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DOI
10.3997/2214-4609.2024101243

Publication date
2024

Document Version
Final published version

Citation (APA)
Shaker Shiran, B., Aarra, M., Djurhuus, K., Zamani, N., Solbakken, J., Dopffel, N., & Hajibeygi, H. (2024). *Underground Hydrogen Storage: Effect of Cyclic Flow and Flow rate on H2 Recovery Efficiency*. Paper presented at 85th EAGE Annual Conference & Exhibition 2024, Oslo, Lillestrøm, Norway. https://doi.org/10.3997/2214-4609.2024101243

Underground Hydrogen Storage: Effect of Cyclic Flow and Flow rate on H2 Recovery Efficiency

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Summary

Hydrogen, regarded as a clean energy carrier, holds potential for subsurface porous media storage to balance energy supply and demand. Investigating the interactions between hydrogen and porous media, especially the potential residual trapping during cyclic injection and production, becomes imperative. Experimental studies were conducted to examine the influence of flow rate and cyclic injection/production on hydrogen storage and recovery efficiency. Findings reveal generally low hydrogen saturation in brine-saturated porous media during storage process, due to notable flow instability. However, higher injection rates contribute to increased hydrogen saturation. Moreover, observations indicate that cyclic hydrogen storage and drainage may lead to hysteresis in hydrogen storage process. That is, cyclic hydrogen storage and drainage may result in undesired residual trapping of hydrogen in porous media. This study underscores the need for a comprehensive investigation to validate these observations, shedding light on the complexities of hydrogen storage dynamics in subsurface porous media.

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Introduction

Hydrogen is recognized as a clean energy carrier as it can be produced and consumed without producing greenhouse gasses, and therefore contributes to mitigating climate change. One of the beneficial aspects of hydrogen as an energy carrier is that it can be stored in large-scale (TWh equivalent) quantities in the underground reservoirs. Depleted oil and gas reservoirs are potential candidates for this underground hydrogen storage (UHS) technology, due to their geological stability, large storage capacity and availability of surface and subsurface infrastructure. Successful development of UHS in depleted reservoirs depends on reliable assessments of hydrogen interaction with rock and reservoir fluids, hydrogen transport and trapping mechanisms as well as its purity and recovery efficiency. In this study, we have performed several hydrogen flow experiments in porous media to quantify its storage and drainage efficiency and trapped volume influenced by the injection and production flow rate and cyclic frequency.

Hydrogen displacement experiments in porous media

Hydrogen displacement experiments in porous rocks provide valuable insights into its transport mechanisms, retention/trapping, and recovery efficiency in depleted reservoirs. However, experimental studies of hydrogen flow in porous media, especially at high pressure and temperature conditions, is challenging because hydrogen is a highly flammable gas with high risks of explosion. As a result, working with hydrogen requires strict safety measures when designing such experiments. Due to these challenges, there is a limited number of publications dealing with the experimental investigation of hydrogen storage, flow, and drainage in porous media. Therefore, further research is needed to explore various aspects of UHS in porous rocks, specially including hydrogen interactions with the hosting rock, the amount of gas trapping and recovery efficiency. As UHS is a cyclic process, the effect of repeated injection/withdrawal cycles on operational efficiency is particularly important to be quantified.
One of the key challenges in UHS in porous media is the initial storage volume and residual hydrogen trapping which lowers the recoverability of the injected hydrogen, reducing the overall efficiency of the entire storage process. High density contrast between hydrogen and the reservoir brine also results in a complex flow regime which is challenging to be appropriately upscaled (Boon and Hajibeygi, 2022, and Al-Yaseri et al., 2022). The study by Al-Yaseri et al. (2022) reports very low initial (4%) and residual (<2%) hydrogen saturation in sandstone rock samples made of mainly quartz minerals. Displacement of brine with nitrogen, at the same capillary number, is reported to result in much different values of 15% and 8%, respectively. This indicates the challenges of storing large volumes of hydrogen in porous media. Understanding the interaction between injected hydrogen and the reservoir brine and rock is also essential in designing a successful underground hydrogen storage project.
Recently, Jangda et al. (2023) reported an initial H_2 saturation of about 36% during drainage of a Bentheimer rock sample with both H_2-equilibrated and non-H_2-equilibrated brine solutions. However, imbibition of non-H_2-equilibrated brine resulted in hydrogen recovery factor of 43% compared to 32% for the case with H_2-equilibrated brine. That is, the dissolution of hydrogen in brine may affect the hydrogen trapping mechanism and volume in the reservoir and its final recovery efficiency. Furthermore, the injection method and cyclic rates may also affect the effective hydrogen storage volume and its residual trapping. Whether hydrogen injection rate is high or low can influence the initial gas saturation and the level of trapped gas in porous media. Very recently, Spurin et al. (2024) studied the effect of injection method on residual trapping of CO_2 and reported that the high to low injection rate scenario is the most favorable technique to maximize the amount of trapped CO_2 in porous media. Unlike CO_2 storage, hydrogen storage is considered temporary, and the aim is to minimize residual trapping and maximize hydrogen recovery efficiency. Thus, unlike the case of CO_2 storage, the injection strategies for UHS should be aimed at minimizing the residual trapping.
The role of rock wettability (Higgs et al., 2024), hydrogen separation/segregation in the porous media (Berenblyum et al., 2023), molecular diffusion (Arekhov et al., 2023), the use of other gases as cushion gas (Mirchi et al., 2023) and the possible influence of microbial activities in the reservoir on hydrogen

