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Near-wellbore hydrate effect on CO2 injection: insights from microfluidics and core flood experiments

L. Yan[1], M. Schellart[1], D. Voskov[1,2], R. Farajzadeh[1,3]

[1] Delft University of Technology; [2] Stanford University; [3] Shell Global Solutions International BV

Summary

Understanding CO2 hydrate formation near the injection wellbore is critical for improving the safety and efficiency of geological CO2 storage. Hydrate formation can significantly reduce rock permeability and impair injection performance, yet its pore-scale behavior and impact under realistic reservoir conditions remain insufficiently understood. This study combined microfluidic and core-flood experiments to investigate hydrate morphology, formation dynamics, and their effects on injectivity. Microfluidic chips with well-characterized pore structures were used to directly observe hydrate structures under gaseous and liquid CO2 phases, which reveal eight distinct morphologies, including pore-filling, load-bearing, cementing, grain-coating, patchy, worm-like, laminated-like, and banded-like forms where resulted in hydrate saturations reaching up to 15%. Complementary core-flood experiments on rock samples with permeabilities ranging from 0.004 to 2 Darcy employed high-resolution X-ray CT imaging to monitor CO2 and water saturations dynamically. Results indicated that lower permeability cores showed faster hydrate formation and higher saturation increases (up to 16%), which is consistent with microfluidic findings. This multi-scale experimental approach provides deeper insight into hydrate behavior under field-relevant conditions and its influence on CO2 injectivity and offers valuable guidance for optimizing injection strategies in geological carbon storage.

Near-wellbore hydrate effect on CO2 injection: insights from microfluidics and core flood experiments

Introduction

Storing CO2 subsurface in deep saline aquifers and depleted reservoirs is a key approach to mitigate greenhouse gas emissions. When CO2 is injected, especially under high pressure and relatively low temperature conditions, it can cause CO2 hydrates to form (Aminnaji et al., 2024). These are ice-like crystals made when CO2 molecules get trapped inside water cages. The Joule-Thomson cooling, obvious temperature drops, can appear near the wellbore due to CO2 expansion which creates favourable conditions for hydrate formation (Aghajanloo et al., 2024b). Once hydrates form, these hydrates have the potential to clog pores and narrow CO2 pathways inside the rock. As a result, the rock permeability and the efficiency of CO2 injection get reduction (Aghajanloo et al., 2024a). However, due to the complexity of rock and various reservoir conditions, hydrates behaviour and their effects on the injection efficiency are still not fully understood.

Researchers have conducted laboratory experiments to study how hydrate formation affects porous media at both pore and core scales. Lei et al. (2019) used micro-CT to visualize methane hydrate formation in sediment matrices. They quantitatively showed that hydrate volume fraction rapidly increased to approximately 15-20% of the pore space during nucleation and growth phases. Their work highlighted the complex morphologies such as film-like and granular clusters forming preferentially in larger pores, which obstruct fluid pathways. Wang et al. (2021) used microfluidic lab-on-a-chip technology to directly observe methane hydrate formation and dissociation, which identified four distinct growth patterns and quantified microbubble dynamics during hydrate dissociation. They found that microbubbles promote local hydrate re-formation and significantly influence phase. This study demonstrated that microfluidics offered a powerful platform for detailed pore-scale hydrate morphology and multiphase flow analysis. Yu et al. (2025) investigated CO2 hydrate formation kinetics in microfluidic models simulating cold aquifers. The results revealed that higher injection rates shorten hydrate induction time but have limited effect on lateral propagation velocity, which strongly depended on subcooling temperature. They showed that porous media tortuosity, CO2 saturation, and intrinsic velocity controlled hydrate growth velocity at the pore scale. Their findings suggested that the injection strategies could be optimized for avoiding rapid hydrate formation and reservoir clogging.

Although many studies have investigated hydrate properties under specific laboratory or reservoir conditions, a comprehensive understanding of hydrate behavior across varying injection environments and scales remains lacking. This limits the ability to predict how hydrates form and impact CO2 injectivity under the complex, coupled thermal, hydraulic, and geochemical conditions encountered in real reservoirs. Therefore, there is a necessity for systematic investigations that integrate multi-scale experiments and consider a broader injection scenarios to better characterize hydrate dynamics and their effects on storage performance. The objective of this study is to gain deeper insights into hydrate formation behaviours closer to field-relevant environments and to comprehensively evaluate their impact on CO2 injectivity from pore scale to core scale. To achieve this, we first developed a microfluidic platform enabling micro-scale observation and analysis of hydrate morphology in the whole porous network, formation dynamics, and pressure transients under both gaseous and liquid CO2 phases. Subsequently, analogous experiments were conducted in 3D core samples under same temperature and pressure conditions to examine cross-scale effects on hydrate properties and their influence on injection performance.

