HyUSPRe

Hydrogen **U**nderground **S**torage in **P**orous **Re**servoirs

Webinar #4

Hydrogen flow in porous subsurface reservoirs

Prepared by: Holger Cremer, TNO

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The HyUSPRe consortium

Funded by

Acknowledgement

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No 101006632. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

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Executive summary

On 23 November, 2023 HyUSPRe organized a webinar entitled Hydrogen flow in porous subsurface reservoirs. Two presentations were given during the webinar: [1] Diffusion measurements with hydrogen and methane through reservoir rock samples, and [2] Cyclic flow characteristics is sandstones during geological hydrogen storage. The speakers shared and discussed with the audience results of their experimental work on hydrogen flow in porous sedimentary rocks. Both webinar presentations are attached to this report.

About HyUSPRe

Hydrogen **U**nderground **S**torage in **P**orous **Re**servoirs

The HyUSPRe project researches the feasibility and potential of implementing large-scale storage of renewable hydrogen in porous reservoirs in Europe. This includes the identification of suitable geological reservoirs for hydrogen storage in Europe and an assessment of the feasibility of implementing large-scale storage in these reservoirs technologically and economically towards 2050. The project will address specific technical issues and risks regarding storage in porous reservoirs and conduct an economic analysis to facilitate the decision-making process regarding the development of a portfolio of potential field pilots. A techno-economic assessment, accompanied by environmental, social and regulatory perspectives on implementation will allow for the development of a roadmap for widespread hydrogen storage towards 2050; indicating the role of large-scale hydrogen storage in achieving a zero-emissions energy system in EU by 2050.

This project has two specific objectives. Objective 1 concerns the assessment of the technical feasibility, risks, and potential of large-scale underground hydrogen storage in porous reservoirs in Europe. HyUSPRe will establish the important geochemical, microbiological, flow and transport processes in porous reservoirs in the presence of hydrogen via a combination of laboratory-scale experiments and integrated modelling, establish more accurate cost estimates and identify the potential business case for hydrogen storage in porous reservoirs. Suitable stores will be identified and their hydrogen storage potential will be assessed. Objective 2 concerns the development of a roadmap for the deployment of geological hydrogen storage up to 2050. The proximity of hydrogen stores to large renewable energy infrastructure and the amount of renewable energy that can be buffered versus time varying demands will be evaluated. This will form the basis to develop future scenario roadmaps and prepare for demonstrations.

Document information, revision history, approval status

Document information

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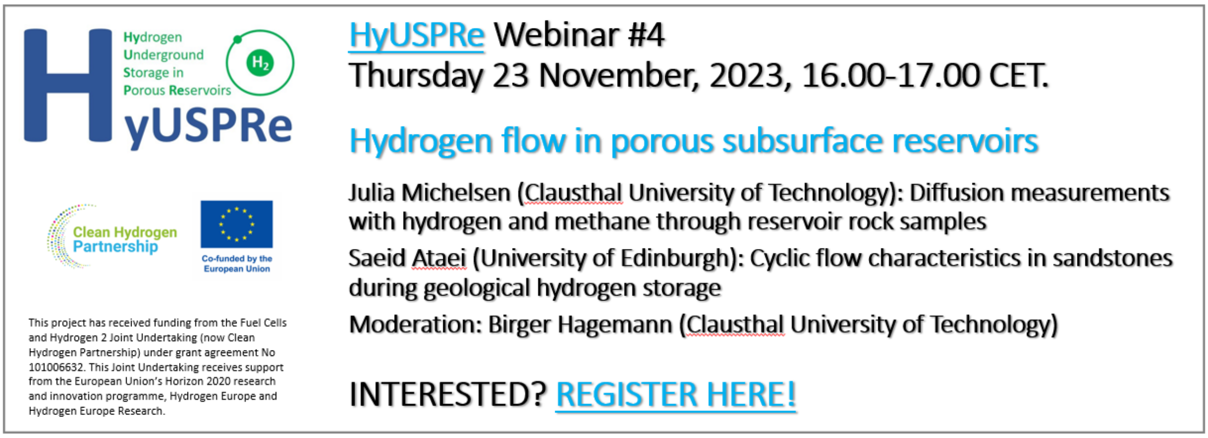
Table of Content

1 Introduction

The HyUSPRe project achieves results in seven technical work packages. Results are laid down in reports and presentations, most of them are public and as such published on the project's website.
Part of the results are shared with the hydrogen storage interested community through webinars. HyUSPRe will organize a total of five webinars. The **first webinar** was organized as knowledge sharing event in June 2022 together with the HYSTORIES project. The **second webinar** was organized in December 2022 and shared insights into the hydrogen storage potential of depleted gas fields and aquifers in Europe, whereas the **third webinar** was held in February 2023 and was entitled 'Microbial impact on subsurface hydrogen storage'.

The here reported fourth webinar was organized in November 2023 and shed light on flow characteristics of hydrogen in porous subsurface reservoirs.



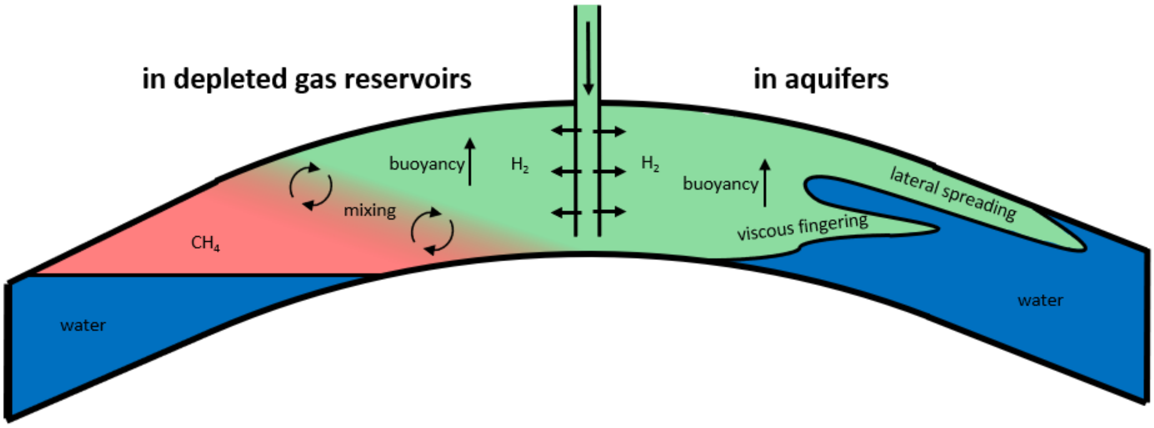
The webinar offered two presentations:

- Diffusion measurements with hydrogen and methane through reservoir rock samples, given by Julia Michelsen from Clausthal University of Technology, and
- Cyclic flow characteristics in sandstones during geological hydrogen storage, given by Saeid Ataei from the University of Edinburgh.

The webinar was moderated by Birger Hagemann from Clausthal University of Technology.

2 Webinar report

A total of 54 participants joined the webinar and represented the European community interested in flow characteristics of hydrogen in the subsurface. The complete set of slides is attached to this report (see Attachment).
Understanding of hydrogen flow characteristics is important as mixing processes between hydrogen and residual gas in the reservoir and also gravity segregation processes may have an influence on the effective and safe storage of hydrogen in depleted gas reservoirs and aquifers.



Gas mixing and hydrodynamic effects in a hydrogen gas storage. Figure from Michelsen et al., 2023.

