubing
- Agglomerates

Particle Image Velocimetry
- High particle density each
- Groups of moving particles are analyzed

Particle Tracking Velocimetry
- Sparse seeding
- Each particle is analyzed individually

PTV measurements
Micro-continuum model for multiphase flow

Volume-of-Fluid (VOF) approach\(^1\) with CSF\(^2\) and phase change\(^3\)

Penalized VOF with Darcy term and wall adhesion condition (Horgue et al.\(^4\))

Evolution of the solid volume fraction with liquid acid concentration

Transport of acid concentration with thermodynamics equilibrium at gas/liquid interface (Haroun et al.\(^5\))

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\(^1\) Hirt, C. & Nichols, B. *Volume of fluid (VOF) method for the dynamics of free boundaries* Journal of Computational Physics, 1981, 39, 201 - 225

\(^2\) Brackbill et al. *A continuum method for modeling surface tension* Journal of Computational Physics, 1992, 100, 335 - 354


Rates at different time steps during the experiment

Dissolution rate vs. gas growing rate

- Dissolution rate (µm²/sec)
- Gas growing rate (µm²/sec)

Rates at different time steps during the experiment:
- 1.25mL/h - 2%
- 0.125mL/h - 2%
- 0.625mL/h - 0.5%
- 0.125mL/h - 1%
- 1.25mL/h - 0.5%
- 1.25mL/h - 1%