Microfluidic study of biomass-growth induced changes on hydraulic properties. Investigation of growth characteristics under varying nutrient gas environments.

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The processes of biomass **accumulation**, nutrient consumption, and growth change the hydraulic properties with time, what are the consequences for underground hydrogen storage and subsurface gas conversion sites?
Observation of residual base permeability - by structure & permeable biomass

\[ K - K_C = \left( \Phi - \Phi_C \right) \tau \]

\[ K_0 - K_C \]

Region of Intr.
- 33 D
- 10 D
- 1 D
- 0.5 D
- solid
- 0.3+0.6 D
- threshold

Filtration Event 1               2

Total Domain
- exp
- 33 D
- 10 D
- 1 D
- 0.5 D
- solid
- 0.3+0.6 D
- threshold
Methods and Materials

Fig. Microfluidic setup

Fig. M. formicicum serum bottle

Fig. Micromodel

Methods and Materials

single-phase nutrient flooding

flow direction

two-phase gas flooding

Time development

H₂/CO₂ gas phase

aqueous phase with biomass

bloom accumulation
Experiment: M.formicicum_2022

Response summary

Single-phase flow (60h record)

Two-phase flow (14h record)

Exp.1_M.formicicum_2022
Substrate: $V_{\text{CO}_2}=2.5\%$; $V_{\text{H}_2}=10\%$

$\Delta p$

$P_{\text{abs}}\text{[mbar]}$

$P_{\text{diff}}\text{[mbar]}$

Saturation [%]

$\text{Sat}_{\text{gas}}$

$\text{Sat}_{\text{bio}}$

0 24 48 72 96 120 144 168 192 216
0
10
20
30
40
50
60
70
80
90
100

Two-phase flow

Single-phase flow

$0 24 48 72 96 120 144 168 192 216$
0
10
20
30
40
50
60
70
80
90
100
Biomass and permeability evolution

Single-phase flow

![Diagram showing experimental data for exp. permeability, kinetic permeability, and porosity over time and relative time. The graph includes two experiments: Exp.1 (2021) @ q=0.2 mL/h and Exp.2 (2022) @ q=0.05 mL/h, with non-linear extrapolation for permeability evolution. Filtration events and a missing pressure record are also indicated.]
Experimental data and simulation results

Single-phase flow

Offset corrected-discrepancy between experiment and simulation

Fig. Segmented view of Experiment 2 (60h record & 4h capture)
Way forward

- REV dependencies
- Reasons for offset between numerical and experimental results → improvement of sim. methods
- Evaluation of two-phase experiments →
  - Effective gas permeability, \( f(t) \)
  - Growth characteristics
- Evaluation of reactive system →
  - Gas chromatography
  - Controlling parameters (Pe, Da)
- Impact of velocity and shear rates
- Multiscale experiments – rock samples →
  - Link to associated research
- Iteration towards injectivity, conversion, and storage shortcomings
Questions?

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- Daniel Grogger
- Pit Arnold
- Boris Jammernegg
- Holger Ott
- Markus Pichler
- Stephan Bauer
- Bergit Brattekås
- Martin Fernø
- Hannes Konegger
- Andreas Loibner
- Frieder Enzmann
- Saeid Sadeghnejad
- Michael Kersten
Backup

- Growth rate

- MER
Phase 1.

Static growth rate and methane evolution rate determination

- Microbes maturity before injection (optical density)
  \[4H_2(g) + CO_2(g) \rightarrow CH_4(g) + 2H_2O(l) \rightarrow \Delta H_R^0 = -253 \text{ kJ/mol}_{CH_4}\]

Micromodel saturation with bacterial suspension

- Multi-rate \( k \) [exp]
  - HM in GeoDict [sim]
  - Permeability evolution [sim]

- Time laps-Imaging
  - porosity reduction [exp | sim]
  - biomass increase [exp | sim]
Phase 2.

Micromodel pressurization
Substrate in pressure equilibrium

- **Drainage** by liquid phase suction
  - Vindum-Pump at constant pressure operation
  - Saturation determination after Bt (Swir)
- **Imbibition**
  - Residual gas saturation as f(Nc)
  - Displacement/dissolution of substrate
  - Gas trapping by snap-off (diffusive dissolution as f(Nc,p))

Fig. Multi-K permeability determination

\[ \text{pressure [mbar]} \]
\[ \text{time [hh:mm]} \]
\[ 103 \text{ mbar @ 1ml/h} \]
\[ 51 \text{ mbar @ 0,5 ml/h} \]
\[ 20 \text{ mbar @ 0,2 ml/h} \]
\[ 5 \text{ mbar @ 0,02 ml/h} \]

\[ y = 38.746.100.786.432.90x - 89.38 \]
\[ R^2 = 1.00 \]

\[ k = 2.61 \text{ D} \]
Experimental pressure records

Delta_p [mbar] vs. time [h]

Single phase flow
Two-phase flow
Multi-rate k

Absolute_p [mbar] vs. time [h]

Single phase flow
Two-phase flow

Pc @ Bt
Time development of hydraulic properties

Single-phase flow

Fig. Segmented view of Experiment 2 (60h record α' 4h capture)
Biomass and nutrient gas interaction

permeability [D]  
Biomass [%]  
pdiff [mbar]  
nno filtration events  
exponential growth phase  
permeability plateau
Fig. Segmented view of Experiment 1 (48h record)
Materials and samples

- wide range pressure applications -

\[ p = 1-30 \text{bar} \]

\[ \Delta p = 3 \text{bar} \]

Q: 0.01-10 mL/h

Microbes abundance Lehen-field

Synthetic brine with M.formicium