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Editorial

Subsurface multiphase reactive flow in geologic CO_2 storage: Key impact factors and characterization approaches

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Multiple measurements and data sets show unequivocally that levels of carbon dioxide (CO_2) have been increasing in the Earth's atmosphere for the past several centuries, with the rate becoming steeper in recent decades (Soeder, 2021). Carbon capture, utilization and storage (CCUS) has been regarded as an effective approach to swiftly cut CO_2 emissions. Among the existing CCUS technologies, CO_2 geological utilization and storage has the highest technological maturity, and is the most vital "sink" to consume the captured CO_2. For CO_2 geological utilization and storage, large amounts of CO_2 need to be injected into the deep subsurface, and the CO_2 flow in the subsurface is a very complicated process. The flow system is a two-phase or even a three-phase system, and flow in pores needs to be clearly distinguished from flow in fractures and wellbores. Most importantly, wettability, pore structure, geochemical reactions play very important roles in governing subsurface CO_2 flow. Without a clear understanding of how the impact factors affect CO_2 flow, it is difficult to predict the CO_2 storage capacity and the risk of CO_2 leakage, which directly impairs the confidence of policy makers and investors to support large-scale geologic CO_2 storage. To study CO_2 flow, there is a need to develop effective approaches to characterize CO_2 flow in subsurface system. This work discusses several key factors that have strong impact on subsurface CO_2 flow, and an effective approach for CO_2 flow characterization.

Impact of wettability and pore structure on multiphase flow. The injection of CO_2 into geological formations displaces brine from pore spaces, resulting in various CO_2-brine displacement patterns, such as capillary fingering, viscous fingering, crossover, and compact displacement. These patterns also occur as the brine later flows back to displace supercritical CO_2 when the injection stops. The CO_2-brine displacement results in CO_2 becoming trapped as droplets and ganglia in pore spaces, referred to as residual trapping or capillary trapping. Wettability and pore structure have significant effects on CO_2-brine displacement patterns and capillary trapping. The wettability represents the affinity of fluid to the solid surface. By changing the capillary force governed by the Young-Laplace law, the wettability modifies the local pore-filling events and thus impacts the displacement patterns. Increasing the wettability of the invading fluid from drainage to imbibition stabilizes the displacement front due to the cooperative pore-filling events at the pore scale (Holtzman and Segre, 2015). However, the displacement pattern will change

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extensively as a result of corner flow when the invading fluid is strongly wetting to the solid surface (Hu et al., 2018). On the other hand, the role of pore structure in displacement patterns may depend on the type of permeable media. The pore-scale disorder, which represents the randomness of pore size, changes the threshold capillary pressure and affects the local pore-filling paths. Increasing disorder promotes unstable displacement patterns for both drainage and imbibition conditions (Toussaint et al., 2005), but under certain wettability conditions, higher disorder may enhance cooperative pore-filling events and thus smooth the displacement front. The roughness variations in the aperture between the two rough surfaces determines the flow path and controls the displacement patterns for a fractured medium. Therefore, the transition of CO_2-brine displacement patterns under various wetting and pore structure conditions is an open challenge and a very active area of research.

Impact of geochemical reactions on multiphase flow. Geochemical reactions play a key role in determining CO_2 flow patterns. Though geochemical reaction-induced mineral trapping can only become vital after hundreds to thousands years of CO_2 injection in reservoir scale, fast mineral dissolution and precipitation in micro-scale flow channels of host rocks and caprocks can change permeability of the rocks and thus influence the migration behaviour of injected CO_2 (Zhang et al., 2019). For carbonate rocks, CO_2 injection usually causes opening of flow channels due to dissolution of carbonates, which enhances CO_2 injectivity and is beneficial for large-scale CO_2 storage (Yang et al., 2020). A sandstone reservoir that contains large amounts of feldspars and glauconite may have a strong CO_2-sandstone interaction, which usually causes sealing of flow channels due to precipitation of secondary minerals (Xu et al., 2004). However, given different types of flow channels and varying reaction environments, it is very difficult to precisely predict if a given flow channel in a rock will open or close under the influence of geochemical reactions. Therefore, an important research direction in the future is to find out a criterion that can determine if a flow channel will open or close under the influence of geochemical reactions, with the consideration of complicated reaction environments.

Pore-scale modeling of multiphase reactive flow. Compared with continuum-scale models, pore-scale modeling, which directly reflects the realistic porous structures, provides a powerful tool for studying the multiphase flow, species transport, chemical reaction and mineral dissolution/precipitation processes (Chen et al., 2022). Effects of pressure, temperature, fluid properties, wettability, pore size and porous morphology on the supercritical CO_2-water two-phase flow and distributions have been extensively studied by pore-scale modeling. Pore-scale modeling that reveals the mechanisms of non-equilibrium supercritical CO_2 dissolution into the surrounding brine will be beneficial for enhancing CO_2 solubility trapping. Recently, supercritical CO_2 storage in the depleted oil reservoir has also drawn increasing attention, and the resulting supercritical CO_2-oil-water three-phase flow are extremely complicated (Zhu et al., 2021). Pore-scale modeling is an ideal tool to study the effects of structure heterogeneity, mineral composition and reaction kinetics on the rock dissolution processes. Further pore-scale modeling work to investigate the effects of two-phase or three-phase flow on mineral dissolution/precipitation processes are helpful for better understanding the CO_2 storage processes in saline formations or depleted oil reservoirs.

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Conflict of interest

The authors declare no competing interest.

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