Experimental Methods

Microfluidic experiments

We have developed a well-controlled setup for the microfluidic experiments, as shown in Figure 1. The micro-chips are fabricated through an acid chemical etching method, resulting in isotropic etching features. Chip 1 is initially designed for investigating small pore size effect on the hydrate kinetics. The grain shape is randomly generated with a MATLAB code based on an X-ray scanned image of a rock structure. The geometric mean of pore size is 80 µm. The pore depth is 5 µm and the permeability is ≈0.55 Darcy. Chip 2 is a commercial chip and featured with a rock-shaped structures designed by the Micronit company. This chip has a range of pore size from 75 µm to 675 µm, with a geometric median value of 280 µm. It has a pore depth of 20 µm and permeability of ≈7.2 Darcy. Chip 1 allows us to add more connection points to the porous media.

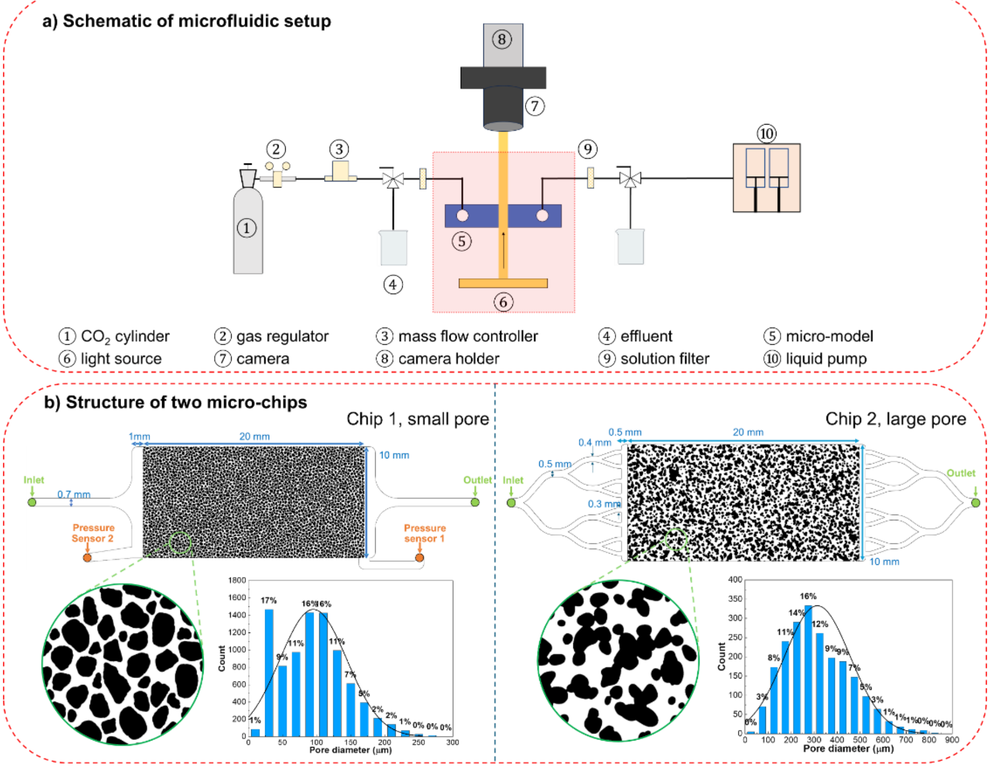

Figure 1 *Pictures of the experimental set-up. a), Top part is the schematic of microfluidic setup. b), the bottom part is the structure of two chips and their pore size distribution. White represents pore space and connections with inlets and outlets, and black represents solid grains. The pore size distribution of the pore space is shown below. The solid line represents a fitted normal distribution.*

Core-flood experiments

We have conducted the core flood experiments for five cores with different permeability from 0.004 Darcy to 2 Darcy. The experimental setup is shown in Figure 2. The system integrates a high-pressure CO₂ injection apparatus, a medical X-ray CT scanner, and a rock sample placed inside a core holder for dynamic imaging and pressure monitoring. The scanner is the Siemens SOMATOM third-generation CT scanner with a resolution of 5.12 pixels/µm and a voxel size of 0.023 mm^3, which enables real-time 3D imaging of water/CO2 distribution and saturation.

