Characterizing 3-D flow velocity in evolving pore networks driven by CaCO$_3$ precipitation and dissolution

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Precipitation alters structure

Fluids move through void spaces, marked here with blue epoxy, in sandstones.

Open pores enhance porosity

Plugged pores reduce porosity

Mehmani et al. 2012
Outline

1. Precipitation in micromodels
2. Flow in micromodels
3. Interaction of precipitation and flow in micromodels
Pore-scale reactive transport

Micromodel Experiment

- Two solutions are mixing along the centerline and CaCO$_3$ precipitates
- Range of concentrations and solution chemistry vary
- Microscopic images are taken over time

Microscopic image of calcium carbonate (CaCO$_3$) precipitates

Yoon et al., 2012
Reaction experimental results

\[ \text{CO}_3^{2-} \text{ (pH=\text{\sim 11}) \quad [\text{Ca}^{2+}]_T=[\text{CO}_3^{2-}]_T=25 \text{ mM at \sim 2 hrs} } \quad \text{Zhang et al., 2010} \]

\[ \text{Ca}^{2-} \text{ (pH=\text{\sim 6})} \]

\[ [\text{Ca}^{2+}]_T=[\text{CO}_3^{2-}]_T=6.5 \text{ mM at \sim 24 hrs} \]

\[ [\text{Ca}^{2+}]_T=[\text{CO}_3^{2-}]_T=10\text{mM} \quad \text{&} \quad [\text{Mg}^{2+}]_T=40 \text{ mM at \sim 16 hrs} \quad \text{Boyd et al., 2014} \]

• Precipitation \sim along the centerline within 1-2 pore spaces in the transverse direction
• Width of the precipitate line \sim increase with distance from the inlet
• Rate of precipitation is concentration and species dependent
Reactive transport [\& flow]

Amorphous Calcium Carbonate

Transformation

1 min
6 min
15 min
18 min
21 min
30 min
60 min
75 min

Boyd et al.

Calcite crystals
Experiment Set Up 1

Laser-scanning Confocal Microscope

Zeiss LSM500 Meta, AxioCam

3D flow fields

modified from Lima et al. (2006)
Experiment Set Up 2

Steady, single-phase flow

Etched silicon dioxide wafer with 100nm silicon dioxide coating

Pore network porosity is ~0.39

modified from Yoon et al. (2012)

Illumination: HeNe @ 543nm
Objective: 10x/0.3NA
16-bit, 512x512 pixels ~ 0.98μm/pix
Pinhole = 1AU ~ optical depth of 13μm
Laser scanning time 786 ms
FluoSpheres® from Life Technologies
2-μm, 1055kg/m³, 580nm/605nm
Particle Image Velocimetry (PIV)

Particle images $\rightarrow$ Velocity Fields

$\Delta t$ $\rightarrow$ $\Delta x / \Delta t$

$\Delta y$ $\rightarrow$ $\Delta y / \Delta t$

Instantaneous Velocity Field

$v_x = \Delta x / \Delta t$

$v_y = \Delta y / \Delta t$
Experiment Results 1

Steady, single-phase flow

Analysis: Particle Images ➔ Velocity Fields

PIVLab software

• Pre-process:
  • histogram equalization – 20 pixels
  • High-pass filter – 15 pixels
  • Intensity modification
  • Adaptive Weiner denoise filter – 3 pixels
• Direct cross correlation
  • Interrogation area – 32 pixels, 50% overlap
• Post processing
  • 2D Gaussian function peak filter
  • Smoothing algorithm
  • Manual removal of outliers near boundaries

Fast in pore throat
Slow in pore body
Experiment Results 2

Steady, single-phase flow

Similar flow patterns at all depths ~ 3D effects are negligible in steady, single-phase flow

Time-averaged velocity fields with N = 200
Comparison of 2D profiles
Illustration of Optical Depth

\[ z[\mu m] \]
\[ y[\mu m] \]
\[ x[\mu m] \]
\[ V_{\text{mean}}[\mu m s^{-1}] \]

Optical Depth

\[ z \]

\[ |V| \]
Simulated flow in pore-body

Steady, single-phase flow

- Sierra Mechanics – CFD
- Finite element
- Solves Navier-Stokes equations
- 2D domain – 5000µm x 5000µm
- Array of solid cylinders 300-µm
- Uniform mass flux
- Water
- Re < 1

Symmetric flow
Precipitation and flow

CaCO_3 Precipitates

Flow

Na_2CO_3

CaCl_2

20mm

10mm
2d Flow Induced by Precipitates

Case 1a: Flow in a channel

1.47 mm

0.49 mm

V_{\text{mean}} [\mu m s^{-1}]
2d Flow Induced by Precipitates

Case 1b: Obstacle in a channel

\[ V_{\text{mean}}[\mu\text{m/s}] \]

\[ x[\mu\text{m}] \]

\[ y[\mu\text{m}] \]

\[ 0.89\text{mm} \]

\[ 0.18\text{mm} \]
2d Flow Induced by Precipitates

Case 2b: Obstacle in a pore body

1.47mm  0.49mm
2d Flow Induced by Precipitates

Case 2c: Obstacles in a pore body

0.89mm 0.18mm

V_{\text{mean}}[\mu \text{ms}^{-1}]
Precipitation in pore bodies

3D pore structure from confocal microscope → Mesh generated from structure image → Simulated flow in pore using Lattice-Boltzmann method

Like bathymetry or topography …
Next: Dynamic features

Precipitates change the structure/geometry of the pore body over time.

How different do the flow fields look at each of these moments?
Conclusions and future work

• We directly visualized 2-D velocity vectors at multiple z positions in a micromodel using micro particle image velocimetry and a laser scanning confocal microscope.

• When the structure of the model is static and the flow is steady, our measured 3-D velocity vectors compare well to 2-D simulated flow fields, suggesting 3-D effects are minimal in this case.

• Several different pore structures in micromodels are being tested to validate applicability of microPIV using LSCM

• Future work will include:
  • experimental and numerical validation of 3D velocity fields in representative precipitation patterns.
  • estimation of reactive surface area from 3D profiles of precipitates and reaction rates across scales
  • Extend the current work flow to multiphase flow in heterogeneous pore structure and mineral distributions