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Diffusion Hysteresis in Unsaturated Water Flow: A Microfluic study

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In unsaturated flow studies, water saturation is commonly used as the sole descriptor for macroscale flow models. However, this approach often results in hydraulic hysteresis in capillary pressure and relative permeability during drainage and imbibition processes. Furthermore, the effects of these behaviors on solute diffusion remain unclear. To address this knowledge gap, we conducted microfluidic experiments to investigate these hysteresis relationships. We firstly implemented drainage and imbibition processes in the micromodel to establish pore-scale water configurations. Subsequently, we upscaled the capillary pressure and diffusion coefficients to the Representative-Elementary-Volume scale. Our results revealed that, at the same saturation levels, the unsaturated diffusion coefficients during drainage were at least 6.1% higher than during imbibition, indicating the presence of diffusion hysteresis. We observed that this hysteresis was influenced by capillary number and residual water saturation. An increase in the capillary number reduced diffusion hysteresis, similar to the capillary pressure hysteresis. While a decrease in residual saturation rose diffusion hysteresis. We also proposed a quadratic polynomial model that effectively predicts the diffusion coefficient by incorporating both saturation and capillary pressure. This research emphasizes the importance of historical changes in unsaturated water flow, which hold significant implications for modeling solute transport processes.

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