Particle image velocimetry analysis of immiscible two-phase flow through porous media at the pore scale

Sophie Roman*, Cyprien Soulaine, Moataz Abu AlSaud, Hamdi Tchelepi, Anthony Kovscek

*sroman@stanford.edu

Example of application:
CO$_2$ injection and sequestration

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

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

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, 209080.
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

Zhang et al. (2011), Influence of Viscous and Capillary Forces on Immiscible Fluid Displacement (…), Energy & Fuels 25, 3493-3505


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
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.

### Experimental Setup: Micromodels

- **Microfabrication of 2D etched-silicon micromodels**

  - **Coating**: PR → Si
  - **UV exposure**: Photomask → PR → Si
  - **Development**: PR → Si
  - **Etching**: PR → Si
  - **Cleaning**: Si
  - **Glass bonding**: Glass → Si

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

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**Figure:**
- **Sandstone pattern**: (grains 30-200µm)  
Pore throats<7µm

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**Experimental Setup**

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

50µm

Original image sequence
X200

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

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

PIV tool for MATLAB*

II/ Experimental Setup

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

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
PIV measurements in micromodels: validation

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**
- Microchannels
- Inlet
- Flow direction
- Outlet

**Fluid:** water seeded with micro-particles

Q = 1.10^{-4} to 1.10^{-3} mL/min

**Numerical Simulation**
- Flow direction, 45°
- Flow pathways strongly influenced by the pore geometry

**Periodic boundary conditions**

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**PIV measurements in micromodels: validation**

Sandstone pattern: single phase flow

**Experiments, zoom**
- Vector resolution: 2.2µm x 2.2µm grid
- Up to 1.2µm x 1.2µm vector grid

**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: µnw/µw=0.145

Representative of CO₂/brine system under aquifer conditions

Drainage experiment

1) Micromodel saturated with the wetting fluid
2) Injection of the non-wetting fluid at 2.5.10⁻³mL/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 \( \rightarrow \) perturb the wetting phase before the passage of the interface.


**Microdynamics of two-phase flow**

**µ-PIV results**

Displacement along x (\( U_x \)) and along y (\( U_y \)) of the wetting phase as a function of time for 3 positions in the porous medium.
**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?


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**Microdynamics of two-phase flow**

**Interface tracking**

- Interface > 500 µm/s
- Wetting phase: 20-100 µm/s

“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 and optimized

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

We have a tool to investigate two-phase flow mechanisms in micromodels quantitatively with high accuracy

• 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
• Quantification of re-circulations
• 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, SUPRI-B)

Final time = 0.32 seconds
grid: 360 by 120

Thank you for your attention!

Questions?

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