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Marangoni Effect Maintains Fast Evaporation in Near-Fracture Porous Media

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When dry CO2 is sequestrated into saline aquifer, CO2 preferentially goes through high-permeability pathways, leaving the water in unswept low-permeability porous media evaporating into the CO2 phase. Similar scenarios that volatile liquids evaporate into high-permeability pathways can also be observed in gas condensate reservoir recovery, shale gas recovery, and fuel cell water management, etc. Evaporation changes fluid saturation as well as local temperature and pressure that determines the flow and transport performance of abovementioned natural and engineering processes. Specifically, when extensive evaporation occurs, significant temperature and concentration gradients may occur that complicates the flow dynamics.

In this study, we conduct visualized micromodel experiments to investigate the evaporation of volatile liquids in porous media after dry gas flowing through an adjacent fracture. The porous medium is saturated first with pentane (for fast evaporation tests) or isoheptane (for mild evaporation tests), and air is then continuously injected to flow through the fracture. Evaporation rate is controlled by the choice of liquid and the injection rate. Peclect number (Pe) in the fracture ranges from ~0.1 to 107.

Surprisingly, the evaporation pattern under extensive evaporation and mild evaporation are qualitatively different, even under same (and negligible) shearing from gas flow in the fracture. When the evaporation is mild ($1.2*10\text{-}4$ kg/m2/s), the air invades into the porous media layer-by-layer, in a classic "capillary fingering" pattern, and forms a dry fracture/matrix interface. The evaporation rate gradually slows down by scaling $dS/dt \sim t^{(-1/2)}$, as a natural consequence of enlarging mass transfer distance from the drying front to the fracture. However, when the evaporation is ten thousand times faster (0.7 kg/m2/s), the evaporation front and the displacement front separates: the gas invades deep into the porous medium through preferential paths, while the main drying front keeps unmoved and stable at fracture/matrix interface (see Figure 1), even when the displacement rate is still in the "capillary fingering"regime. As long as the evaporation front is pinned, the evaporation rate keeps constant without slowing down.

Isothermal theory cannot rationalize this dramatic contrast behaviors of mild and extensive evaporation in near-fracture zone. We therefore use infrared camera to record the experiment, and discover a strong cooling belt around the interface at high evaporation rate. The existence of significant temperature gradient in this condition implies the involvement of Marangoni effect: strong evaporation cools down the fracture-matrix interface, resulting in higher interfacial tension (IFT) near the fracture than in deeper region of the porous matrix. This IFT gradient along the liquid-gas interface drives liquid in deeper matrix towards the fracture that supplies the evaporation front. As a result, the evaporation front is pinned at the fracture/matrix interface that maintains a constant evaporation rate.

This discovery that Marangoni effect reshapes evaporation pattern in near-fracture zone highlights the significance to take non-isothermal effect into consideration, when extensive phase changes emerge in CO2 sequestration, hydrocarbon recovery and fuel cell design.

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References

Time Block Preference

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Participation

Online

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