The first talk of Julia Michelsen introduced a new experimental setup for the measurement of diffusion of hydrogen through typical reservoir rocks at typical storage conditions. Theoretical considerations of molecular diffusion of hydrogen, the experimental setup and the calculation of effective diffusion coefficients were explained. For the study, 7 sandstone and 1 limestone sample were measured. Clear trends were observed for the calculated diffusion coefficients in relationship to porosity, pressure, temperature, and water saturation. On the other hand, experimental diffusion coefficients in relationship to temperature and pressure only partially fit with the diffusion model of Millington & Quirk. Future experimental work will refine the observed findings of this study.

In the second talk, Saeid Ataei reported on an experimental program carried out to study cyclic flow characteristics of hydrogen in sandstones in saline aquifers. Specifically three research questions were investigated: [1] residual trapping of hydrogen during cyclic flow scenarios, [2] the impact of the pore network or rock type on the magnitude of residual trapping under cyclic flow and [3] generation of experimental data for reservoir simulation. Detailed information was given on the experimental design and procedure. Results suggest that different rock types do have different flow characteristics, that there were no geochemical reactions observed and that the residual trapping remained constant after the first cycle. As for the first talk, future experimental work needs to confirm and refine these observations.

The discussion with the audience following both talks showed that flow characteristics of hydrogen in subsurface reservoirs is an relevant and important topic.

3 Attachments

The following presentations were shown during Webinar #4 and are attached to this report:

- Hydrogen flow in porous subsurface reservoirs. Introduction to the webinar by Birger Hagemann, Clausthal University of Technology
- Diffusion measurements with hydrogen and methane through reservoir rock samples (Julia Michelsen, Clausthal University of Technology)
- Cyclic flow characteristics in sandstones during geological hydrogen storage (Saeid Ataei, University of Edinburgh)

HYUSPRE – WEBINAR #4
23 NOVEMBER 2023, 16.00 – 17.00 CET

HYDROGEN FLOW IN POROUS SUBSURFACE RESERVOIRS

B. HAGEMANN | CLAUSTHAL UNIVERSITY OF TECHNOLOGY
K. EDLMANN | UNIVERSITY OF EDINBURGH

TU Clausthal
THE UNIVERSITY of EDINBURGH

Hydrogen Underground Storage in Porous Reservoirs
HyUSPRe

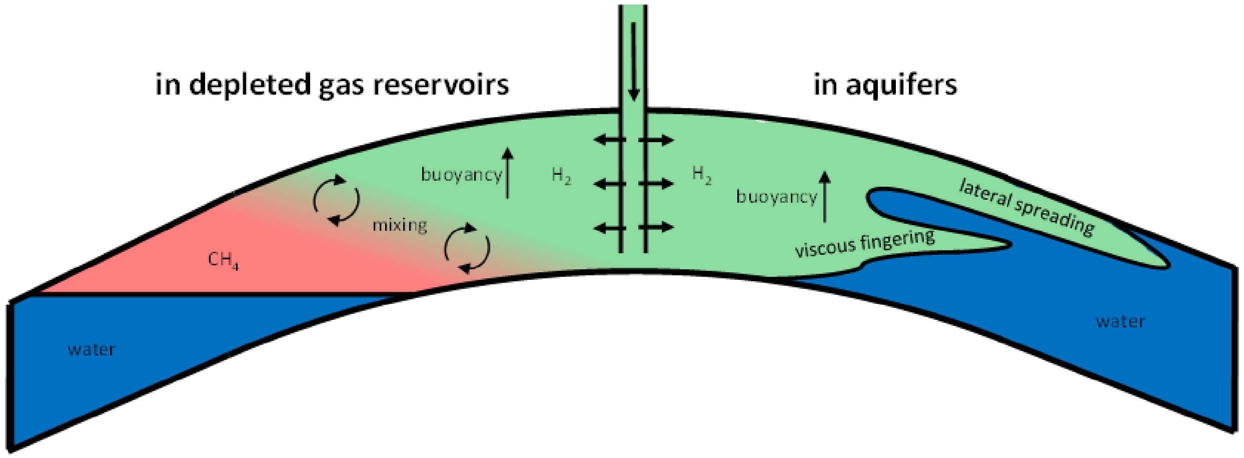
Clean Hydrogen Partnership

Co-funded by the European Union

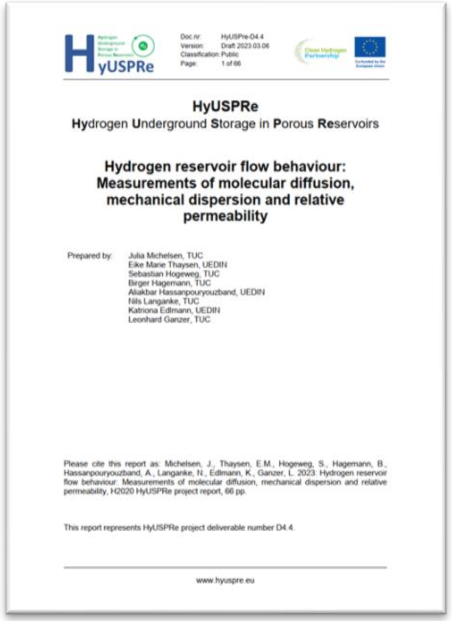
This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No 101006632. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

WP4 “H_2 FLOW BEHAVIOR”

- Objectives
  - Measurement of effective molecular diffusion coefficients (H_2-CH_4)
  - Measurement of mechanical dispersivities (H_2-CH_4)
  - Determination of relative permeability curves for the hydrogen-brine system
  - Provide experimental data to validate numerical models in WP6



Final report published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Version: Draft 2023.03.06
Classification: Public
Page: 1 of 66

HyUSPRe
Hydrogen **U**nderground **S**torage in **P**orous **Re**servoirs

Hydrogen reservoir flow behaviour: Measurements of molecular diffusion, mechanical dispersion and relative permeability

Prepared by: Julia Michelsen, TUC
Eike Marie Thaysen, UEDIN
Sebastian Hogeweg, TUC
Birger Hagemann, TUC
Aliakbar Hassanpouryouzband, UEDIN
Nils Langanke, TUC
Katriona Edlmann, UEDIN
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This report represents HyUSPRe project deliverable number D4.4.

www.hyuspre.eu

AGENDA

Webinar – Hydrogen flow in porous subsurface reservoirs
Thursday, 23 November 2023, 16.00 – 17.00 CET

Presentations:

1. Julia Michelsen (Clausthal University of Technology)
   Diffusion measurements with hydrogen and methane through reservoir rock samples
   (15-20 min presentation + 10 min questions and discussion)

2. Saeid Ataei (University of Edinburgh)
   Cyclic flow characteristics in sandstones during geological hydrogen storage
   (15-20 min presentation + 10 min questions and discussion)

HYUSPRE
HYDROGEN FLOW IN POROUS SUBSURFACE RESERVOIRS

THANK YOU FOR LISTENING

Hydrogen Underground Storage in Porous Reservoirs

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TU Clausthal

Diffusion measurements with hydrogen and methane through reservoir rock samples

J. Michelsen, N. Langanke, B. Hagemann, S. Hogeweg, L. Ganzer

Institute of Subsurface Energy Systems, Clausthal University of Technology

23 November 2023

HyUSPRe Hydrogen Underground Storage in Porous Reservoirs

Clean Hydrogen Partnership

Co-funded by the European Union

Outline

1. Underground hydrogen storage (UHS)
2. Molecular diffusion of hydrogen
3. Experimental procedure
4. Calculation of effective diffusion coefficients
5. Core samples
6. Results
7. Comparison with correlation
8. Conclusion and outlook