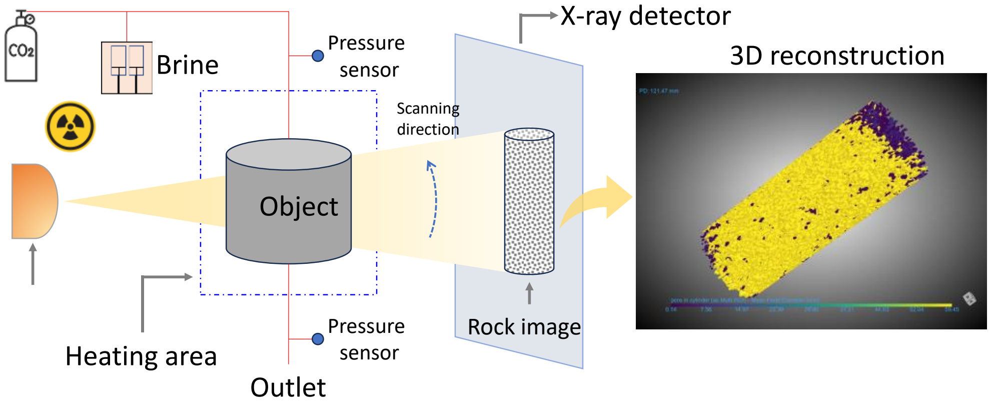

Figure 2 *Experimental setup for the core flood experiments.*

Results in microfluidic experiments

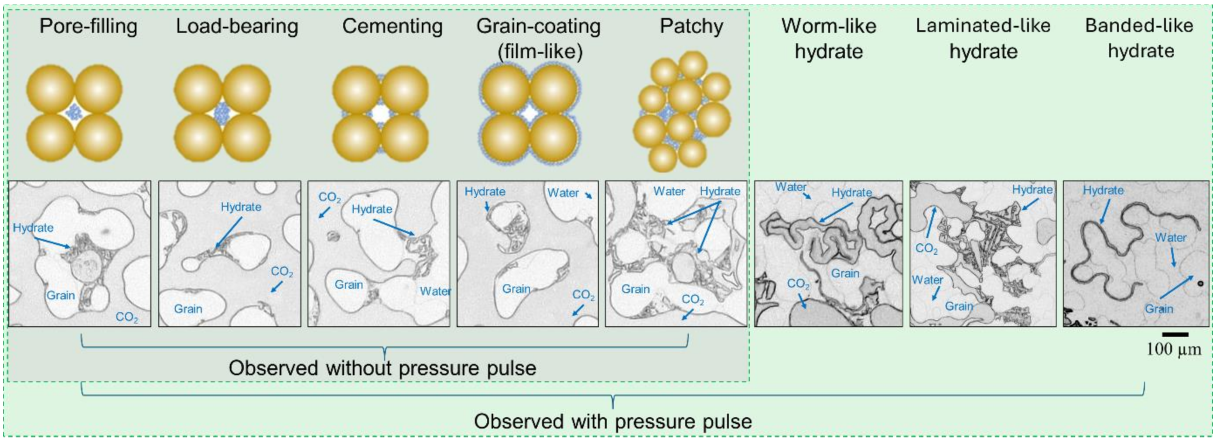

Figure 3 *Pore-scale morphologies of CO2 hydrates.*

Figure 3 illustrates various pore-scale morphologies of CO2 hydrates observed during injection experiments. The captured hydrate structures include pore-filling, load-bearing, cementing, and grain-coating (film-like) forms to patchy distributions, which are primarily observed without pressure pulses. Under the influence of pressure pulses, more complex morphologies such as worm-like, laminated-like, and banded-like hydrates, which indicates that pressure fluctuations promote the evolution and diversity of hydrate structures. These distinct hydrate patterns demonstrate how hydrates occupy pore space differently and the effect of hydrate distributions on fluid flow. More details and observations, such as the water and hydrate dynamic saturations, will be presented in the conference presentation.

