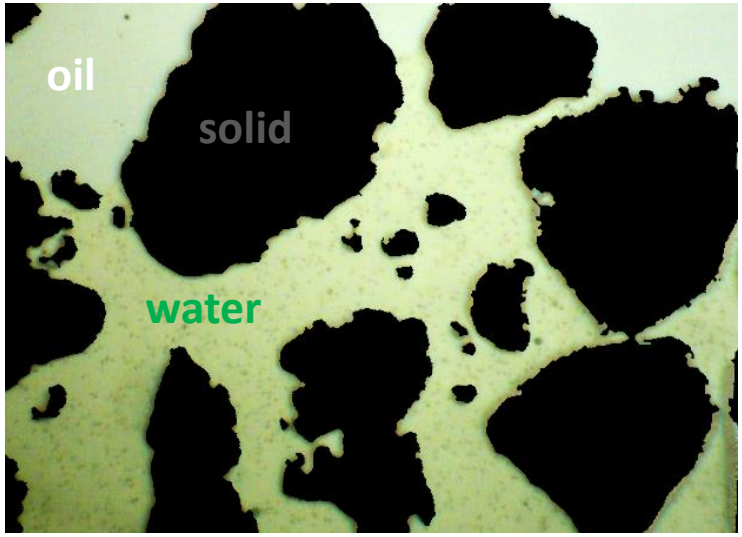
Image Analysis to Improve Data Acquisition During Micromodel Experiments



Sophie Roman, Anthony Kovscek

Stanford Center for Carbon Storage Annual Meeting, May 11-12, 2016

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

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

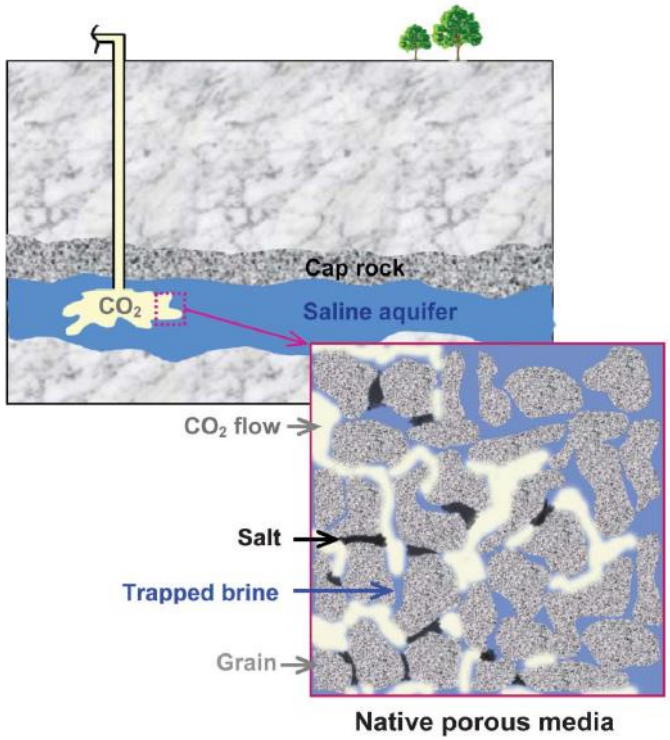
    - Tracking of a Fluid-Fluid Interface in Real-Time

  - Quantification of Calcite Dissolution in Micromodels

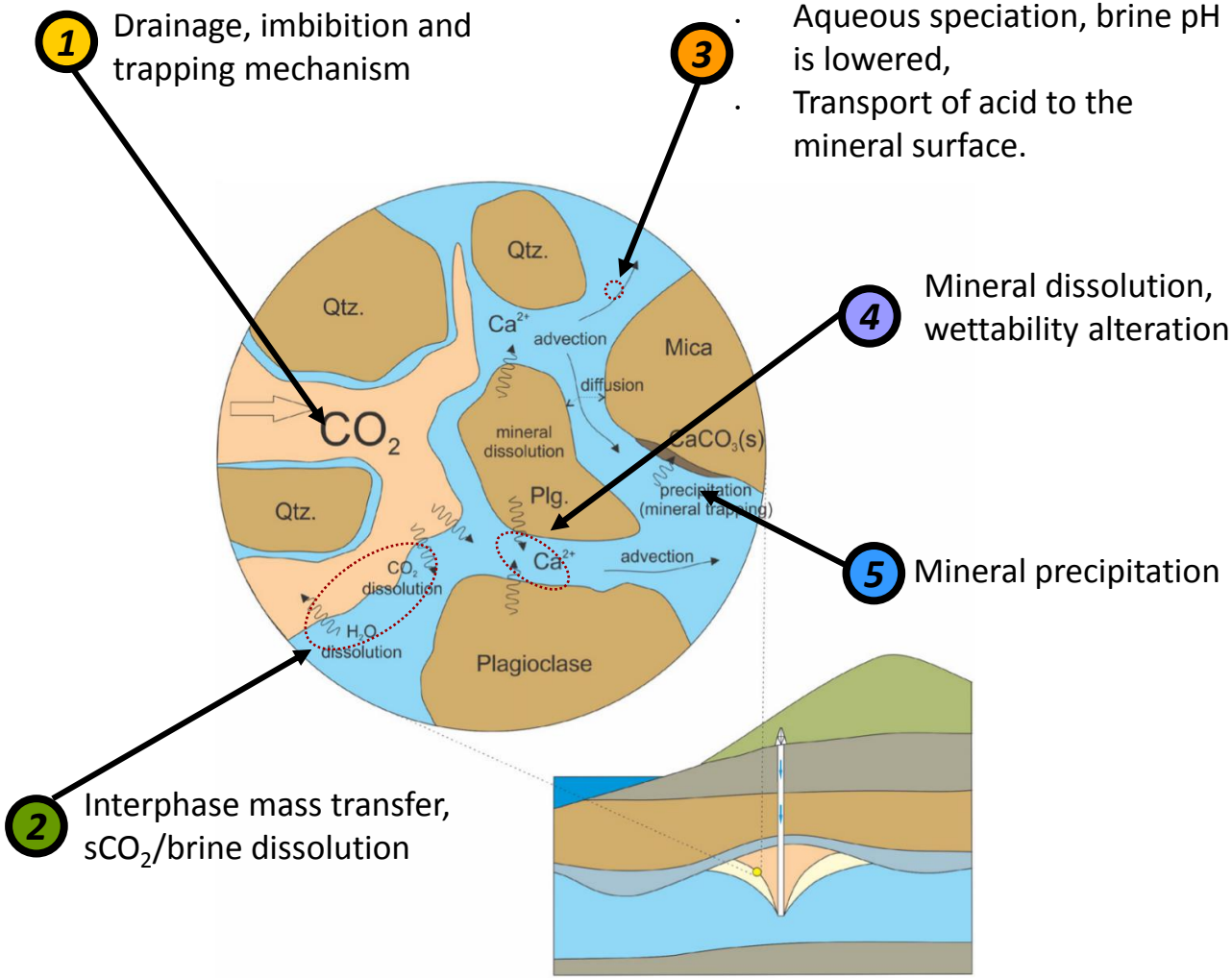
- Conclusion and Future Work

Multiphase Flow in Porous Media

CO_2 injection and sequestration



CO_2 sequestration into deep saline aquifer and pore-scale CO_2 flow in native porous media [1]

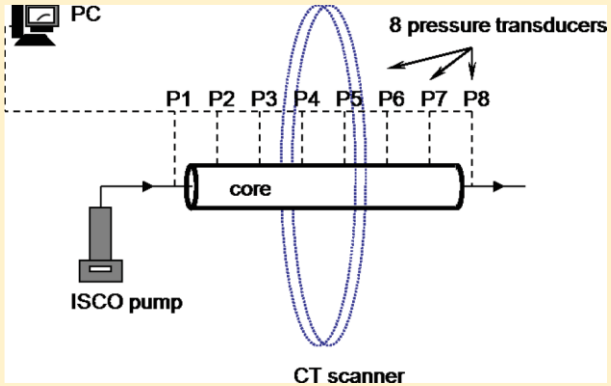


[1] Kim et al. (2013) *Aquifer-on-a-Chip: understanding pore-scale salt precipitation dynamics during CO_2 sequestration.* Lab on a Chip 13, 2508.
[2] Steefel et al. (2013), *Pore Scale Processes Associated with Subsurface CO_2 Injection and Sequestration Reviews in Mineralogy and Geochemistry*, 77, 259-303

Multiphase Flow in Porous Media

Experimental investigations

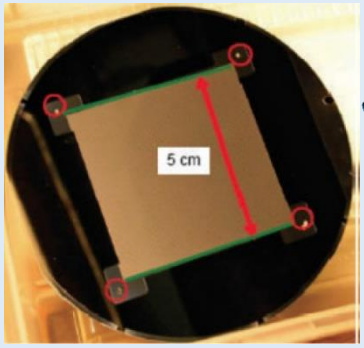
Core-scale



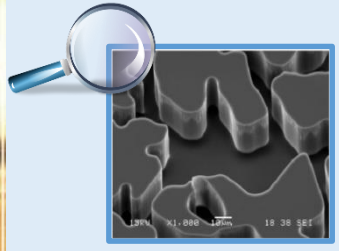
Two-phase immiscible drainage experiments [1]
Dissolution in fractured carbonate experiments [2]

2D Micromodels [2]

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



Etched pore pattern



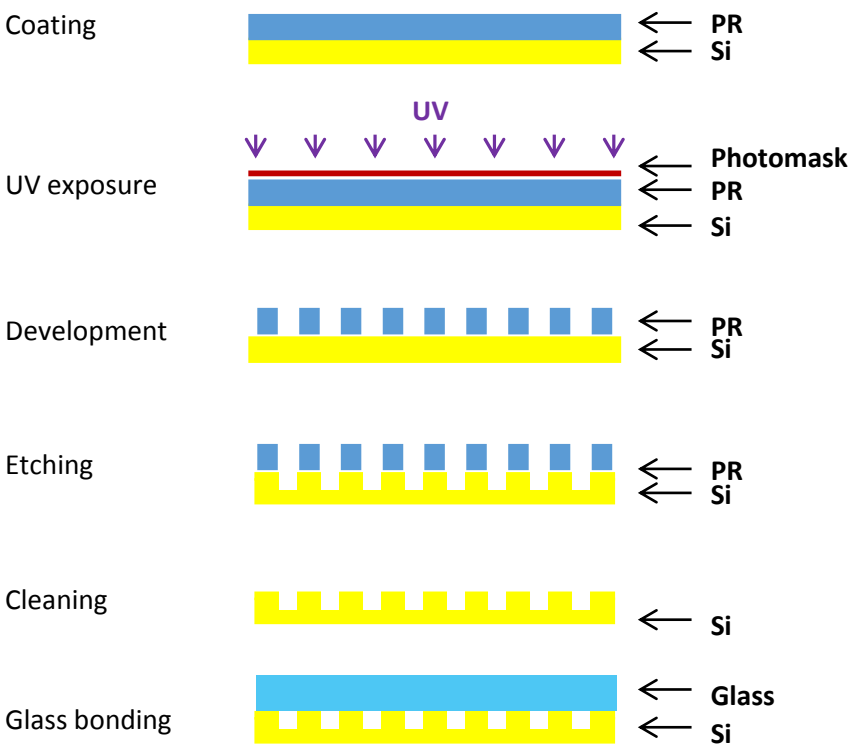
[1] Aryana and Kovscek (2012), *Experiments and analysis of drainage displacement processes relevant to carbon dioxide injection.* Phys. Rev. E. 86, 066310
[2] Elkhoury et al. (2013), *Dissolution and deformation in fractured carbonates caused by flow of CO2-rich brine under reservoir conditions*, Int. J. Greenh. Gas Control
[3] Buchgraber et al. (2011*) A microvisual study of the displacement of viscous oil by polymer solutions*. SPE Reservoir Evaluation & Engineering 14, 269280.