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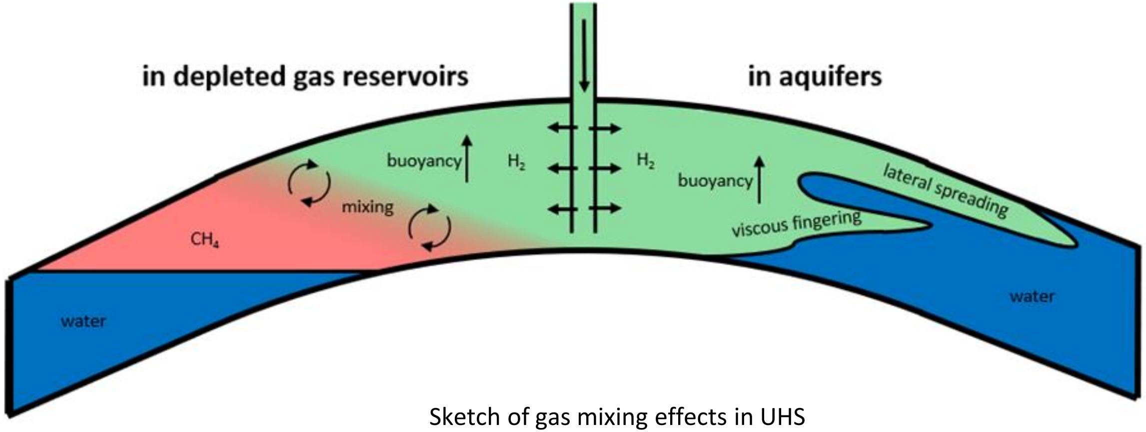
Underground hydrogen storage (UHS)

- Storage in porous reservoirs: **Depleted gas reservoirs** or aquifers
- Mixing effects in depleted gas reservoirs
  - Mixing of injected and initial gas
  - Gravity segregation



Sketch of gas mixing effects in UHS

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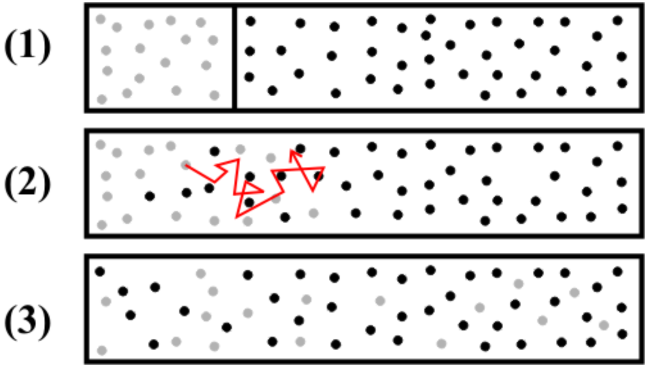
Molecular diffusion of hydrogen

- Molecular diffusion is a physical process which is driven by chemical potential and occurs even without pressure difference
- The process refers to the movement of molecules driven by the inherent tendency to equalize concentration gradients (Fick's law)
- The effective diffusion coefficient can be described as:

$$D_{eff}^{AB} = \phi S_g \tau D_{bulk}^{AB}(p,T)$$

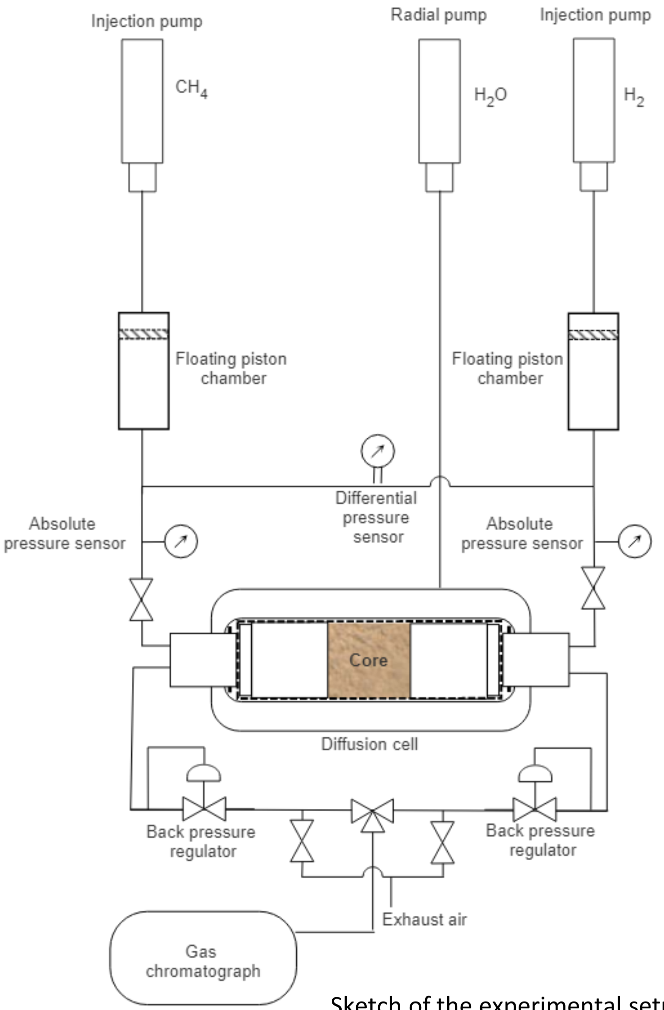
D_{eff}: effective diffusion coefficient for the binary system [m²/s], ϕ: porosity, S_g: gas saturation, τ: tortuosity factor, D_{bulk}^{AB}: bulk diffusion coefficient [m²/s]



Source: Krieger (2010)

Experimental procedure

- Modified version of Wicke and Kallenbach (1941) method
- Measurement of effective diffusion for binary gas systems (H_2, CH_4)
- Main component: Diffusion cell with rock sample (6 cm length, 3 cm diameter)
- Two chambers separated by rock sample
- Constant injection of two samples gases
- Outflowing gas composition is analyzed by gas chromatography
- Alternative: Quasi-stationary measurement where gas is only injected at one side and the opposite chamber is larger



Sketch of the experimental setup

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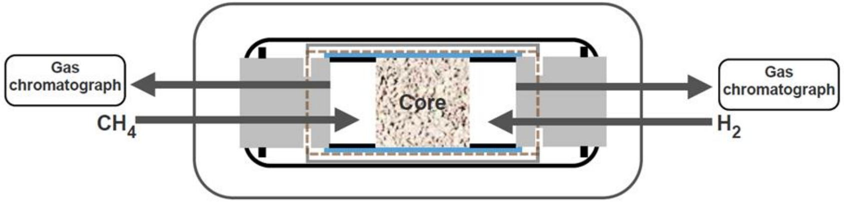
Experimental procedure

- Diffusion cell: Rock sample, hollow cylinders, two end pieces
- In total 36 measurements with 9 reservoir rock samples (mainly sandstone)



Experimental procedure

1. *Sample installation:* Rock sample is installed into the diffusion cell, which is connected to the experimental setup.
2. *Leakage test:* Radial and system pressure are built up stepwise to reduce and minimize stresses in the sample. Leakage test is performed.
3. *Preparation:* Large chamber and rock sample are flooded with hydrogen until a gas purity of 99.9 % is reached.
4. *Measurement:* The injection of methane is started at a constant rate. The composition of the outflowing gas is analyzed by a gas chromatograph every three minutes.