storage efficiency are all among the many fundamental parameters that need to be collectively examined through hydrogen displacement experiments, in order to maximize the efficiency of UHS.

Experimental procedure

The hydrogen core flooding experiments in this study were performed at a pore pressure of 35 barg and a confining pressure of 70 barg, at room temperature. A Berea sandstone core sample with length of 26 cm and diameter of 3.8 cm was used. The Berea core was covered by a Teflon plastic sleeve, then a double layer of aluminium foil to avoid gas diffusion and finally a Viton shrinkable sleeve before mounting in the core holder. The core was initially saturated with 2 wt.% NaCl. The pore volume and brine permeability of the core was 65 cc and 300 mD, respectively. The experimental set-up, except for the Quizix pumps, was located inside an EX-zone that was specifically built to perform hydrogen flow experiments. Automated high-pressure valves controlled the inlet and outlet end of the core and a bypass system were both operated from a PC located outside of the EX-zone.
The core was oriented vertically and both brine and hydrogen were injected from bottom and produced from top. Pure hydrogen was injected into 100% brine saturated core to examine two effects: 1) effect of injection rate on brine displacement and hydrogen saturation level in the core and 2) effect of cyclic hydrogen storage on recovery efficiency and trapped saturation of hydrogen gas. The brine solution in this study was not pre-equilibrated with hydrogen. No shut-in time was included in the experiments. The core inlet and outlet pressures, the differential pressure across the core and the produced volumes of hydrogen and brine were monitored to evaluate the efficiency of hydrogen storage and withdrawal process. Samples from the produced hydrogen were analyzed using µ-GC to verify the composition of the produced gas. This was a necessary step to make sure that the accumulated gas was the hydrogen producing from the core and not, for example, nitrogen leakage from the backpressure regulator.

Results: effect of injection rate on hydrogen storage in porous media

Hydrogen was injected at three different rates of 0.5, 5 and 15 cc/min to displace the brine in the core and to examine the effect of injection rate on the storage volume of hydrogen in the core. Figure 1 depicts the results for hydrogen saturation increase at different injection rates. This figure shows the incremental H2 saturation change at each rate. Note that it does not show the residual trapped gas.