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

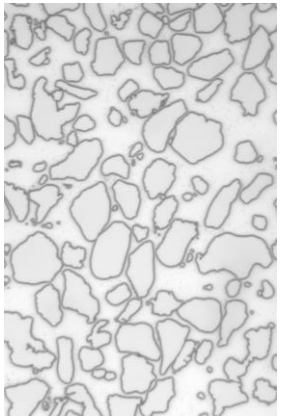
Etched Silicon-Micromodels

- Microfabrication of 2D etched-silicon micromodels

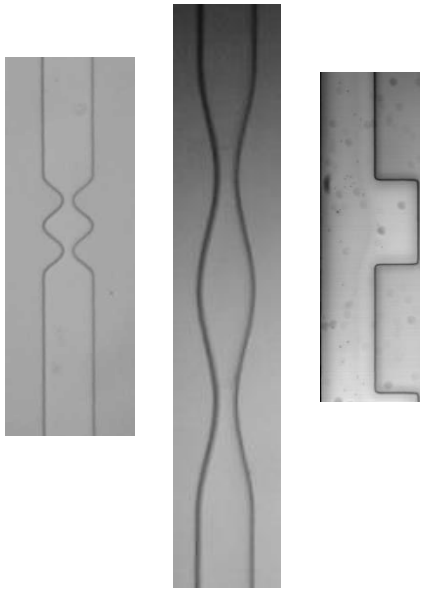


Etching depth: 12-30µm
Micromodel surface: water-wet

- Etched patterns

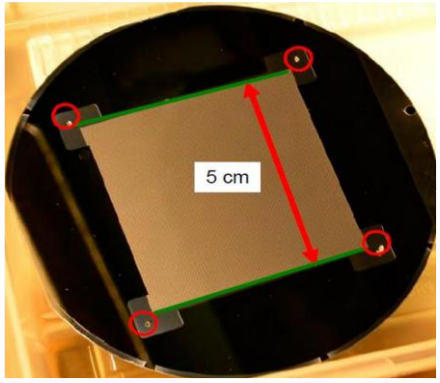


Rock-replica: sandstone
1:1 representation of pore sizes

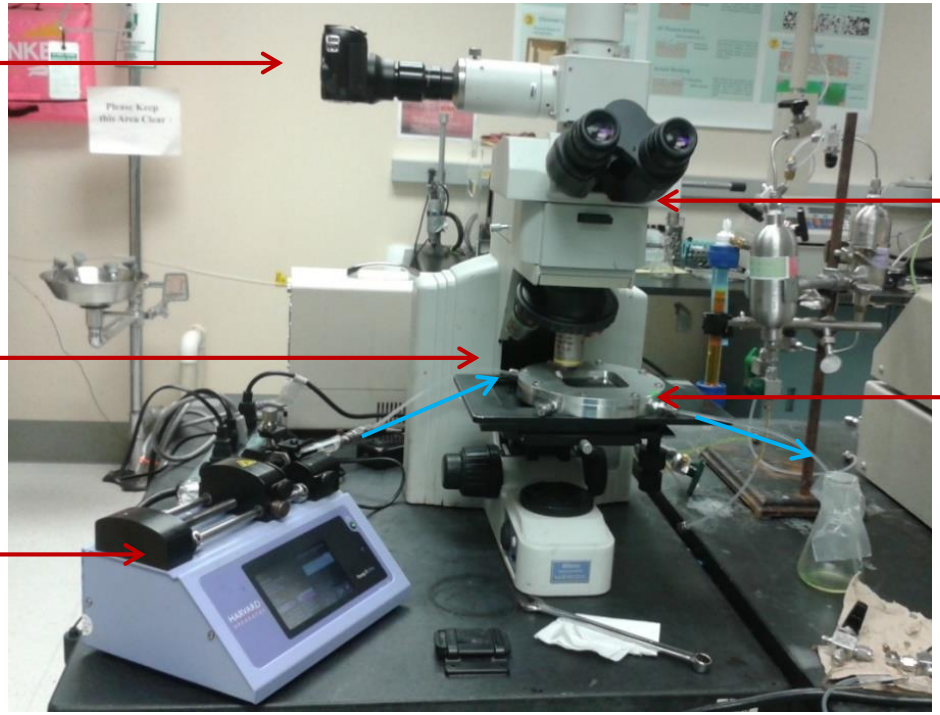


Capillaries with different pore shapes

- 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

Outline

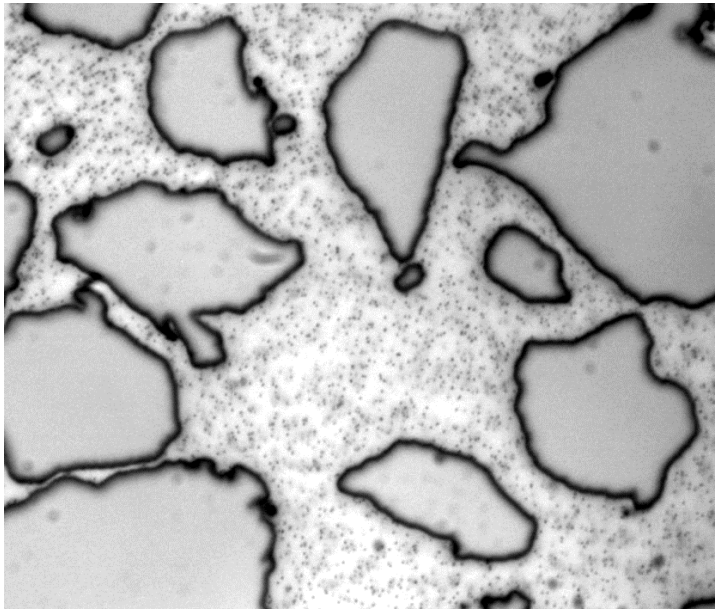
- Scientific Context
- Experimental Setup
- Improving the Visualization of Pore-Scale Mechanisms in Micromodels:
  - Two-Phase Immiscible Flows
    - Particle Velocimetry Analysis of Immiscible Two-Phase Flow in Micromodels
    - Tracking of a Fluid-Fluid Interface in Real-Time
  - Quantification of Calcite Dissolution in Micromodels
- Conclusion and Future Work

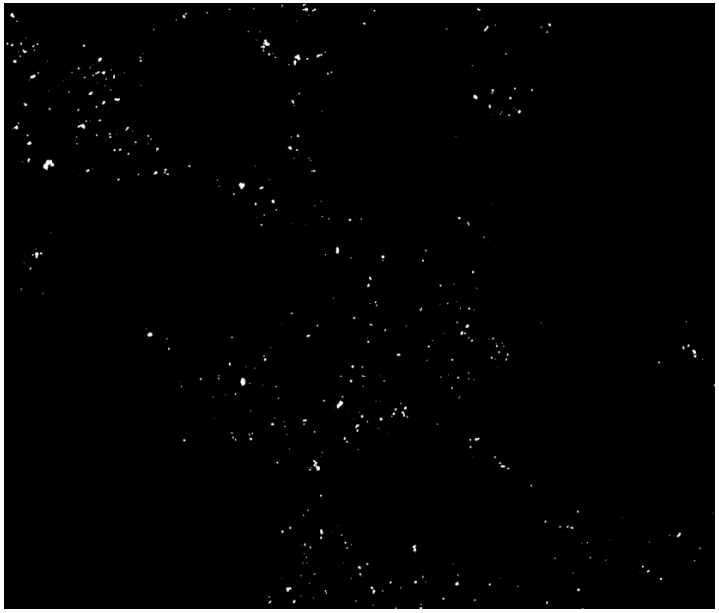
Sequences of images and image processing

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.

50µm





Original image sequence
Single phase flow

After image processing: bright particles, dark background and grains

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

Particle Image Velocimetry (PIV)

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

Image pair

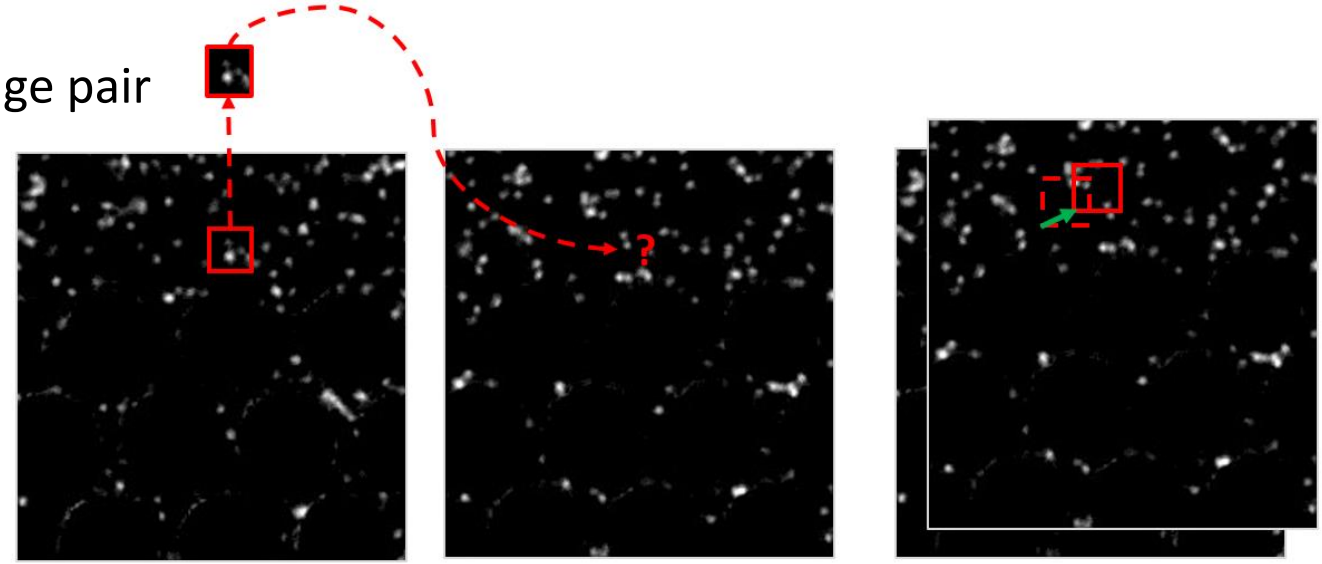
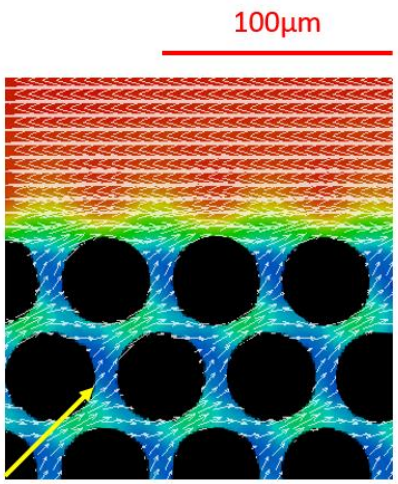


Image at time *t* | *Image at time t+Δt* | *Displacement of the interrogation window for one image pair*

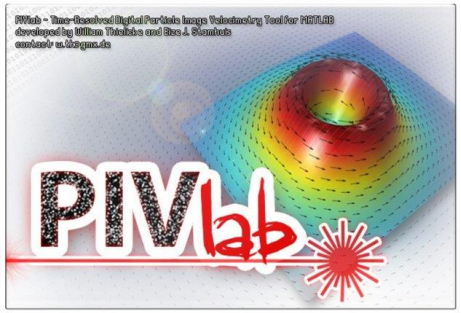


Velocity field

Typical PIV result

- 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+Δt* 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.



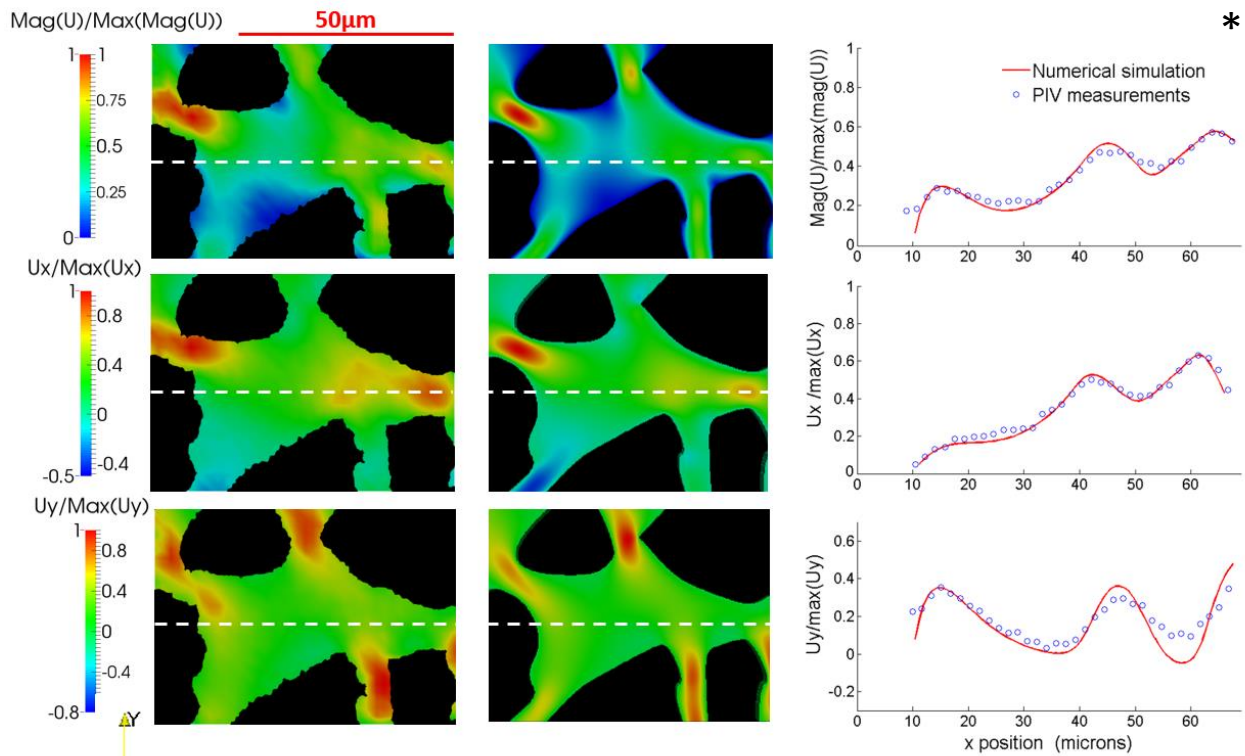
PIV tool for MATLAB

Adrian, R. J. and J. Westerweel (2011*). Particle Image Velocimetry*. Cambridge University Press.