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Calculation of effective diffusion coefficients

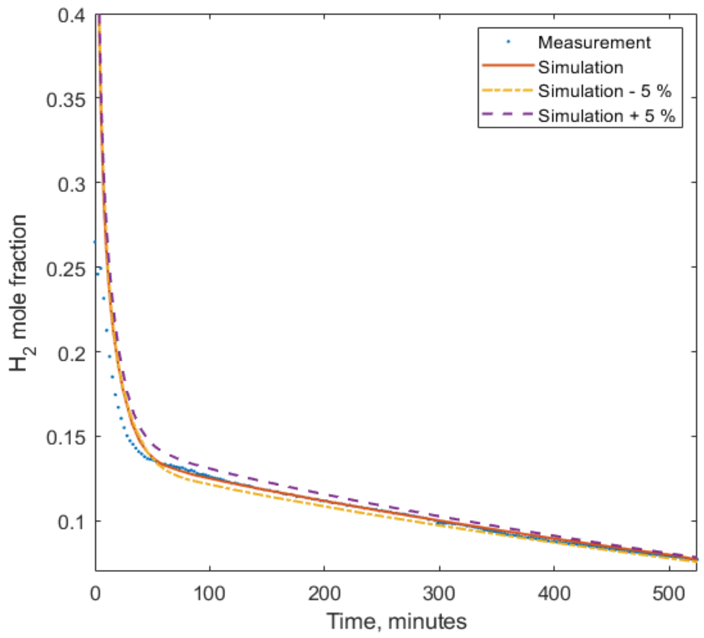
- Experimental results were interpreted by using a one-dimensional numerical simulation model
  - Implementation in COMSOL Multiphysics
- The model solves the following partial differential equation, which is based on Fick's second law:

$$\frac{p}{RT}\phi\frac{\partial c}{\partial t} = \frac{p}{RT}D\frac{\partial^2 c}{\partial x^2}$$

p: measurement pressure [Pa], R: universal gas constant [J/(mol*K)], T: measurement temperature [K], φ: porosity of the sample, c: molar fraction of hydrogen, D: effective diffusion coefficient [m²/s]

Calculation of effective diffusion coefficients

- Comparison of a laboratory measurement with the simulation model (125 bar, 40 °C)
- The determined effective diffusion coefficient is $1.25 \cdot 10^{-7}$ m^2/s



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Core samples

- All samples are measured at 100 bar and 40 °C (reference conditions)
- Each sample is measured under site conditions

Sample source	Lithology	Permeability [mD]	Porosity [%]	Effective diffusion coefficient at reference conditions [m²/s]	Site Conditions Mean Pressure [bar]	Site Conditions Temperature [°C]	Effective diffusion coefficient at site conditions [m²/s]
Bentheimer sandstone	Sandstone	2500	24.7	$1.1 \cdot 10^{-7}$	-	-	-
Chattian Sand	Sandstone	71.0	29.9	$7.0 \cdot 10^{-8}$	106	50	$6.5 \cdot 10^{-8}$
Aquitanian formation	Sandstone	157.6	26.8	$6.0 \cdot 10^{-8}$	53.5	25	$1.1 \cdot 10^{-7}$
Pliocene Sands	Sandstone	718.6	31.7	$2.3 \cdot 10^{-7}$	88.3	45	$2.0 \cdot 10^{-7}$
Ebes Fm.	Limestone	23.6	19.9	$2.6 \cdot 10^{-8}$	140.5	107	$1.7 \cdot 10^{-8}$
Ujfalu Fm. 1	Sandstone	32.1	288.2	$1.2 \cdot 10^{-7}$	116.5	86	$1.1 \cdot 10^{-7}$
Detfurth formation	Sandstone	263.1	27.4	$9.8 \cdot 10^{-8}$	287.25	96	$1.7 \cdot 10^{-7}$
Rough Rotliegendes	Sandstone	17.6	17.2	$1.8 \cdot 10^{-8}$	203	92	$9.0 \cdot 10^{-9}$

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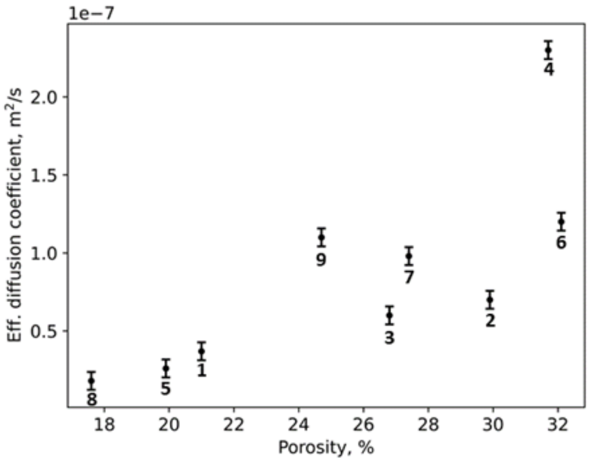
Results

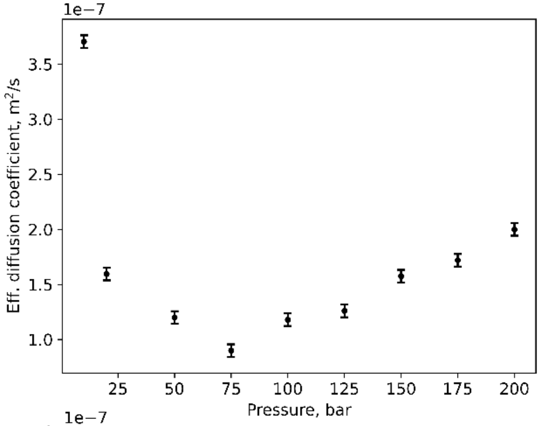
- Effective diffusion coefficient vs. porosity at 100 bar and 40 °C