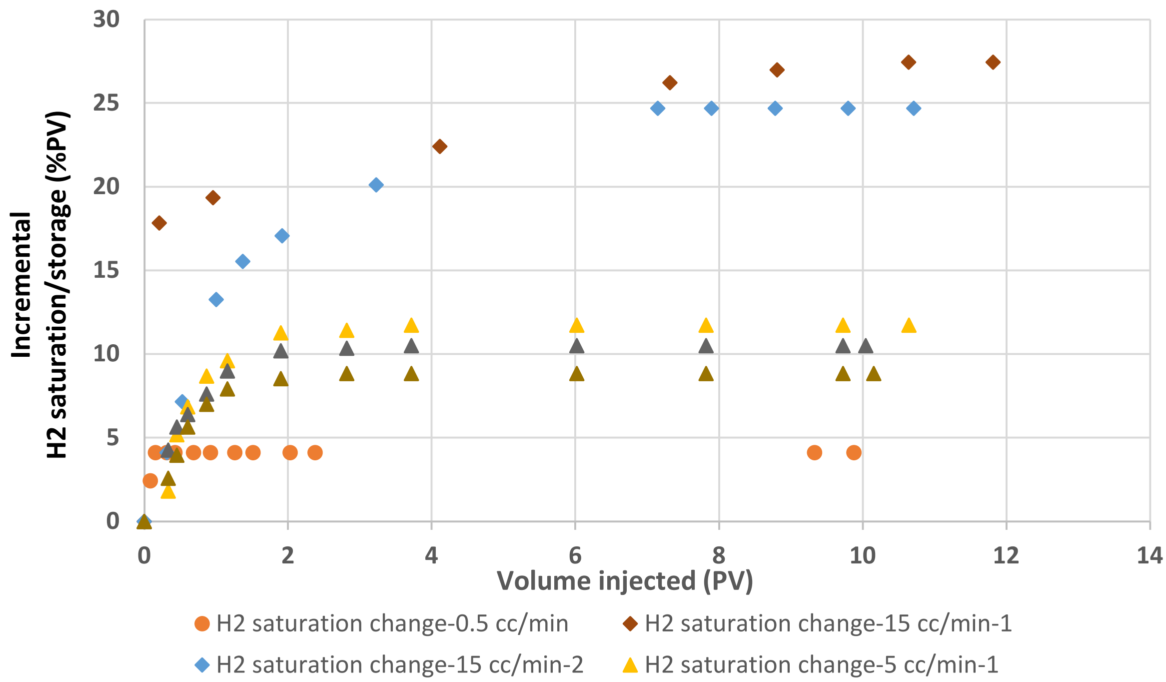

Figure 1 *Effect of injection rate on hydrogen saturation in porous media. Circular, triangular and diamond markers indicate injection rate of 0.5, 5 and 15 cc/min, respectively.*

From Figure 1, it is understood that at higher injection rates, higher hydrogen saturation in the core is achieved. The results indicate that at lower hydrogen injection rates and thereby lower viscous forces the injected hydrogen is more easily channelized through the brine phase and less brine is displaced. At higher injection rates, viscous force is improved, the flow instability is dampened and therefore more brine is displaced, and more hydrogen is stored.
The results of this study also show that as more hydrogen was stored in the core with increasing the injection rate, the residual trapped hydrogen was also increased when the stored hydrogen was displaced by brine. For instance, hydrogen saturation reached to about 0.25 when it was injected at the rate of 15 cc/min. The trapped gas saturation after flooding the core with brine (hydrogen withdrawal phase) at the rate of 15 cc/min was 0.08. However, the stored hydrogen saturation and trapped gas saturation at the rate of 5 cc/min were 0.12 and 0.05, respectively. There was almost no residual trapping of hydrogen at the flow rate of 0.5 cc/min as the hydrogen saturation was found to be only 0.04. It is reported that hydrogen is non-wetting phase in H_2/brine/sandstone system (Goodarzi et al, 2024, Iglauer et al., 2021). In such a wettability condition, hydrogen will occupy the center of relatively larger pores, while brine occupies the regions close to the pore walls and smaller pores. This leads to hydrogen residual trapping mechanism in larger pores through snap-off phenomena (Jangda et al., 2023).

Results: Effect of cyclic hydrogen injection on residual gas trapping

As mentioned before, unlike CO_2 storage process which aims to permanently store CO_2 in the subsurface reservoirs (Krevor et al., 2023), hydrogen storage is designed to store energy during periods of low demand and retrieve it when demand exceeds the production. Therefore, hydrogen injection and withdrawal from the storage sites is a cyclic process. To model the cyclic injection and production of hydrogen and investigate the impact of this cyclic process on its residual trapping, a sequence of cycles involving hydrogen injection and subsequent brine injection for back production of hydrogen was conducted. The flow rate for injection and production of hydrogen was set to be 5 cc/min. The results are presented in Figure 2. As this figure shows, three cycles of hydrogen storage and withdrawal have been performed. The results indicate that, in the first cycle, the initial hydrogen saturation and residual trapped saturation are about 0.12 and 0.05, respectively. The residual trapped hydrogen saturation was increased to about 0.1 and 0.14 in next two cycles, with no plateau in the trapped hydrogen volume between the 2nd and 3rd cycles. Further investigation, especially with more cycles, is essential to quantify whether this is due to hysteresis or other processes such as dissolution of hydrogen in the brine phase.