Validation of micro-PIV in micromodels

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



Experimental data

Numerical simulation

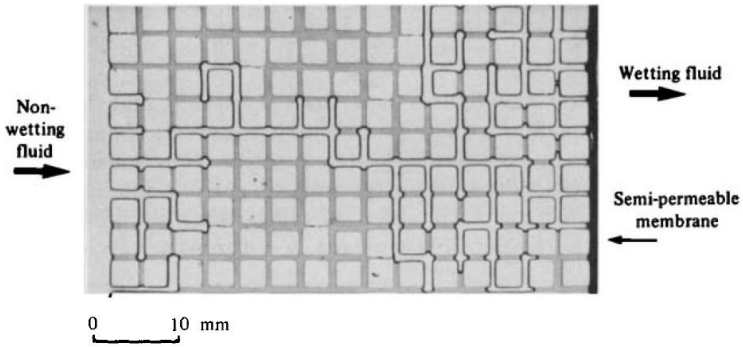
C

- 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

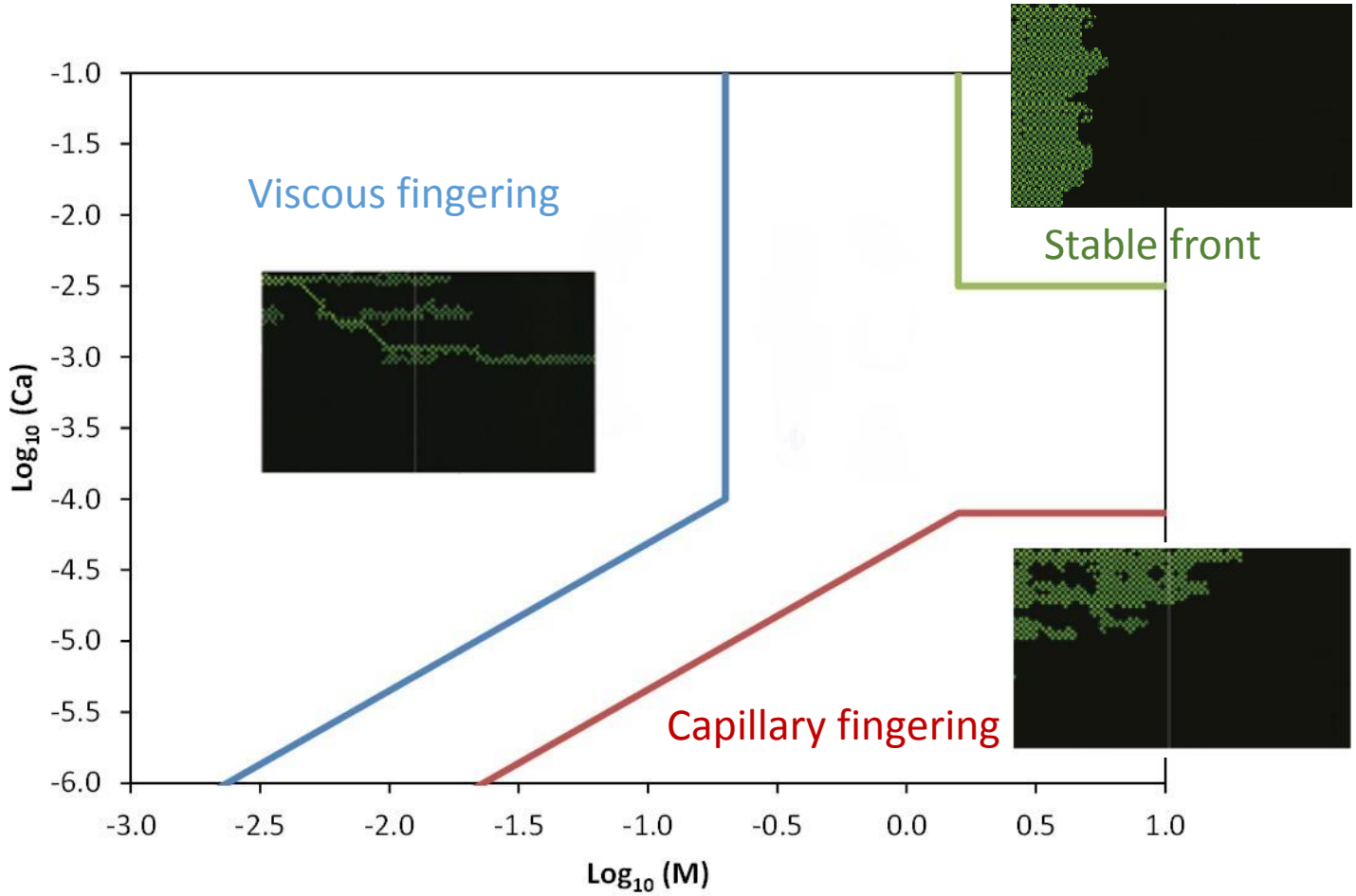


Lenormand, R., C. Zarcone, and A. Sarr (1983). *Mechanisms of the displacement of one fuid by another in a network of capillary ducts*. J. Fluid Mech. , 33753

Viscosity ratio: $M = \mu_{nw} / \mu_w$

Capillary number:
$Ca = \mu_{nw}.u_{nw} / (\sigma_{nw\text{-}w}.\cos\theta)$

nw: non-wetting, *w*: wetting

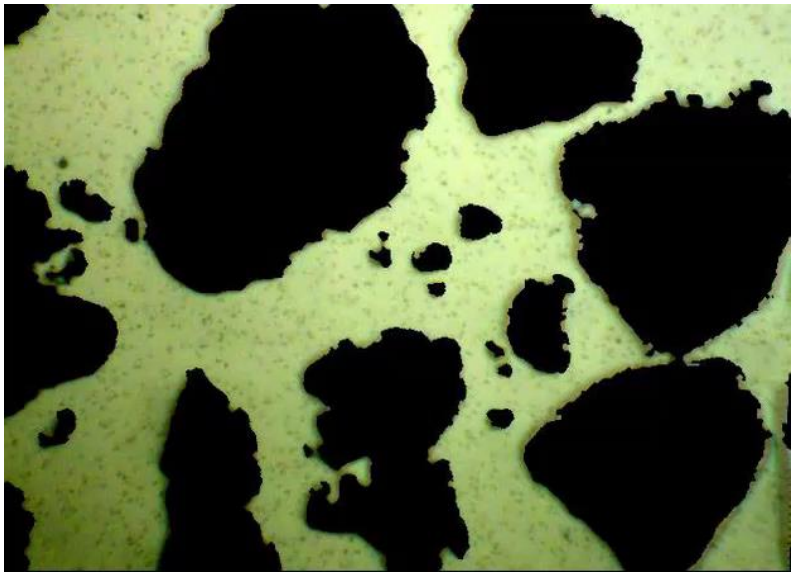


Zhang et al. (2011), *Influence of Viscous and Capillary Forces on Immiscible Fluid Displacement (…)*, Energy & Fuels 25, 3493-3

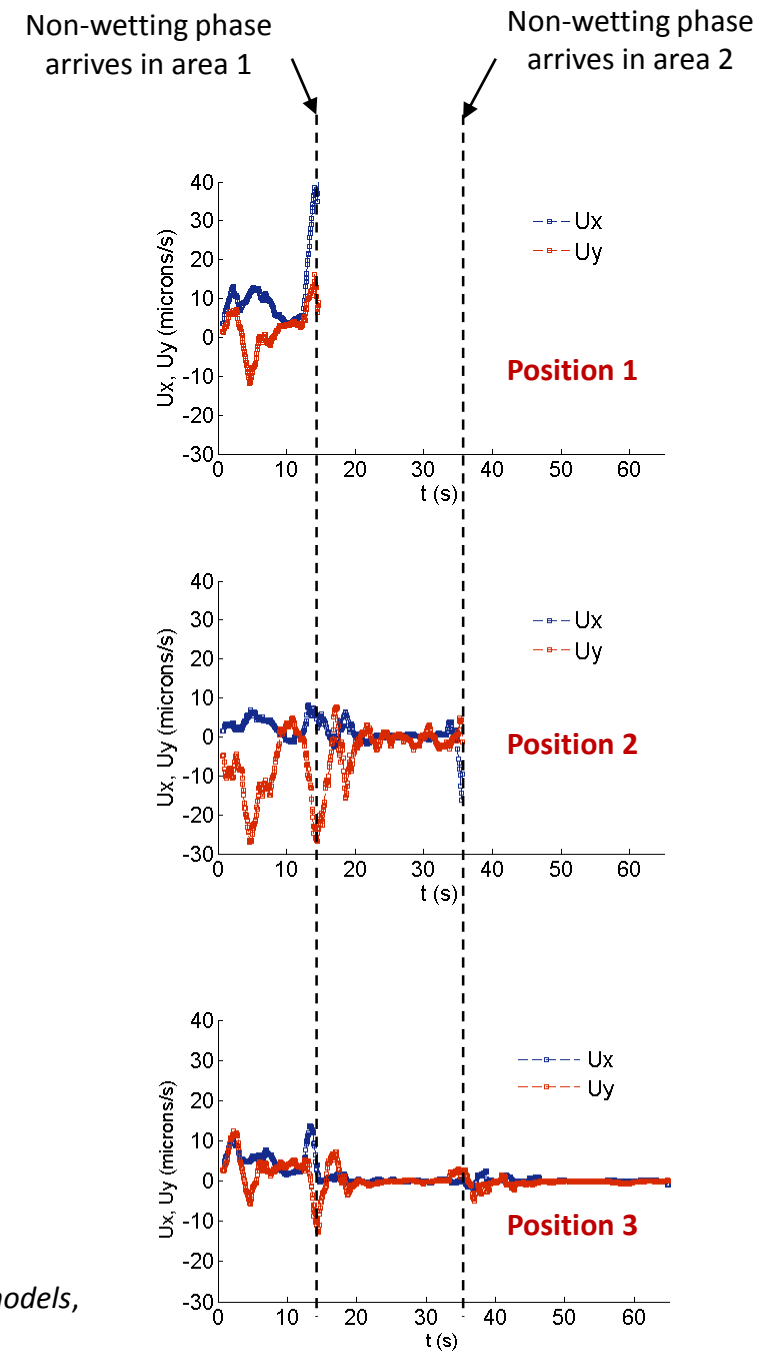
Microdynamics of two-phase flow

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

Range of parameters representative of a CO_2/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

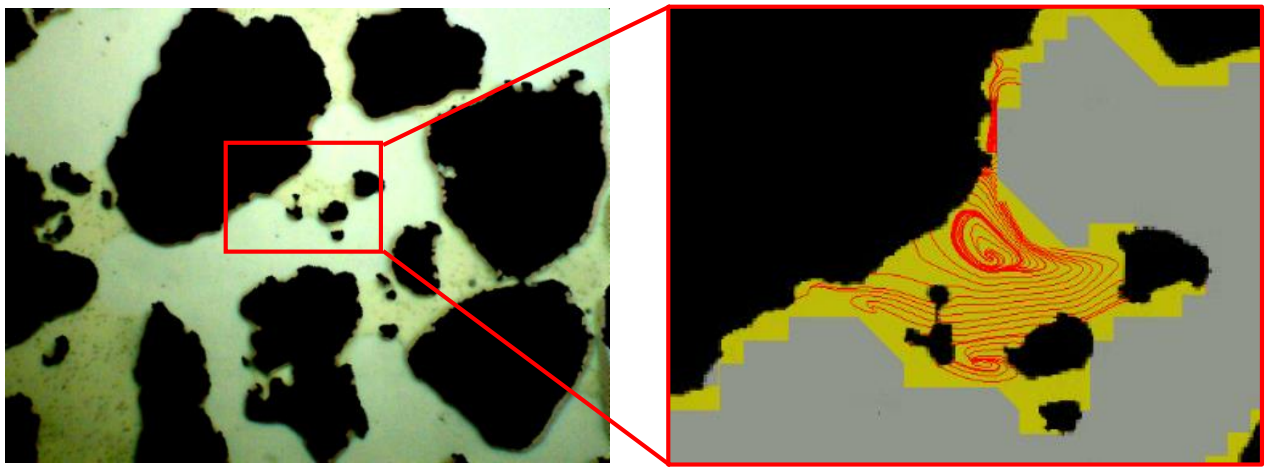
Microdynamics of two-phase flow

Observation and measurement of recirculation intensity

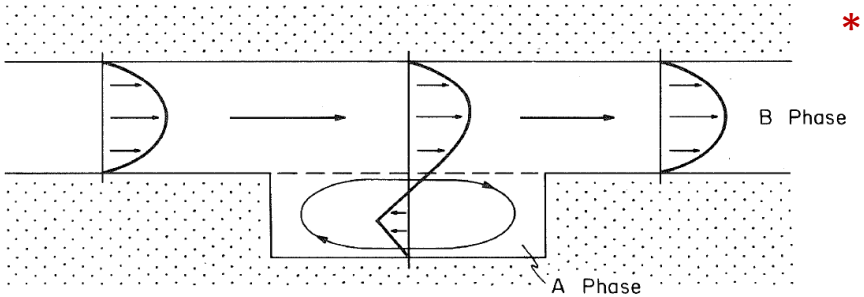
Driven cavity flow due to the shear stress resulting from the non-wetting phase that is still flowing.