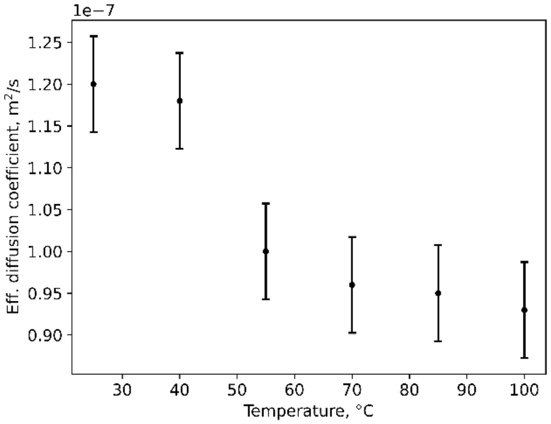


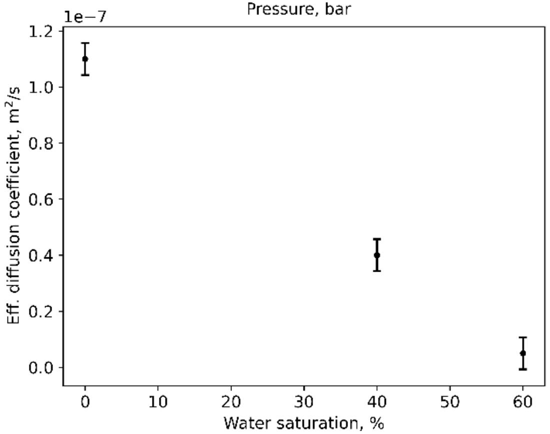
No.	Sample source	Lithology	Site Conditions P [bar]	T [°C]	Effective diffusion coefficient at site conditions [m²/s]
1	Berea sandstone	Sandstone	-	-	-
2	Chattian Sand	Sandstone	106.0	50.0	$6.5\cdot10^{-8}$
3	Aquitanian formation	Sandstone	53.5	25.0	$1.1\cdot10^{-7}$
4	Pliocene Sands	Limestone	88.3	45.0	$2.0\cdot10^{-7}$
5	Ebes Fm.	Limestone	140.5	107.0	$1.7\cdot10^{-8}$
6	Ujfalu Fm. 1	Sandstone	116.5	86.0	$1.1\cdot10^{-7}$
7	Detfurth formation	Sandstone	287.2	96.0	$1.7\cdot10^{-7}$
8	Rough Rotliegendes	Sandstone	203.0	92.0	$9.0\cdot10^{-9}$
9	Bentheimer Sandstone	Sandstone	-	-	-

Results

- Bentheimer sandstone: Effective diffusion coefficients vs. pressure (40 °C), temperature (100 bar) and water saturation (100 bar, 40 °C)

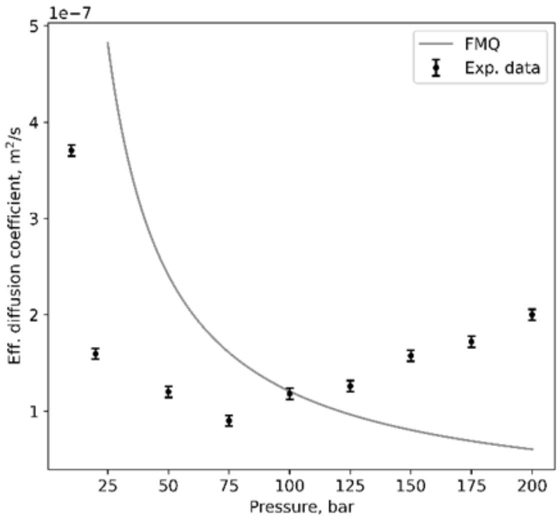


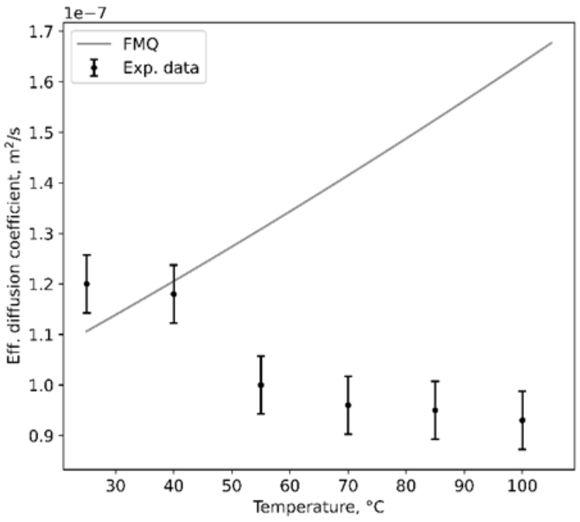




Comparison with correlation

- Comparison of the experimental data of the measurements with the Bentheimer sandstone sample at varying pressures and temperatures with the correlated results of the model by Fuller and Millington & Quirk





Conclusion and outlook

- A new experimental setup was developed for the measurement of hydrogen diffusion through reservoir rocks
- The measurements are repeatable, and the results are comparable to results from other diffusion measurements from literature
- Trends in diffusion coefficients: Effective diffusion coefficients showed clear trends when plotted against pressure, temperature, and water saturation, but different than calculated by conventional correlations
- Future Research: To better understand the influence of temperature and pressure on the diffusion process, further measurements should be conducted to gather additional data points

TU Clausthal

Thank you for your attention!

Hydrogen Underground Storage in Porous Reservoirs

HyUSPRe

Clean Hydrogen Partnership

Co-funded by the European Union

We would like to thank TÜV Nord
for funding Julia's doctoral position

TÜVNORD

Cyclic Flow Characteristics of Sandstones during Geological Hydrogen Storage in Saline Aquifers

Saeid Ataei

November 2023

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Outline

- Background and Objectives
- Experimental Program
- Results and discussions
- Conclusion and Way Forward

Background

- Subsurface Porous Rocks in Aquifers Demonstrate Significant Potential for Energy Storage
  - **Low Demand Season Process:** Hydrogen (H2) Injection
  - **High Demand Season Process:** Hydrogen (H2) Production
- Non-Uniform Cyclic Displacement Processes:
  - Risk of Residual Trapping
- Controls on Residual Trapping:
  - Rock Type
  - Reservoir Conditions
  - Heterogeneity
- Optimizing Efficiency:
  - Impact of Multiple Cycles on Residual Trapping
  - Site Selection: Assessment of Diverse Rock Types and its Impact on Residual Trapping
  - Model the Cyclic Flow Characteristics (Initial Gas Saturation and Residual Trapping)

Aims and Objectives

- Investigate the Cyclic Flow Characteristics:
  - Evaluating Residual Hydrogen Trapping during multiple Cyclic Flow Scenarios
  - Evaluate the Impact of Pore Network (Rock Type) on the Magnitude of Residual Trapping under Cyclic Flow
  - Obtaining Experimental Data (Saturation Profile and Relative Permeability End-points) for Reservoir Simulation

Experiments

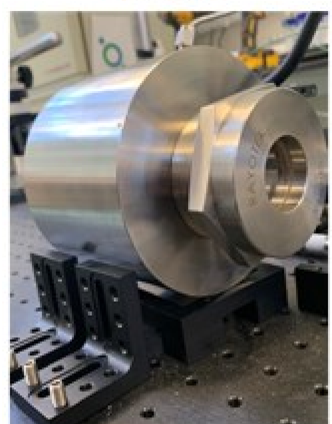
Smaller Scale Tests

- Micro-CT
  - Xray CT Imaging, using in house and Diamond Facilities
    - 5mm Diameter and 47mm Long Core samples
  - Detailed , High-resolution 3D Images
  - Glass micromodels & visual cells

