Non-Fickian dispersion in unsaturated porous media, influence of the Peclet number.

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Résumé

Human activity has a significant impact on the vadose zone, an area located below the land surface and above the water tables, only partially saturated with water. The vadose is susceptible to pollution from agricultural or industrial activities, posing a threat to water resources. Plus, saturation levels vary greatly, especially with the increasing frequency of droughts due to climate change. Hence, predicting contaminant transport in unsaturated conditions is crucial. However, the understanding of dispersion in unsaturated porous media remains limited, due to the complex interaction of multiphase non-miscible flows with the porous medium. Traditional models such as the Fickian model, described by the Advection-Diffusion Equation, fail to accurately capture dispersion in unsaturated porous media.
The objective is to address the issue of transport in unsaturated porous media by identifying relevant properties at the pore scale to understand dispersion at a larger scale. One of the goals is to determine whether dispersion follows Fickian or non-Fickian behavior, as this understanding is crucial for predicting the spreading of pollutant in the vadose zone.

To investigate transport in unsaturated porous media, a dual approach is being employed: pore-scale transport experiments and Lattice Boltzmann simulations. Direct visualization of fluid structure in porous media is challenging. Thus, we use micromodels, transparent interconnected porous networks, to enable optical visualization at the pore scale. First, a micromodel experimental set-up was established and optimized to study multiphase flow and transport. Analysis methods were developed, along with techniques for characterizing dispersion through spatial moment analysis.

A series of experiments were conducted to obtain initial results on multiphase flow and dispersion. The evolution of saturation and phase distributions with the capillary number was characterized. Transport experiments were performed for the entire range of saturations, showing that dispersion increases as saturation decreases. However, analyzing low saturations was challenging due to the significant increase in dispersion and limitations imposed by the micromodel size, preventing the study of long-term dispersion.

To overcome this limitation, Lattice Boltzmann simulations were used for flow and transport,

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as there is no size limitation except for computational time. However, simulating the distribution of two phases after a multiphase flow in a complex porous medium remains challenging. Generating large-scale images of unsaturated porous media based on experimental data was then crucial for observing late-time dispersion. Machine learning techniques, specifically the Multiple Point Statistic algorithm, were employed to generate images of wider unsaturated porous media and a large dataset of smaller images to increase the statistical significance of the study.

Flow and transport simulations were conducted using the generated image dataset to explore the influence of saturation on flow and transport. This involved examining flow properties under saturated and unsaturated conditions. The nature of transport, specifically whether it exhibited Fickian or non-Fickian behavior was investigated. Furthermore, the effect of the Peclet number (a measure of the balance between advection and diffusion) on dispersion for different saturation levels was analyzed.
This study revealed that decreasing saturation significantly increases flow heterogeneity, leading to increased dispersion. Notably, the non-Fickian nature of flow tends to be more pronounced with low saturations. Plus, the transition from Fickian to non-Fickian depends on the Peclet number. There is a competition between advection and diffusion in saturated conditions, resulting in a diffusive Fickian regime for low Peclet numbers. However, transport in unsaturated conditions is mainly advective, even at low Peclet, and thus displays a non-Fickian behavior.