→ 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

**Rose, W.. (1960*). Fluid flow in petroleum reservoirs: III. Effect of fluid-fluid interracial boundary condition.* Illinois State Geological Survey, 1-18

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

Outline

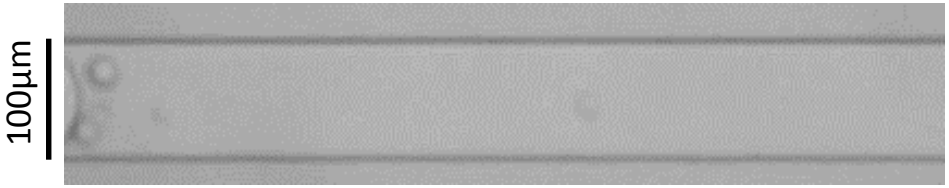
- Scientific Context
- Experimental Setup
- Improving the Visualization of Pore-Scale Mechanisms in Micromodels:
  - Two-Phase Immiscible Flows
    - Particle Velocimetry Analysis of Immiscible Two-Phase Flow in Micromodels
    - Tracking of a Fluid-Fluid Interface in Real-Time
  - Quantification of Calcite Dissolution in Micromodels
- Conclusion and Future Work

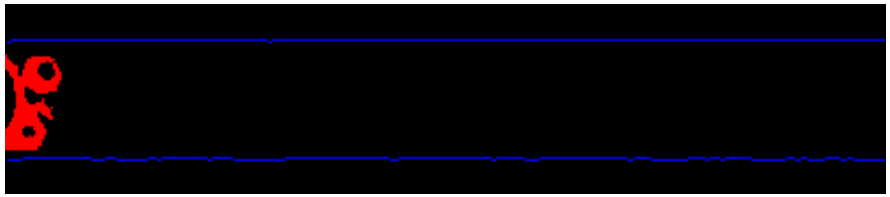
Image processing: detection of interface displacement

Experiments in simplified geometries

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

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





Pauline Louazel's experiments

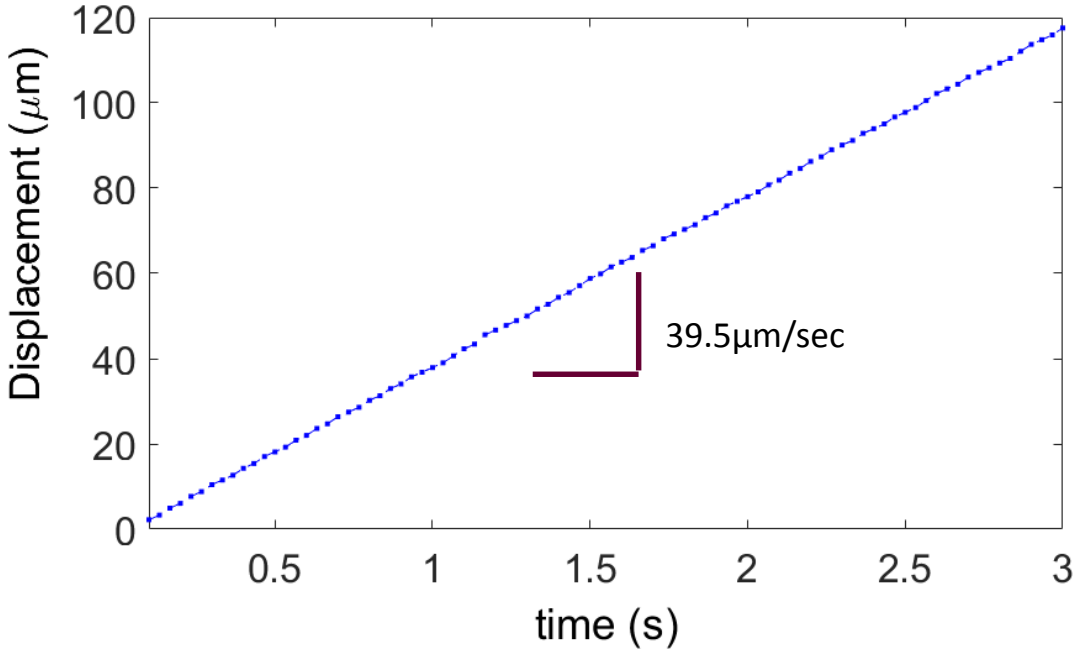
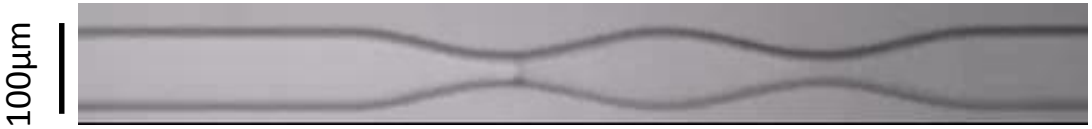


Image processing: detection of interface displacement

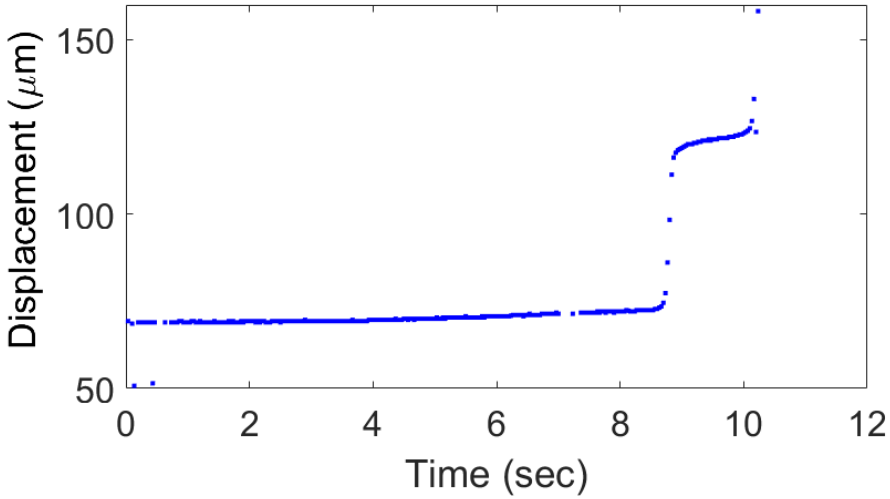
Experiments in simplified geometries

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

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



Pauline Louazel's experiments



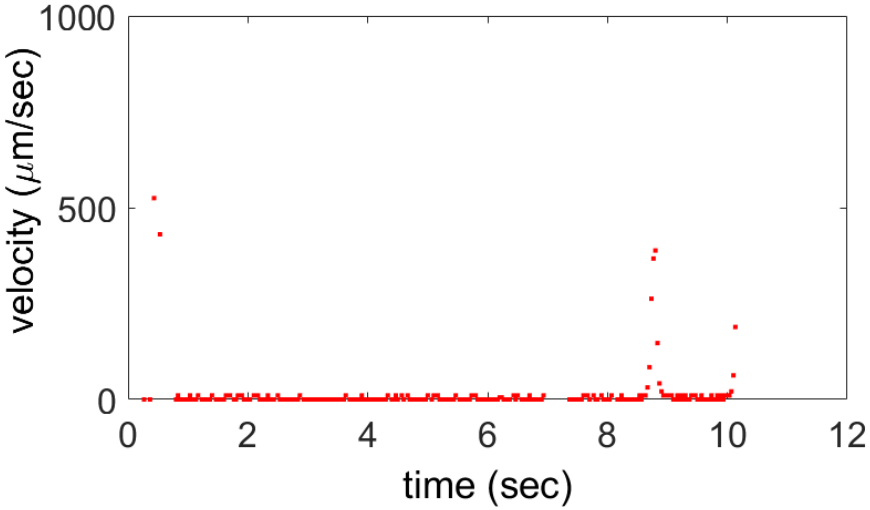
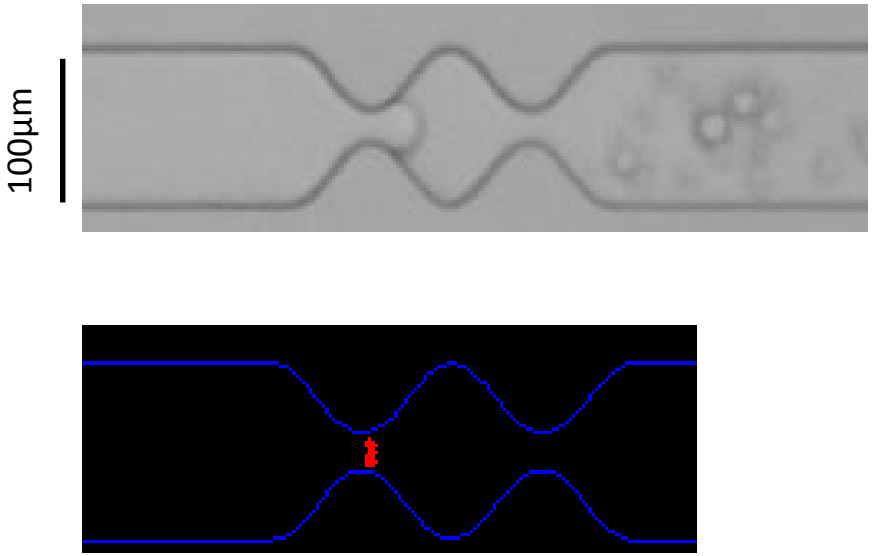


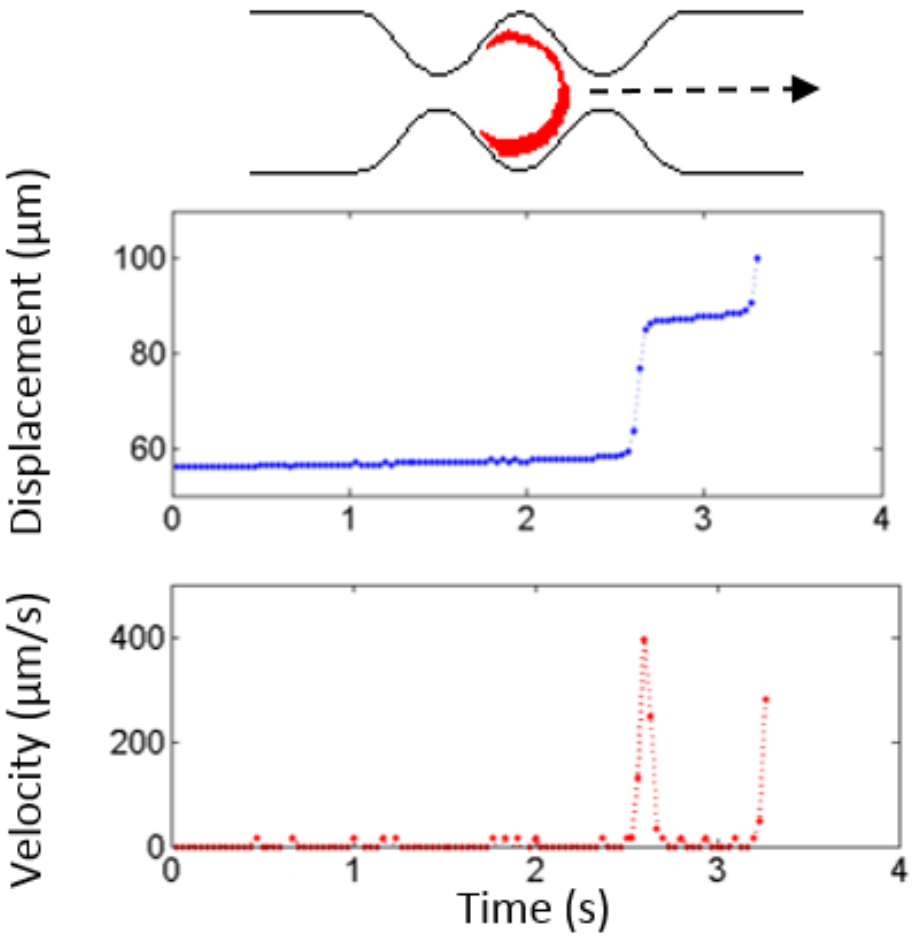
Image processing: detection of interface displacement