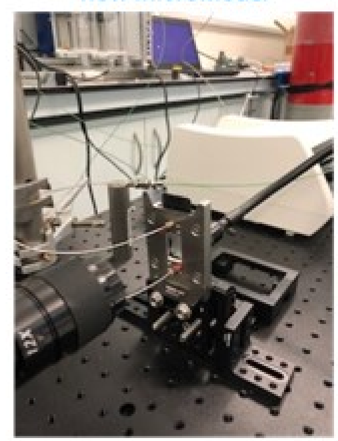
5mm ϕ X-Ray hydrogen flow cell

5mm ϕ X-Ray hydrogen flow cell

Hydrogen high P/T visual cell



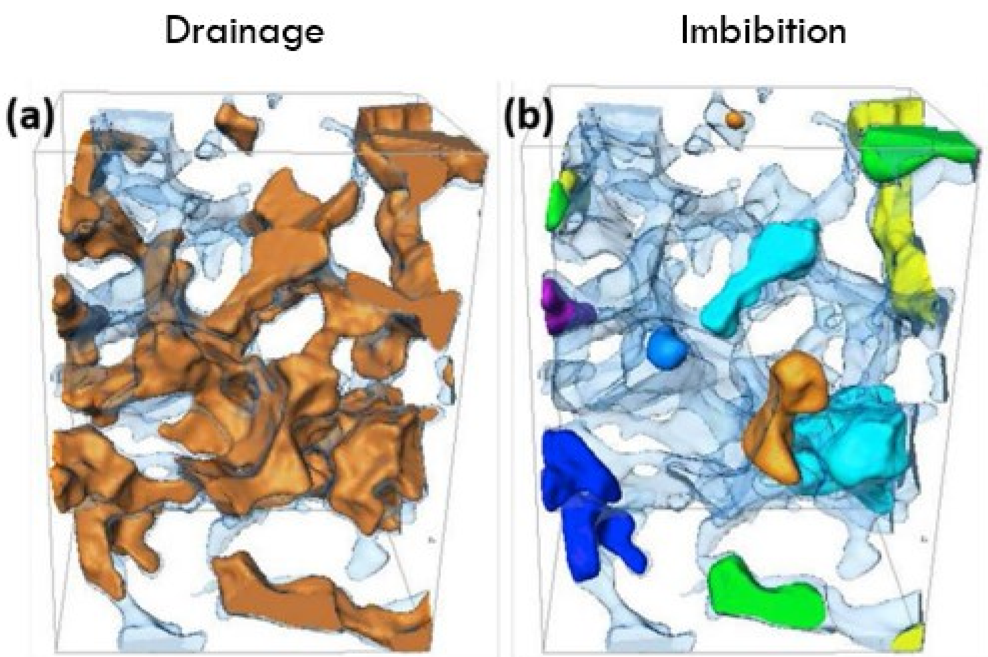
Hydrogen multiphase flow micromodel



Experiments

Smaller Scale Tests

- Snap-off Mechanism is One of the Main Active Mechanism of Residual Trapping of H_2

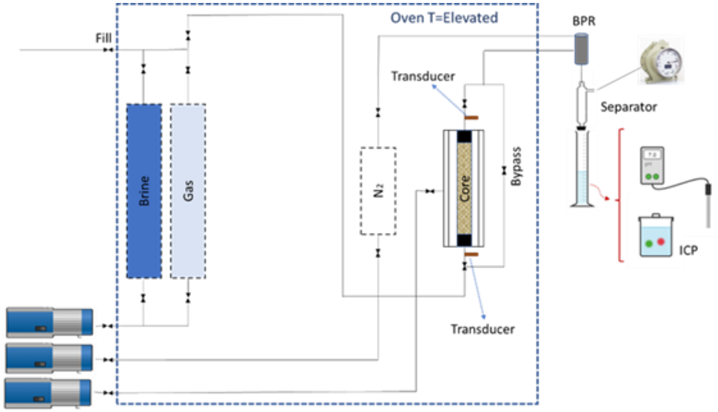


Eike.thaysen@ed.ac.uk https://doi.org/10.1016/j.ijhydene.2022.10.153

Experiments

Larger Scale Tests

- Micro-CT
  - Mechanistic Study of The Capillary Trapping
  - 5 mm Diameter Core Plug
- Core Flooding
  - Input for Reservoir Models
  - Qualitative
  - 38 mm Diameter Core Plug

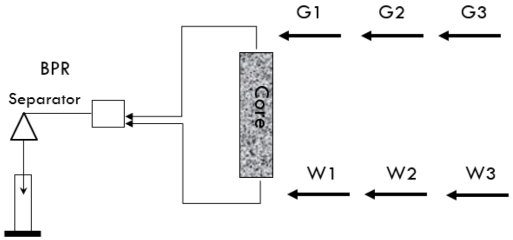


Experimental Procedures

- Core flooding tests
- Core Taking
  - From different reservoir rocks
  - 1.5 inches in Diameter
  - 10 cm in Length
- Core Cleaning
  - Solvents (Toluene and Methanol)
- Core Loading
  - H_2 Leaking
- Basic Properties Measurements
  - Effective Porosity
  - Absolute Permeability
- Sample Selection
  - Core Representation

Experimental Design

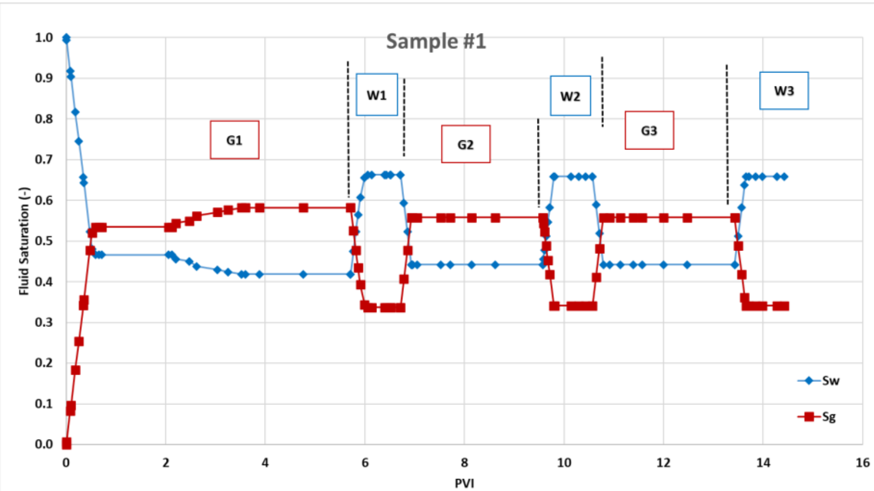
- Core Saturation and Ionic Equilibrium (1 week)
- 1st Gas Cycle
  - Bump Flooding (Increasing Flow Rate Sequentially) to Surpass **Capillary End-effects**
  - Lower Injection Rate to Assess the Possible Geochemical Reaction
- 1st Water Cycle
- 2nd Gas Cycle
  - Lower Injection Rate to Assess the Possible Geochemical Reaction
- 2nd water cycle
- 3rd gas cycle
  - Lower Injection Rate to Assess the Possible Geochemical Reaction
- 3rd water cycle