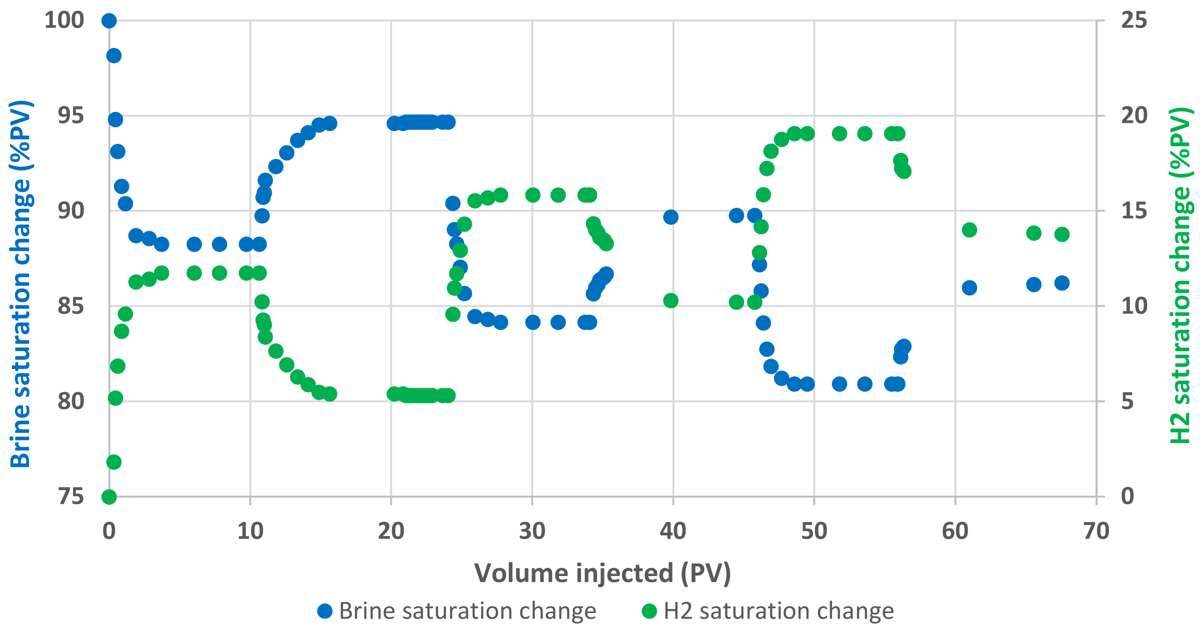

Figure 2 *Effect of cyclic hydrogen injection on residual trapping of hydrogen in porous media. Blue colour is change of brine saturation and green colour is the corresponding change in hydrogen saturation in the core during 3 different hydrogen/brine injection cycles.*

Conclusions

The results of this study show generally low hydrogen saturation (hydrogen storability) in the brine saturated Berea sandstone. Severe channelling or fingering and unstable flow behaviour due to lower hydrogen density and viscosity compared to brine phase may be the reason for low hydrogen saturation in the core. The results indicate that hydrogen injection rate is an important parameter in designing hydrogen storage projects. Higher injection rates result in higher hydrogen saturation in the porous media due to higher viscous force to displace brine inside the pore structure. On the other hand, higher initial hydrogen saturations lead to higher residual trapped hydrogen in the larger pore spaces in porous media.
Furthermore, this study shows that cyclic hydrogen storage and withdrawal practice results in additional residual trapping of hydrogen in porous media. That is, after each storage cycle, more hydrogen was trapped in the core. Thorough investigation is required to quantify how much of this behaviour is due to the hysteresis and how much are due to the other possible reasons, such as hydrogen dissolution in brine phase. Additional experiments, with more number of cycles, are planned to further investigate this observation.

Acknowledgements

The authors acknowledge the financial support from the Norwegian Research Council under Project number: 333151 - FME HyValue – Norwegian center for hydrogen value chain research.

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