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 Louazel's experiments

Detection of interface and µ-PIV

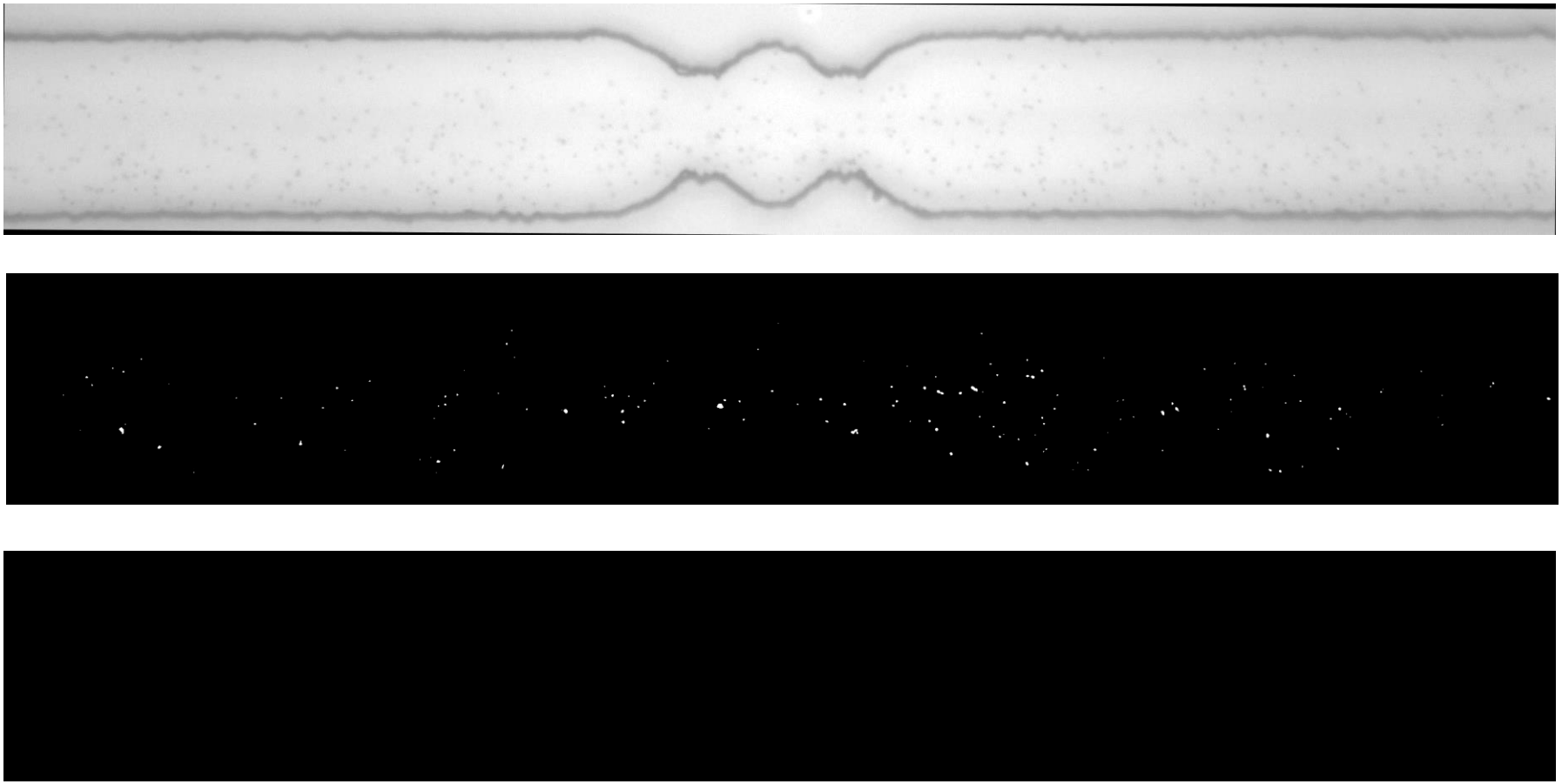
Experiments in simplified geometries

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

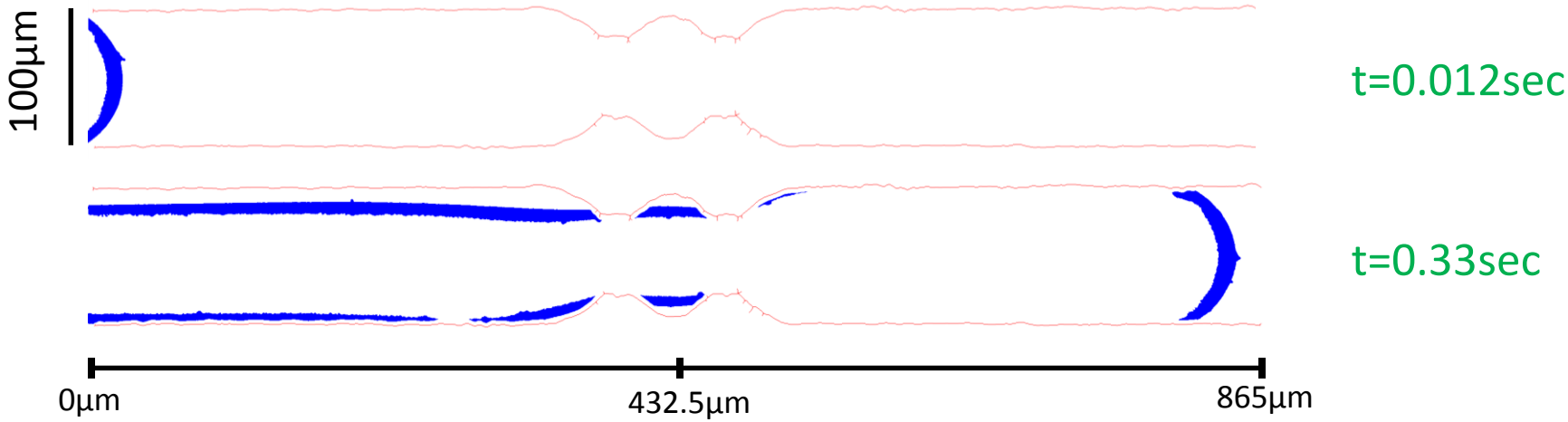
Heptane displacing water seeded with microparticles

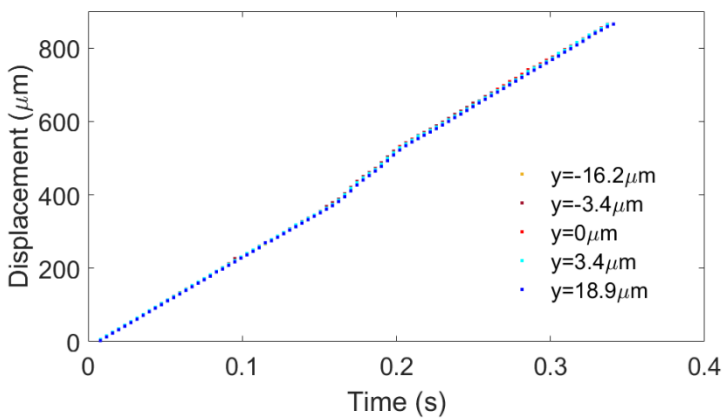
$\mu_o / \mu_w = 0.37$

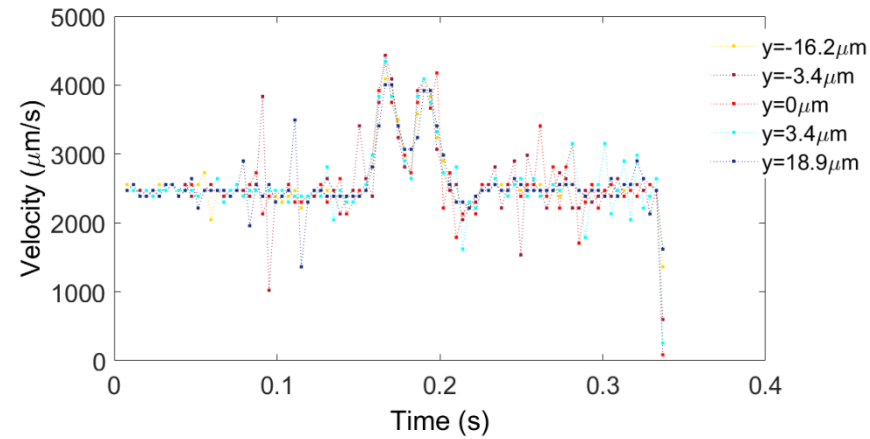
$D_{pore}/D_{throat} = 1.7$

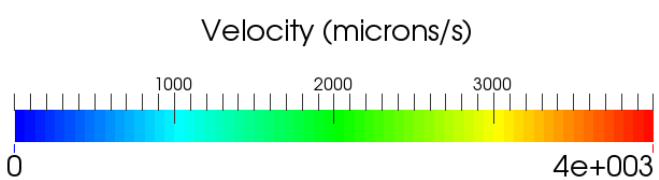


Detection of interface and µ-PIV

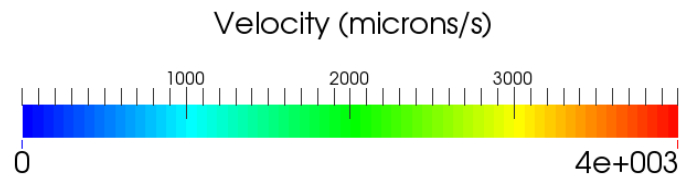




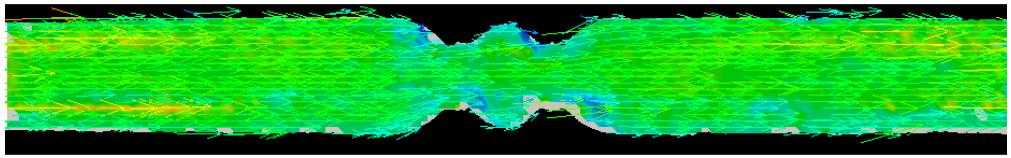




Before interface arrival



t=0.33sec

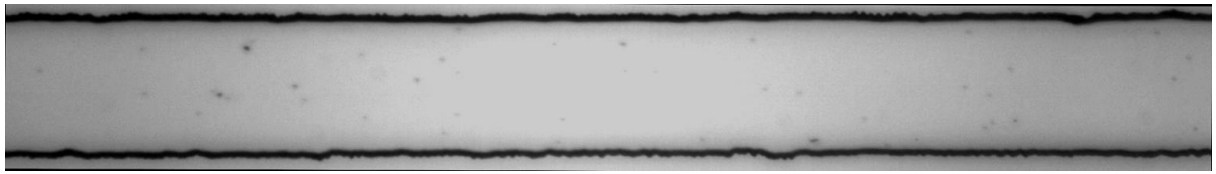


Microdynamics of two-phase flow: conclusion

- 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

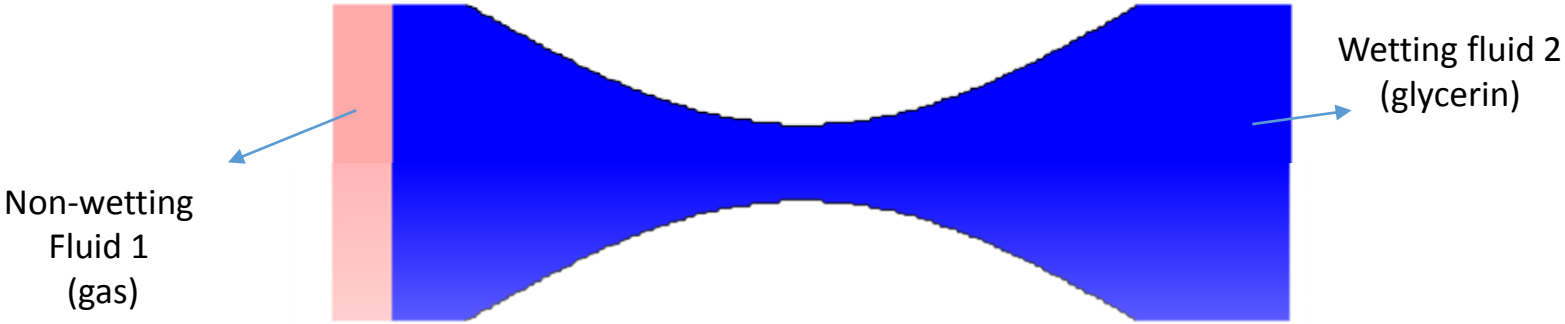
- **Future work**:
  - Extension of µ-PIV measurements to the oil phase

Melamine particles in silicone oil



  - Comparison with numerical simulations

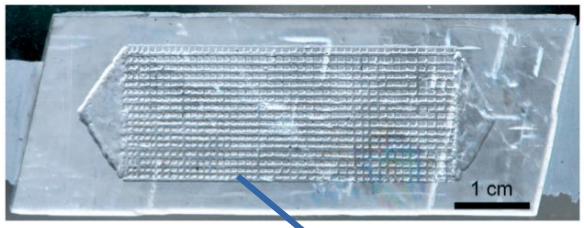
Converging-diverging tube drainage, Moataz Abu AlSaud



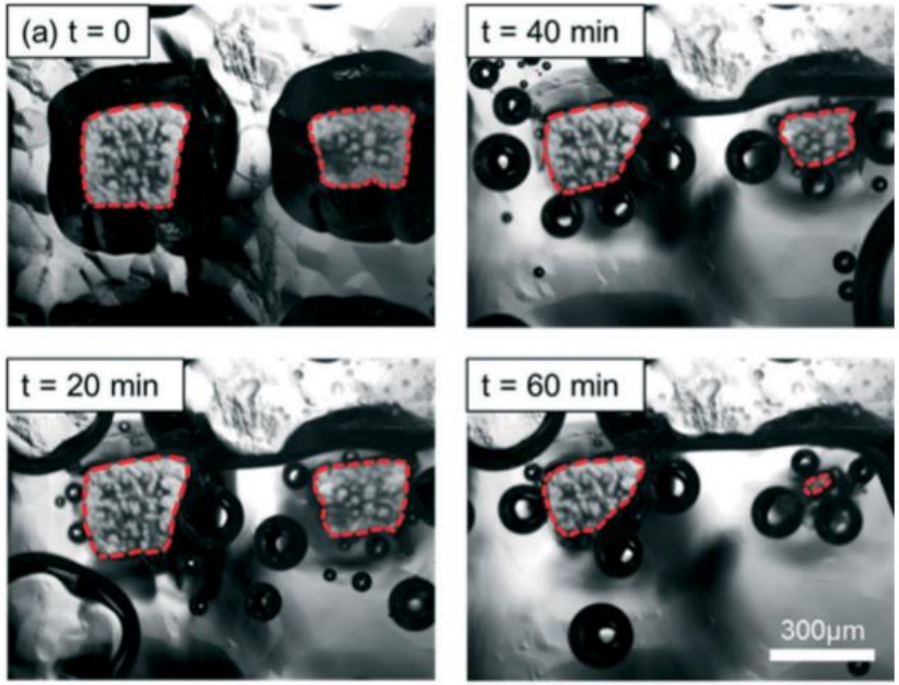
Outline

- 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

Calcite Dissolution in Micromodels



Song et al. experiments*



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

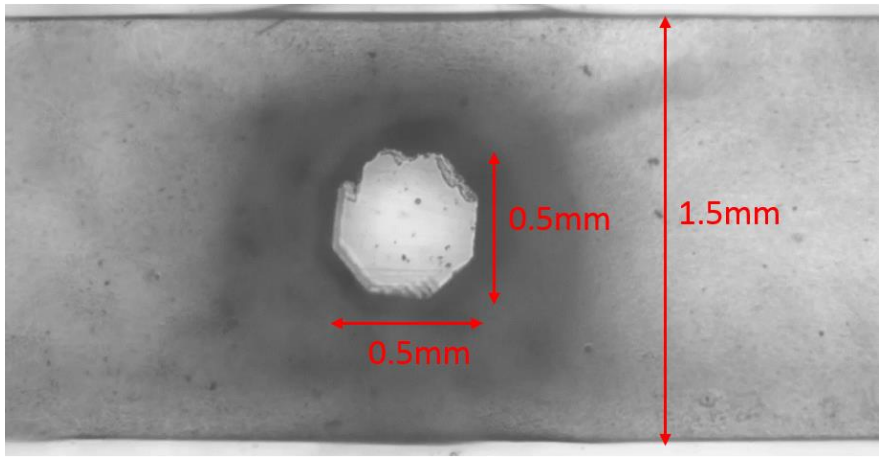
*Song et al. *Chip-off-the-old-rock: the study of reservoir-relevant geological processes with real-rock micromodels* Lab Chip, The Royal Society of Chemistry, 2014, 14, 4382-4390