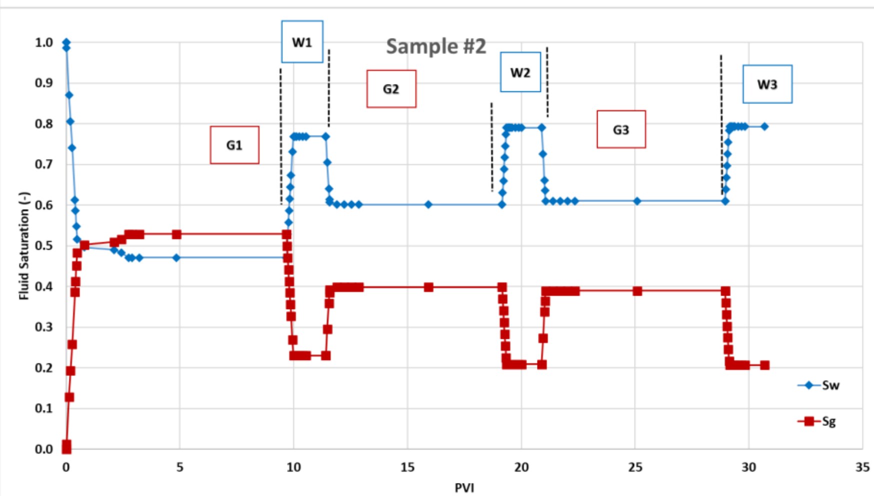


Gravity stable displacement:
Water cycles from bottom
Gas cycles from top

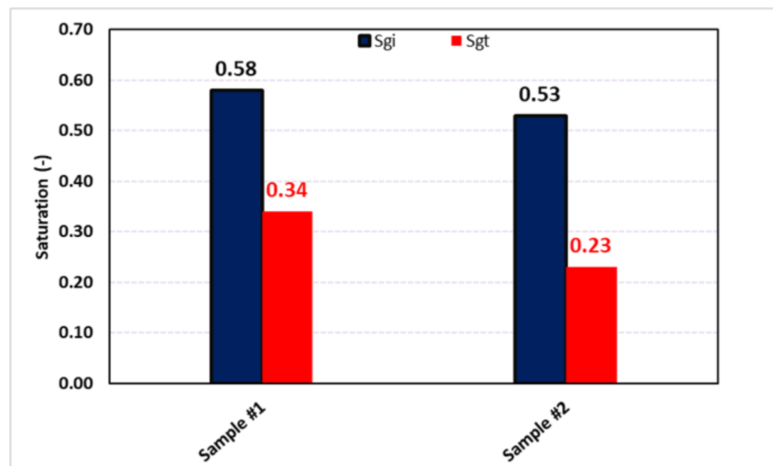
Experimental Results

Saturation Profile





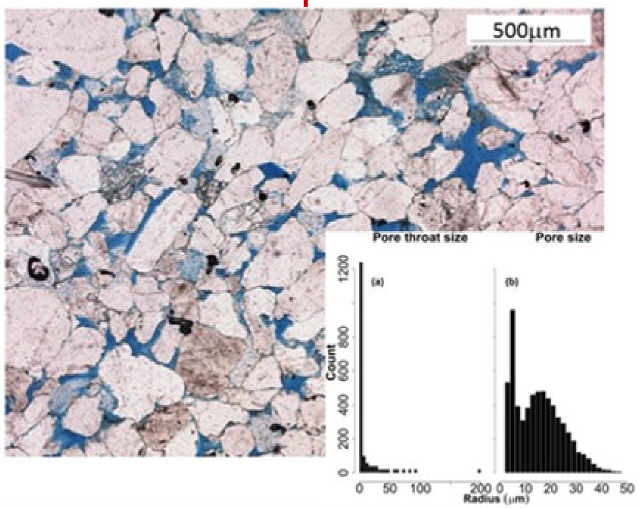
1. Residual Trapping remained unchanged after the 1st Cycle
2. Sample #1 has higher Initial Gas Saturation (Sgi)
3. Sample #1 has higher Residual Gas Saturation (Sgt)



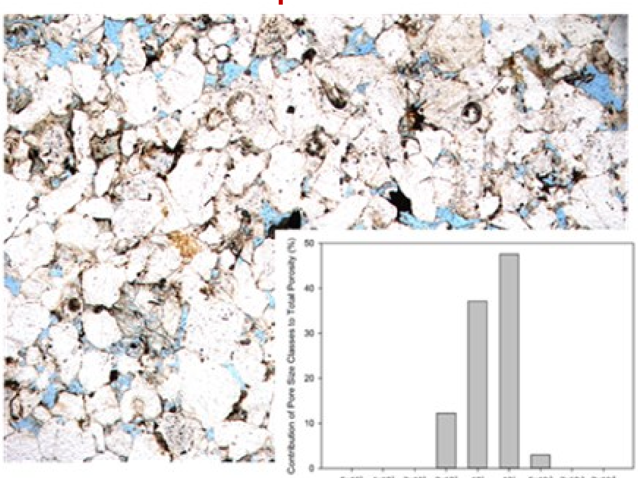
Experimental Results

MICP Test Results

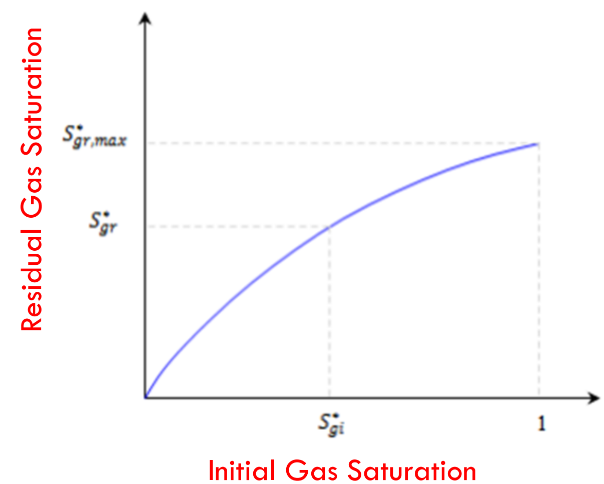
Sample #1



Sample #2



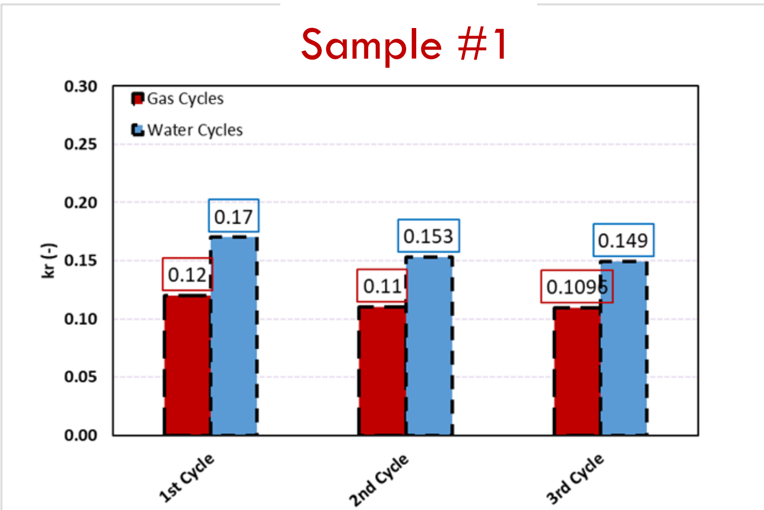
- Sample #1
  - The higher Sgi
  - More Pronounced Snap-off
  - Difference in Pore Size Distribution
- Land model: The higher Sgi, the higher Sgt

