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Experimental study on hysteresis during cyclic injection in hierarchical porous media

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Hydrogen (H_2) energy is being developed as a promising alternative to fossil fuels in response to growing energy demand and the urgent need to mitigate climate change. However, the significant obstacle to its wide application is the storage problem. Underground hydrogen storage (UHS) in depleted hydrocarbon fields and aquifers underground holds great promise. UHS includes temporary storage and later-on extraction (use) processes, corresponding to alternating displacement of hydrogen injection (drainage) and withdrawal (waterflooding). In UHS, a certain quantity of H_2 may be inevitably lost due to residual trapping. Throughout the cyclic injection process, the trapped H_2 might reconnect owing to hysteresis of saturation (Wang, Pereira, Sauret, & Gan, 2023) and relative permeability (Lysyy, Føyen, Johannesen, Fernø, & Ersland, 2022). Therefore, hysteresis effect during gas-liquid cyclic injection in porous media play an important role in application of UHS. Most current research efforts have primarily concentrated on cyclic injection in uniform porous media. However, in natural subsurface rock formations, porous structures typically exhibit multiple levels of pore sizes. There is an absence of experimental studies on the pore-scale mechanism by which geometry affects saturation hysteresis in the existing literature. In this work, based on 3D printing technology, we designed and fabricated the hierarchically structured porous media chip with dual permeability. Gas-liquid cyclic injection in uniform and hierarchical chips was studied by a high-speed imaging system emphasizing the impact of hierarchical structure on invasion behavior. The fingering morphology illustrates preferential invasion in 1^{s}t-order structure and significant capillary trapping in 2^{n}d-order structure, which are reconfirmed by phase saturation at each level of the hierarchical structure. The hysteresis effect was quantified based on Land model, and the result shows weaker saturation hysteresis effect during cyclic injection in hierarchical structure compared with uniform structure. To explore the causes, ganglion mobilization was investigated. Unlike uniform structures, inhibition of ganglion mobilization was observed in the hierarchical structure. Through the analysis of local invasion behavior, the connect-jump invasion method is identified as the primary reason for this suppression. Further, the mechanism behind the hysteresis difference was uncovered from two aspects: topology connectivity assessed by measuring normalized Euler number and relative permeability estimated by employing Lattice Boltzmann method (LBM). The results show the hierarchical structure has higher connectivity and relative permeability, which helps explain its limited hysteresis effect. The findings in this study enhance the understanding of the hysteresis effect when optimizing strategies for storage and extraction in Underground Hydrogen Storage (UHS).

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