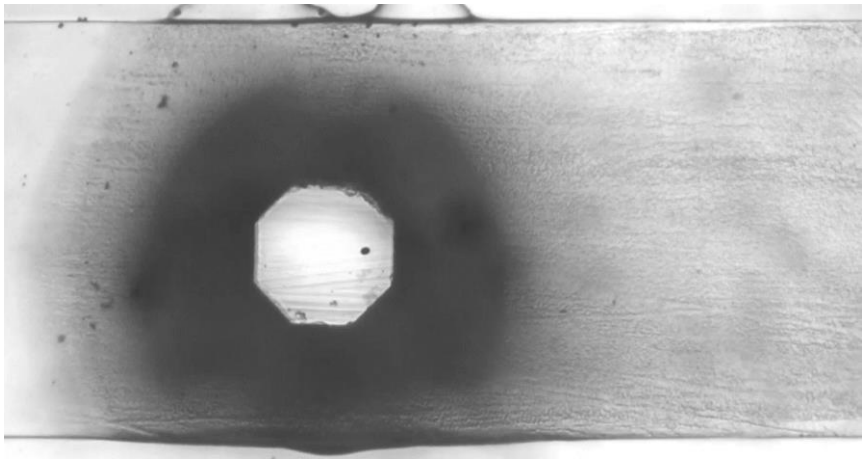
Calcite Dissolution in Micromodels

Experimental setup

- PDMS microchannel
- Calcite Crystal

Acid injection

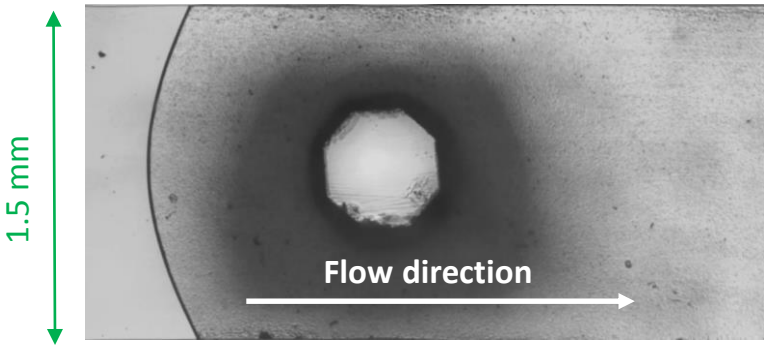




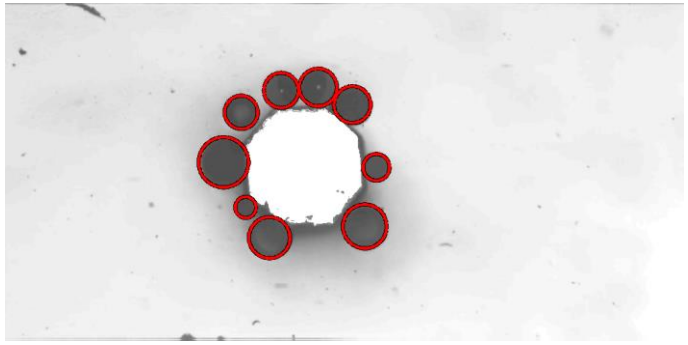
Calcite Dissolution in Micromodels

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

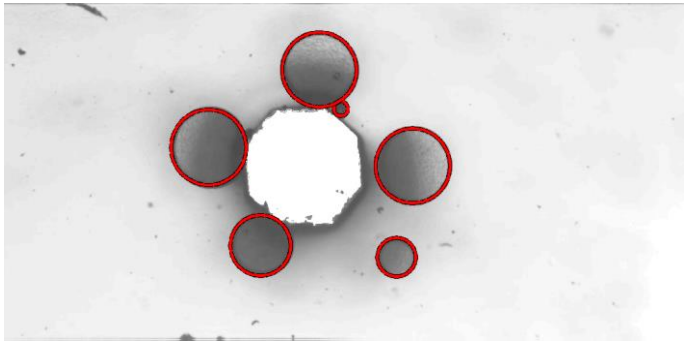
Before the passage of the acid front



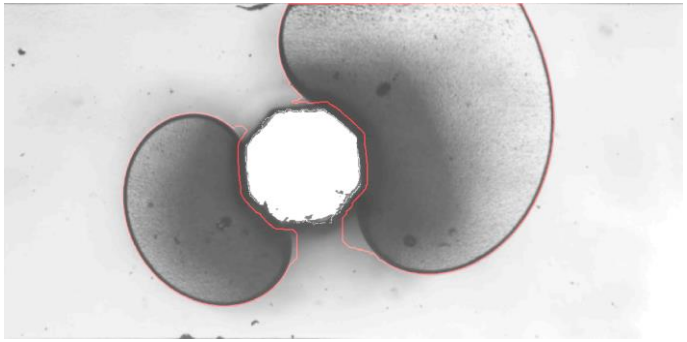
5.7 sec after the passage of the acid front



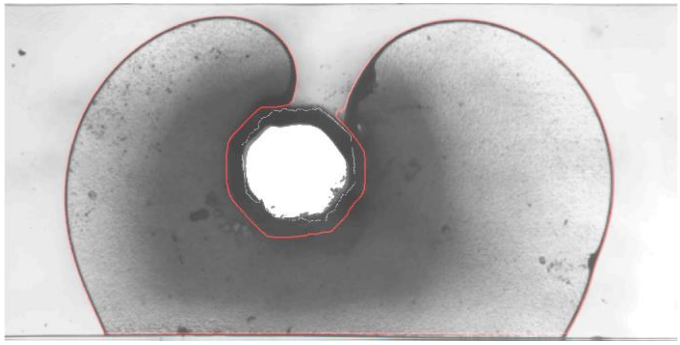
52 sec after the passage of the acid front



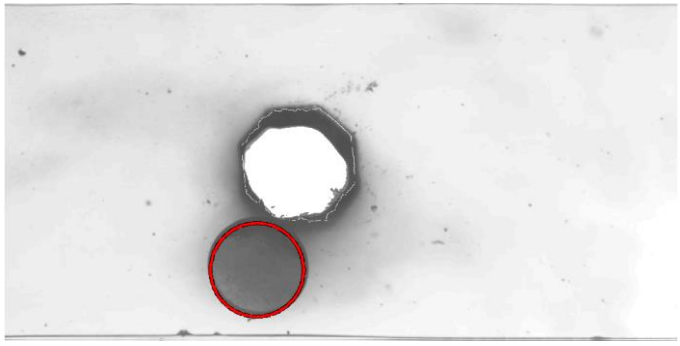
203 sec after the passage of the acid front



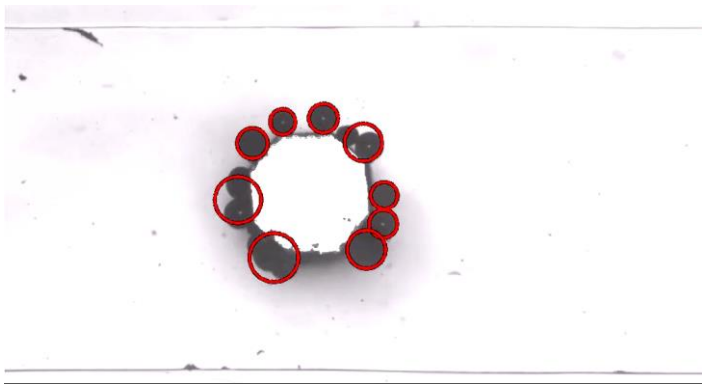
744 sec after the passage of the acid front



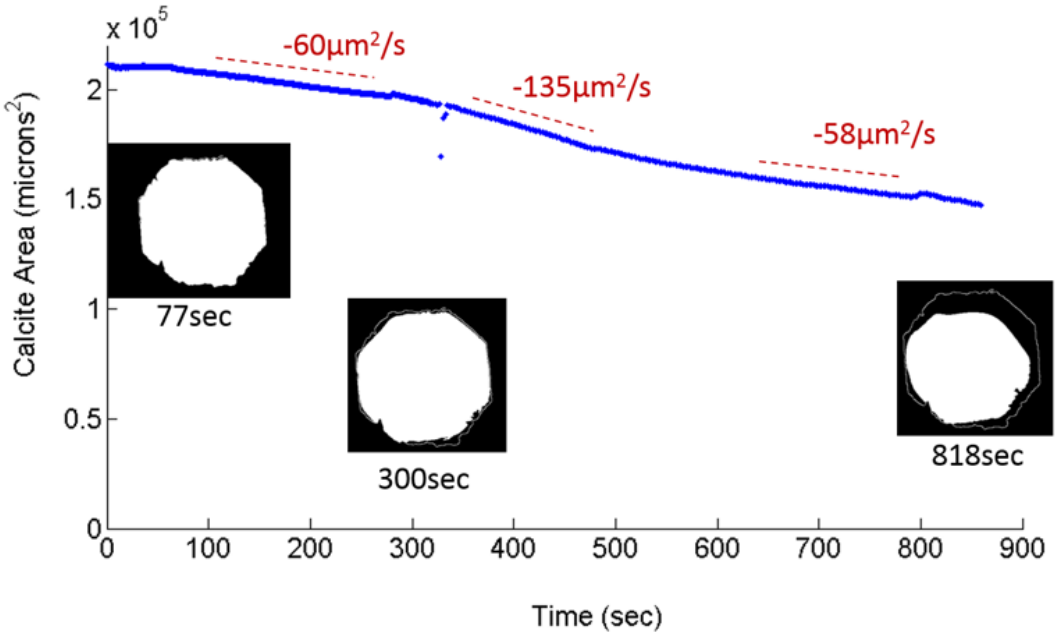
845 sec after the passage of the acid front

