Oxygen propagation fronts in porous media under evaporative conditions

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The exchange of gas components across the subsurface/atmosphere interface impacts a wide range of biogeochemical processes in the subsurface. The atmosphere provides a huge source/sink for gas components, which acts as a driving force for their exchange across the interface. The migration of water vapor from the subsurface to the atmosphere leads to evaporative drying of soil, changes the distribution of fluid phases in the pore space by introducing a drainage-induced phase displacement, and impacts the water quality in the shallow subsurface [1,2]. The atmosphere also provides a source of oxygen and supplies this important component to the subsurface systems where it migrates via different transport mechanisms depending on the spatiotemporal distribution of fluid phases in the pore space. The oxygen migration pattern controls the dynamics of abiotic (e.g., dissolution/precipitation of minerals) and biotic (e.g., soil respiration) processes in the subsurface [3]. Therefore, it is of great importance to characterize the oxygen transport across the subsurface/atmosphere interface under evaporative conditions.

To this end, we performed a set of well-controlled evaporation experiments to determine the spatiotemporal evolution of temperature and oxygen fronts in initially anoxic porous media using non-invasive optical-based sensors. The experiments allowed the investigation of the coupling between mass and heat transfer in porous media with different grain sizes and under different evaporative conditions (i.e., natural and enhanced evaporation). The natural evaporation experiments were performed at room temperature, whereas the enhanced evaporation experiments were conducted by placing a heat source on top of the porous media. In parallel, we also performed a set of single-phase experiments (i.e., no evaporation) using the same porous media. Additionally, we developed and applied a non-isothermal multiphase and multicomponent model at the Darcy scale to simulate phase displacement, heat propagation and component transport within and across the fluid phases in the porous media and to quantitatively interpret the experimental observations. The experiments and the model-based interpretation allowed us to elucidate the effects of external atmospheric forcing (i.e., temperature gradients, humidity conditions) and internal factors (e.g., grain size) on the transport and distribution of water and oxygen components under different conditions.

In the single-phase experiments, the oxygen profiles showed a slow diffusive transport pattern in the initially anoxic porous media. A markedly different oxygen migration behaviour, with a fast and abrupt increase of oxygen in the porous media, was observed during the evaporation experiments. The modelling outcomes revealed that such fast migration of oxygen during the evaporation experiments is induced by the appearance of the gaseous phase resulting from evaporation and is controlled by the advancement of the drying front. Such progressively advancing drying front enhances oxygen diffusion and interphase mass transfer across the fluid phases. The results also demonstrate a larger oxygen penetration depth in the fine-textured porous media in comparison to the coarse-textured porous media, highlighting the importance of internal factors (i.e., grain size) in the distribution of fluid phases and transport of gas components in the two-phase system resulting from evaporation.

References

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