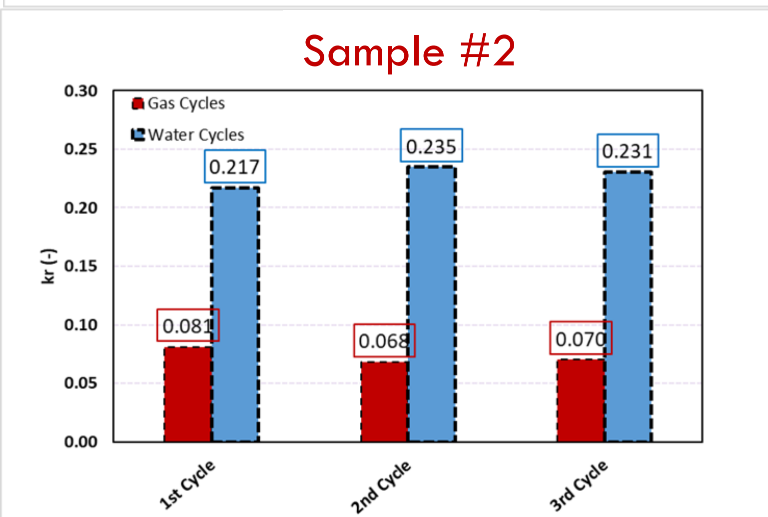


Experimental Results

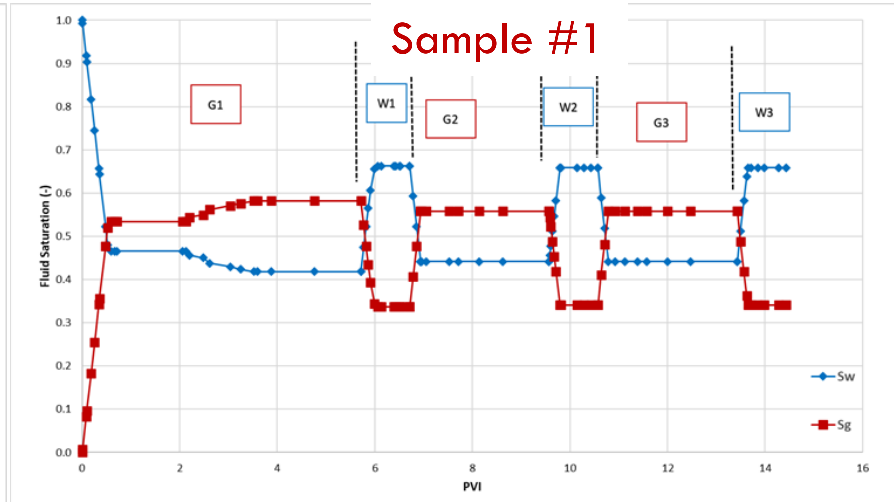
End-points vs Saturation Profile

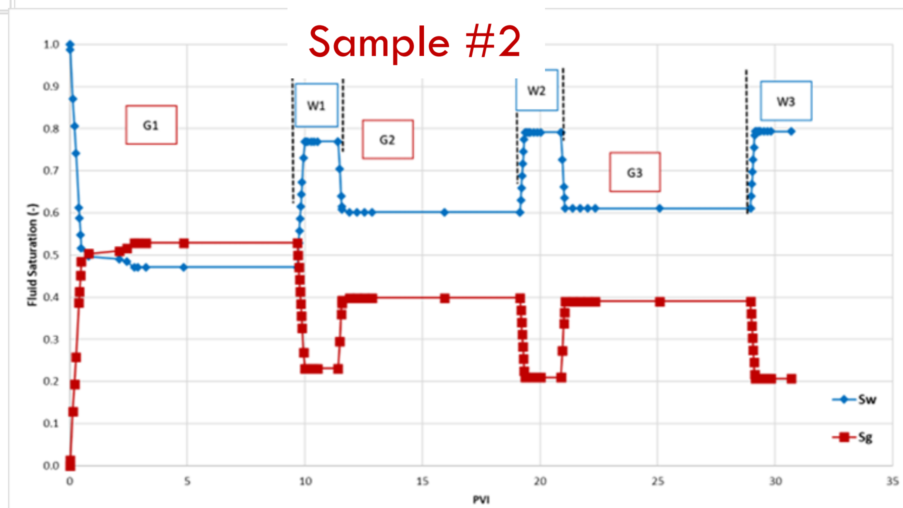
End-points





Saturation Profile

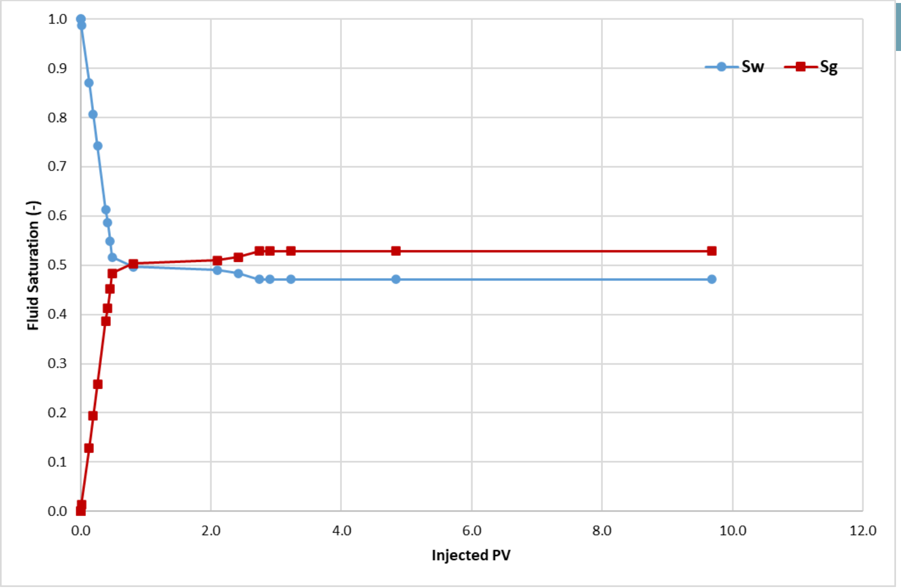


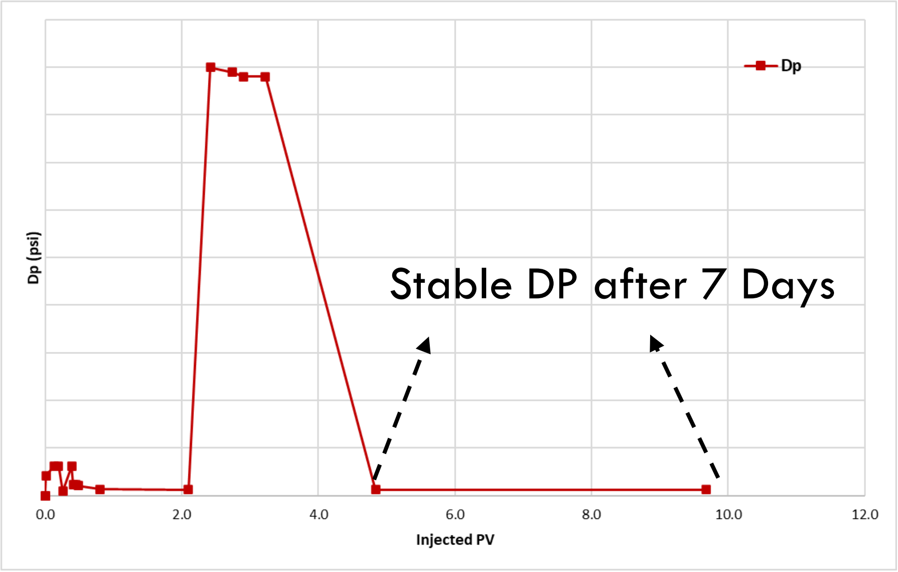


Experimental Results

Geochemical Analysis

- Geochemical Assessments
  - Gas Cycles
  - Sufficient Time after Bump Flooding
  - Saturation Profile and Dp





Steady Dp and Saturation: No Sign of Geochemical Reactions

Conclusion and Way Forward!

- Residual Trapping Remained Constant after 1st Cycle
  - Pore Size Distribution
  - Tracer Test

- Different Flow Characteristics for Different Rock Types

- No sign of Geochemical Reactions

THANK YOU

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