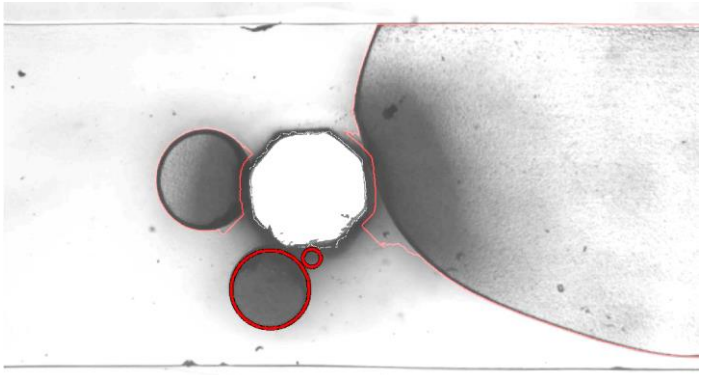


Calcite Dissolution in Micromodels

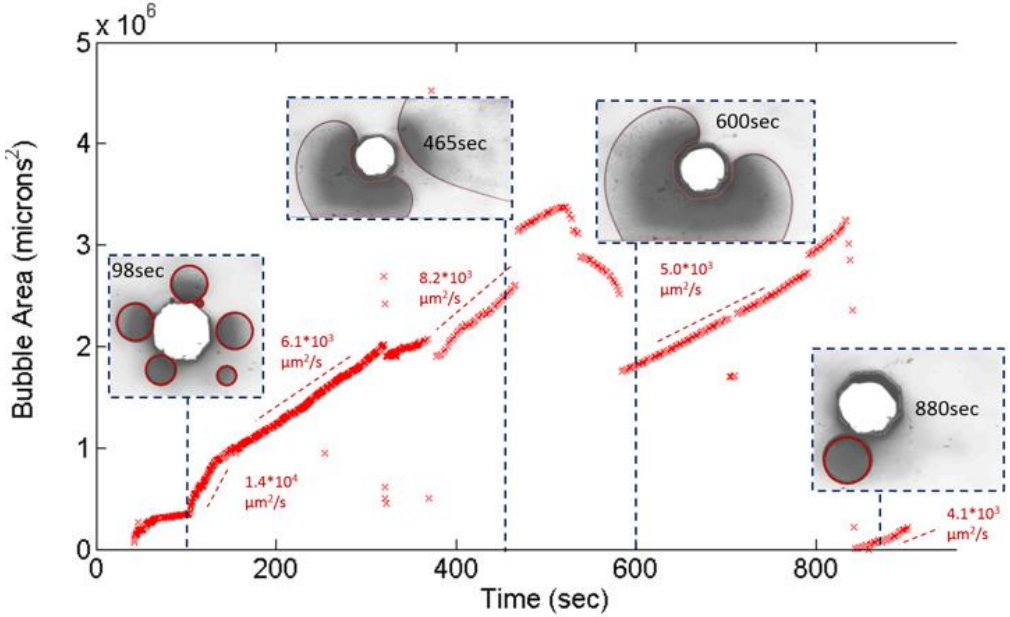


0-300sec





300-860sec



Movies >> X15

Calcite Dissolution in Micromodels: conclusion

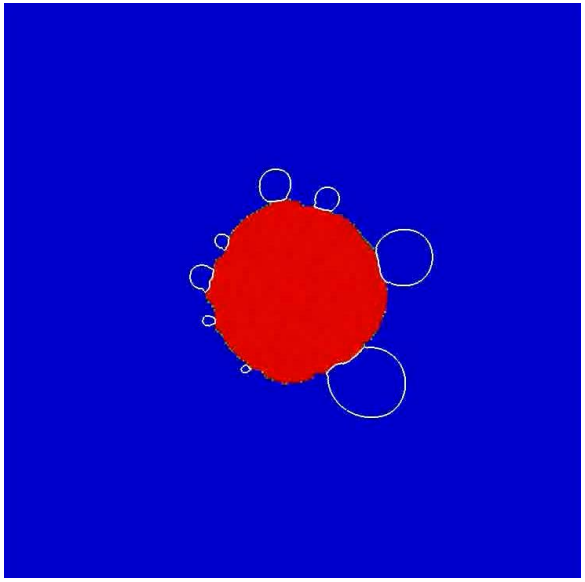
Conclusion:

- 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

Cyprien Soulaine



Red = solid

Blue = fluid

White = gas/liquid interface

Outline

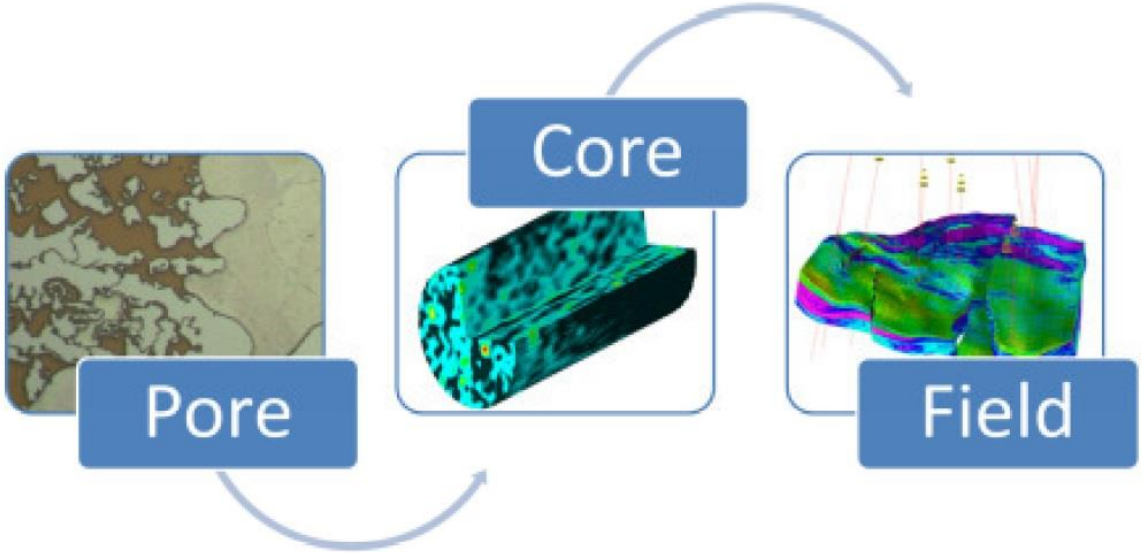
- Scientific Context
- Experimental Setup
- Improving the Visualization of Pore-Scale Mechanisms in Micromodels:
  - Two-Phase Immiscible Flows
    - Particle Velocimetry Analysis of Immiscible Two-Phase Flow in Micromodels
    - Tracking of a Fluid-Fluid Interface in Real-Time
  - Quantification of Calcite Dissolution in Micromodels
- Conclusion and Future Work

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



Buchgraber, M. (2013), Ph. D. thesis, Stanford University

Acknowledgement

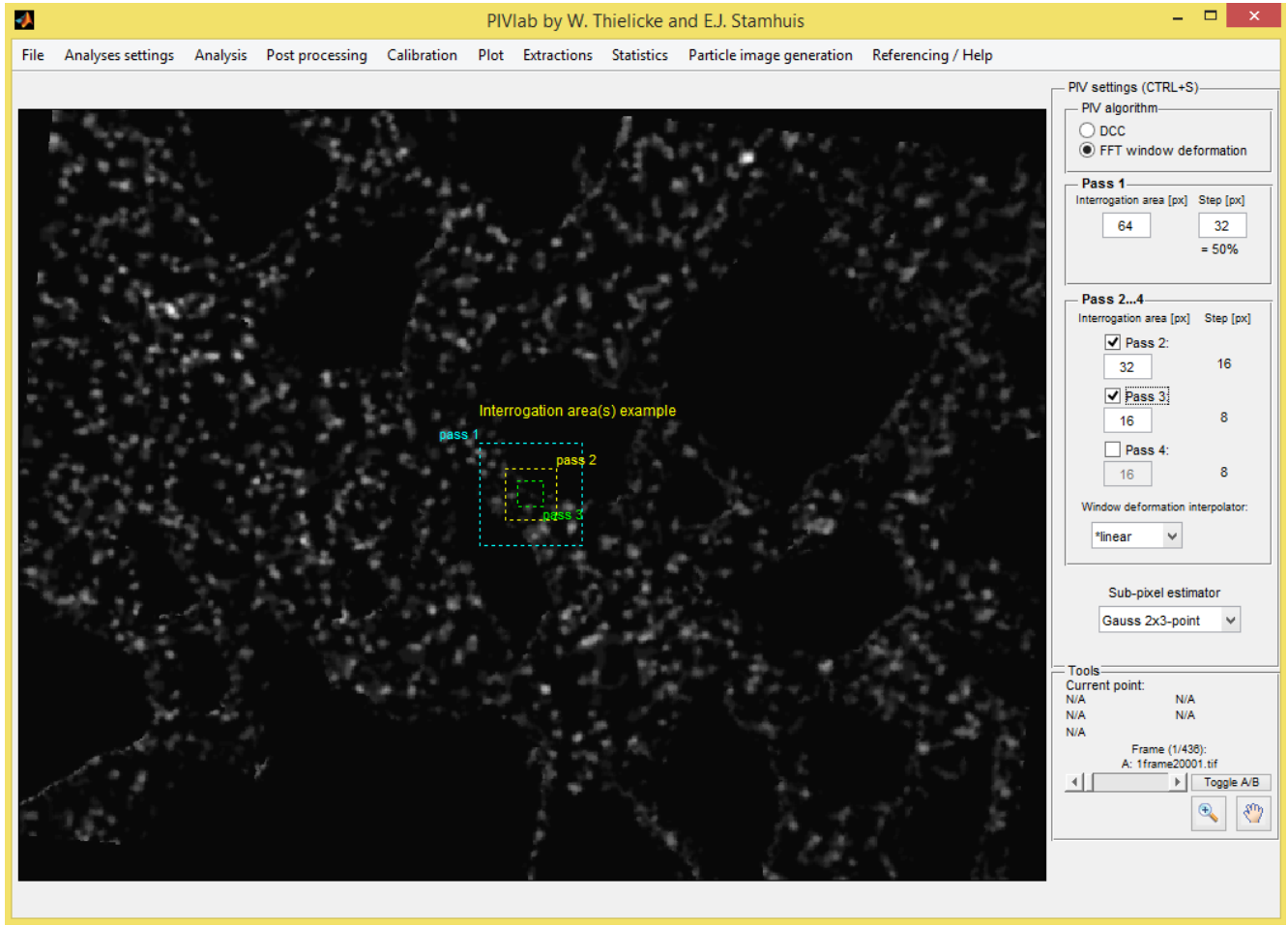
- SUPRI-A Team
- Pauline Louazel, Wen Song
- Cyprien Soulaine, Moataz Abu AlSaud

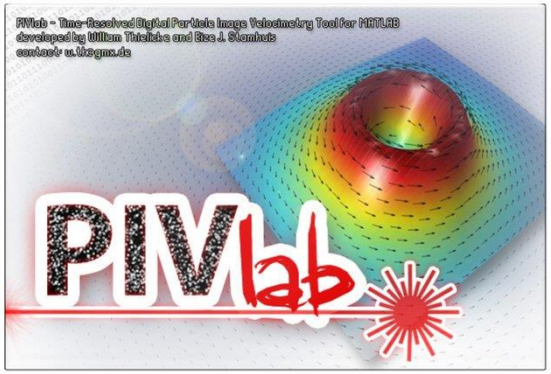
Thank you for your attention!

Questions?

sroman@stanford.edu

PIV measurements





*PIV tool for MATLAB**

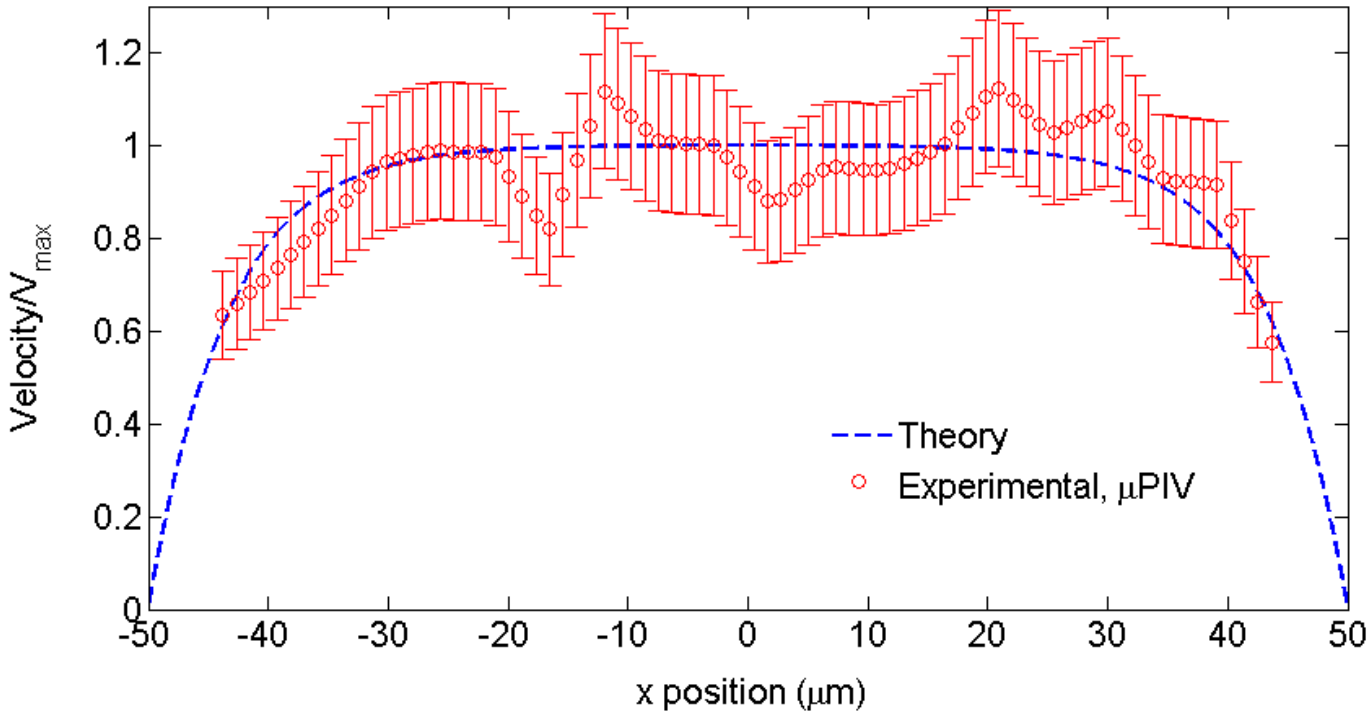
For a successful µ-PIV experiment**, consider:

- 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

* Thielicke, W. & Stamhuis, E. J. (2014): *PIVlab - Time-Resolved Digital Particle Image Velocimetry Tool for MATLAB* (version: 1.35)

**R. Lindken, M. Rossi, S. Große, and J. Westerweel (2009) *Micro-particle image velocimetry (µ-piv): Recent developments, applications, and guidelines*. Lab Chip 9 (17), 2551-2567.