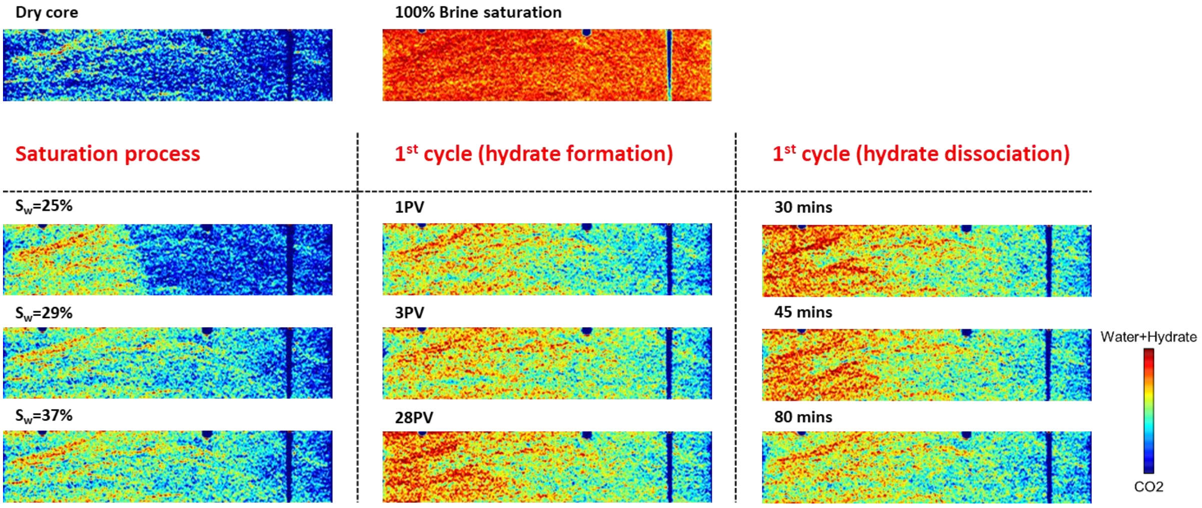

Figure 4 *Reconstruction of CT scanned images to show the hydrate behaviour in the low-permeable rock (4 mD).*

Figure 4 presents the reconstructed CT images for showing the time-lapse saturation changes during CO2 hydrate formation and dissociation cycles observed in a low-permeable rock (4 mD permeability). In the left column, the yellow areas present the water propagation during co-injection of CO2 and 1% NaCl brine to reach the desired water saturation 37%. The middle column captures the first cycle of hydrate formation. The increased red colour indicated the increased solid hydrate presence and the propagation direction starting from the injection point. Due to the expansion of hydrates, the saturation of water+hydrate increased by 16%. The right column displays the first hydrate dissociation cycle, where hydrates gradually disappeared, and the saturation gradually returned back to the similar value as before hydrate formation. This visualization effectively reveals the dynamic interplay between hydrate growth and dissociation and their impact on pore-scale saturation distribution. Additionally, we have observed the pressure increased due to the hydrate blockage, which indicates the permeability reduction.

Conclusions

In this study, we employed two experimental approach to investigate the effects of CO2 hydrate formation on injection performance. At the pore scale, microfluidic chips with well-characterized pore geometries were fabricated and used to directly visualize hydrate morphology and formation dynamics under controlled gaseous and liquid CO2 conditions. This study demonstrates that CO2 hydrate formation near the wellbore significantly alters pore-scale morphology and reservoir permeability. Eight types of hydrate structures were captured, including pore-filling, load-bearing, cementing, grain-coating (film-like), patchy, worm-like, laminated-like, and banded-like. These morphologies appeared under varying pressure conditions, such as with and without pressure pulses. Additionally, the water and hydrate saturations across the whole micro-chip were calculated. The results revealed that the hydrate saturation could reach up to 15%.

Complementarily, core-flood experiments were conducted on natural rock samples with permeabilities ranging from 0.004 to 2 Darcy. Using high-resolution X-ray CT imaging, we dynamically monitored CO2 and water saturations during hydrate formation and dissociation cycles and captured the spatial and temporal evolution of flow changes in the real rock. We found that lower permeability in the porous media induced the shorter hydrate induction and stronger hydrate formation. The maximum expanded water+hydrate saturation in the low-permeable rock were 16%, which was consistent with the result in the microfluidic experiments.

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