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Dynamics of Ostwald ripening in underground hydrogen storage

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Hydrogen is widely recognized as a promising solution for renewable energy storage, thanks to its versatility and high energy density. However, the challenge of seasonal hydrogen storage remains significant, with the absence of scalable storage solutions impeding the widespread adoption of green hydrogen. A 2022 report by the National Energy Technology Laboratory highlights underground hydrogen storage in deep saline aquifers and depleted gas reservoirs as the most viable options for addressing this need. In these systems, hydrogen is injected during periods of high renewable energy production and withdrawn during periods of low availability. This cyclic injection and withdrawal process leads to the formation of trapped hydrogen bubbles of varying sizes and shapes within the subsurface. These bubbles partially mix with the in-situ brine and undergo mass exchange via molecular diffusion, a phenomenon known as Ostwald ripening. The ripening process could have significant impact on the safety, injectivity, and purity of the storage operation.

Here, we study the dynamics of hydrogen bubble evolution in porous media through high-resolution microfluidic experiments. The microfluidic flow cell features a heterogeneous network of pores and throats, connected to boundary channels with larger apertures on the left and right sides. The disparate length scales generate chemical potential gradients that drive hydrogen diffusion from the porous matrix toward the boundary channels. The experiments were conducted at T=40 ℃ and 80 ℃ and different initial gas saturations varying from S=0.4 to 0.6. Each experiment lasted approximately two weeks, allowing sufficient time to capture the long-term dynamics of bubble evolution.

Our results reveal a distinct two-stage ripening process. The first stage involves a relatively slow equilibration phase, during which neighboring bubbles undergo ripening to minimize local variations in interfacial curvature. This is followed by a second stage, characterized by the diffusive loss of gas from the porous matrix to the boundary channels, exhibiting a characteristic diffusive scaling behavior. To further understand this phenomenon, we develop a continuum model of the ripening process that incorporates the capillary pressure-saturation relationship of the porous matrix. The model exhibits excellent agreement with experimental observations. These findings have significant implications for hydrogen storage operations, particularly in estimating equilibration timescales and assessing potential leakage rates in the presence of fracture conduits.

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