Velocity profile before interface arrives
Slide 13&14

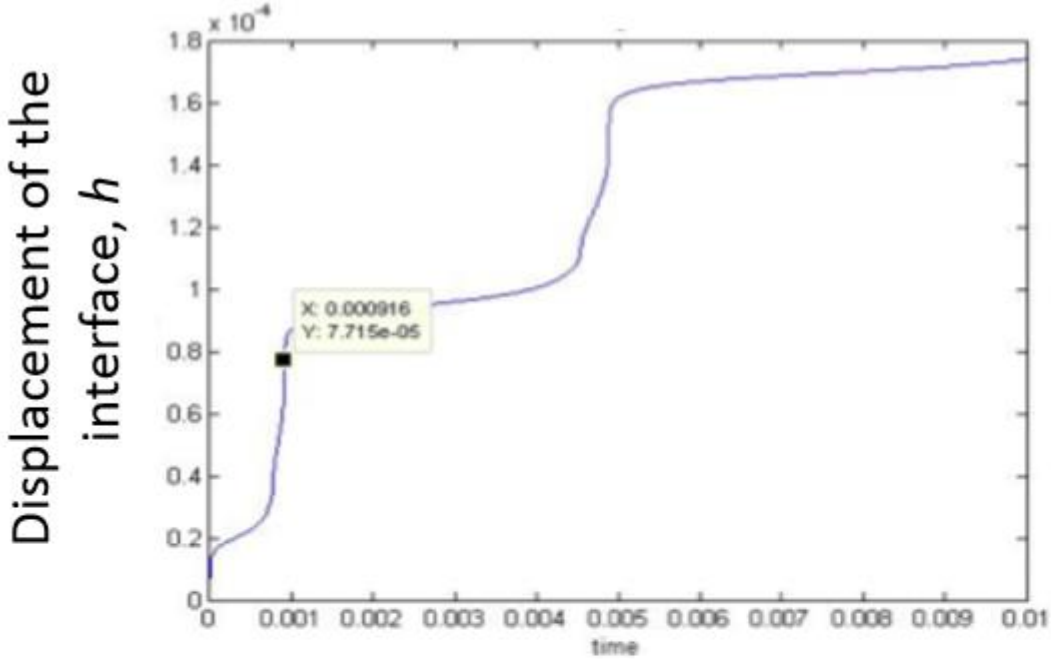


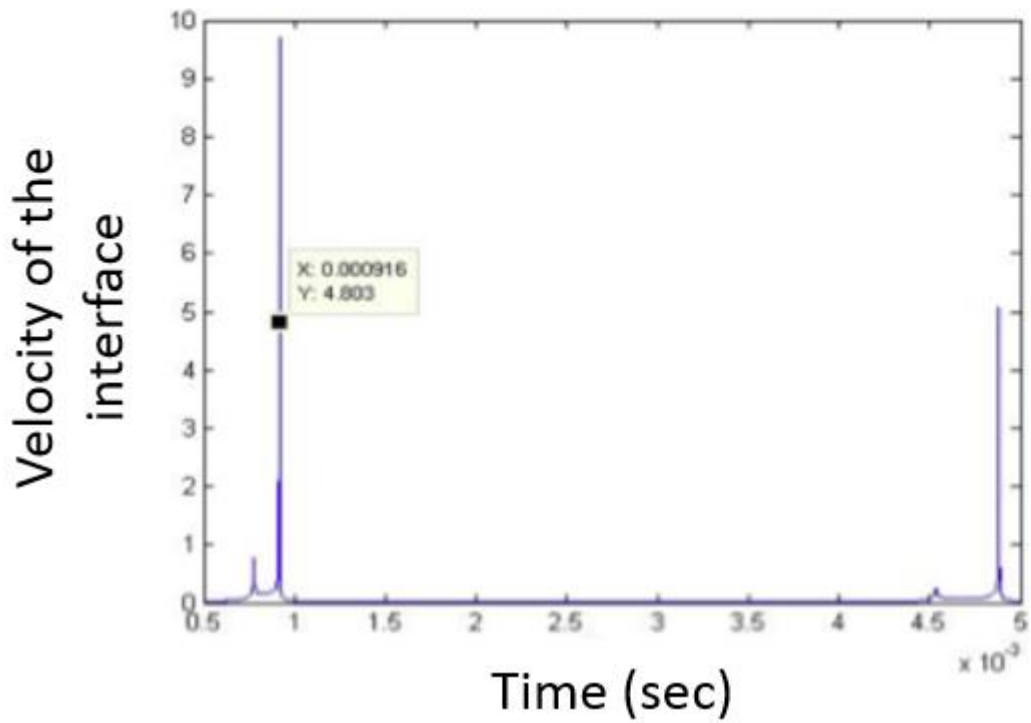
Terminal velocity

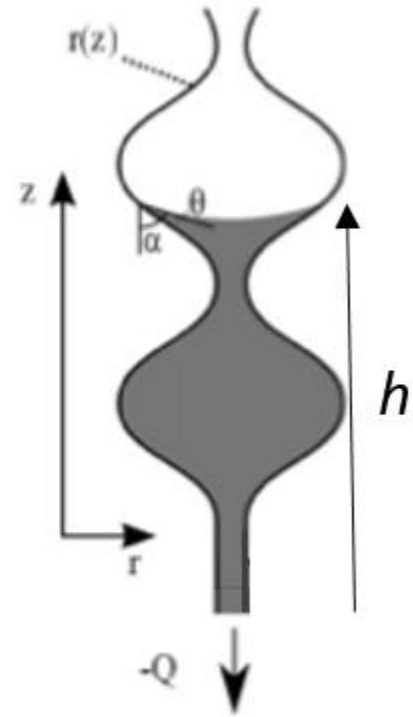
Creeping flow
(Re<<1)

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

Terminal velocity for creeping flow





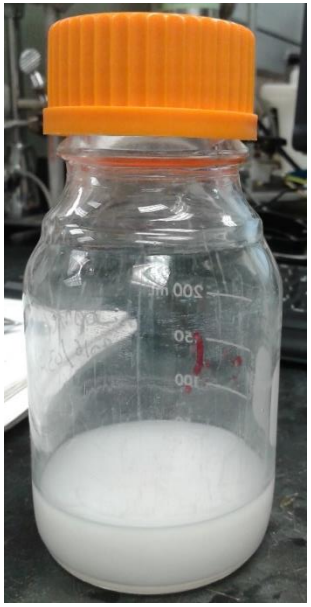


Model of Moebius & Or, 2012

Extend µ-PIV measures to oil phase

Melamine Resin particles*

- Density: 1.51g/cm ^{3}
- 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

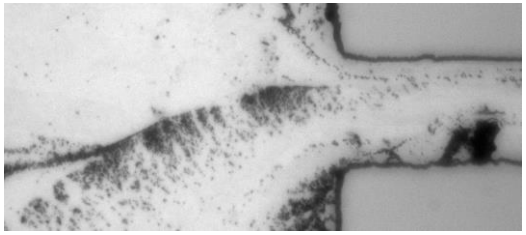


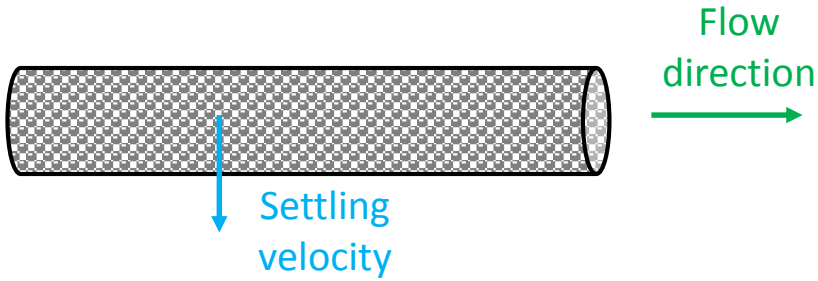
Dispersion in Heptane:
- Density: 0.68g/cm ^{3}
- Viscosity: 0.38cP

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

Dispersion in Silicone oil:
- Density: 0.96g/cm ^{3}
- Viscosity: 96cP

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

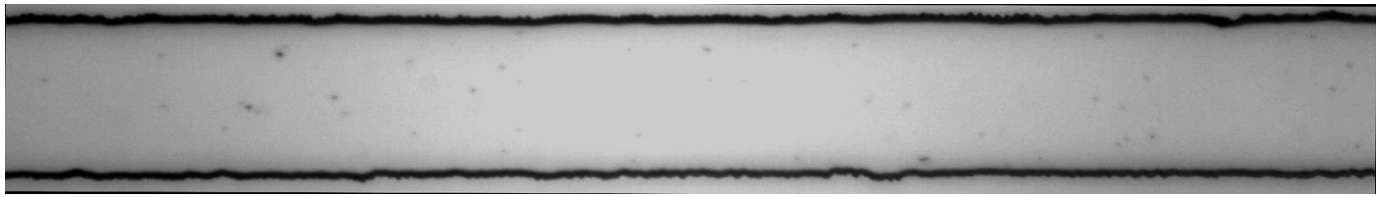




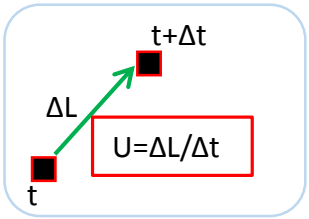
Timgren at al. (2008), Application of the PIV technique to measurements around and inside a forming drop in a liquid–liquid system*, Experiments in Fluids

Extent µ-PIV measures to oil phase

Melamine particles in silicone oil



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

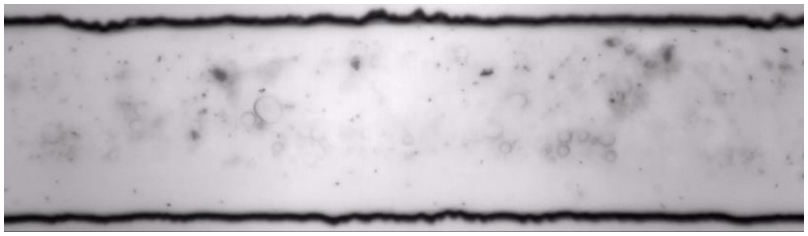


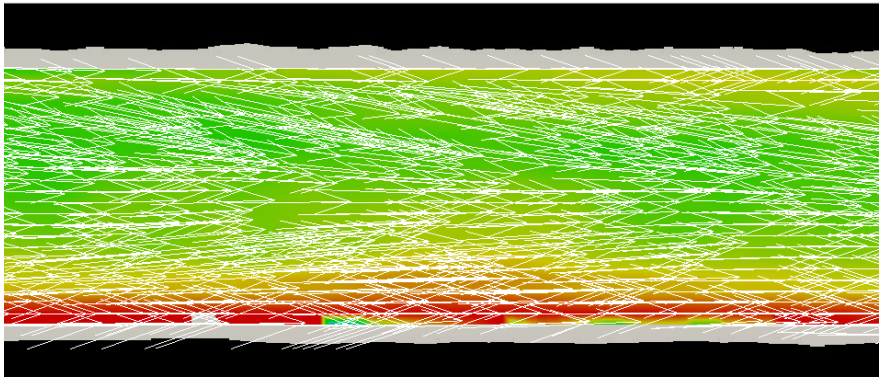
Particle Image Velocimetry

- High particle density each
- Groups of moving particles are analyzed

Particle Tracking Velocimetry

- Sparse seeding
- Each particle is analyzed individually



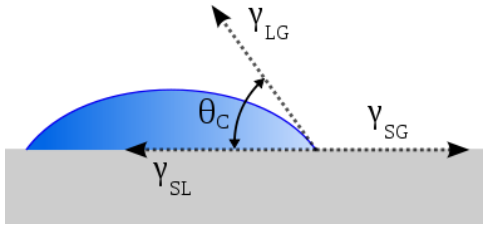


PTV measurements

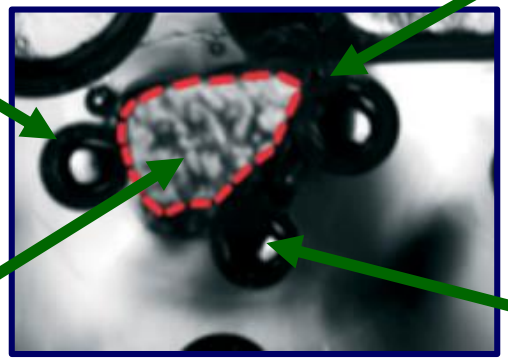
Micro-continuum model for multiphase flow

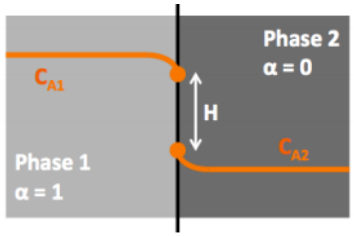
Volume-of-Fluid (VOF) approach[1] with CSF[2] and phase change[3]

0	0	0	0	0	0
0	0	0	0	0	0
0	0.2	0.1	0	0	0.1
0.6	1	0.8	0.4	0.1	0.6
1	1	1	1	1	1
1	1	1	1	1	1



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])

[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

[3]Welch and Wilson. A volume of fluid based method for fluid flows with phase change Journal of computational physics, Elsevier, 2000, 160, 662-682

[4]Horgue et al, M. *A penalization technique applied to the Volume-Of-Fluid method: Wettability condition on immersed boundaries* Computers & Fluids, 2014, 100, 255 - 266

[5]Haroun et al. *Volume of fluid method for interfacial reactive mass transfer: Application to stable liquid film* Chemical Engineering Science , 2010, 65, 2896 - 2909

Rates at different time steps during the experiment