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Spatial moment analysis of single-species transport in unidirectional laboratory tracer tests using rock cores

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In the study of solute transport in porous media, it is common to rely on the Advection Dispersion Equation (ADE) model to interpret effluent breakthrough curves (BTCs) post unidirectional tracer laboratory tests. However, this approach is not suitable for porous rocks, as these are characterised by transport processes that occur over a wide range of length- and temporal scales. To deliver better subsurface engineering solutions in complex porous media, whether it be for groundwater contaminant tracking, carbon capture and storage (CCS), or geothermal/petroleum resource extraction, a workflow that integrates an updated experimental approach, and a novel means of data processing is necessitated.

Here, we deploy a numerical optimisation routine to fit experimental BTC data measured on Bentheimer Sandstone (BS), Ketton Limestone (KL), and Edwards Brown Carbonate (EB), at different flowrates and published previously (Kurotori et al. 2020). Although we use the ADE model to fit the BTC data of BS (a homogeneous sandstone), the Multi-Rate Mass Transfer (MRMT) model was used to fit the BTC data of KL and EB, two highly heterogenous carbonates. The analysis includes the estimation of parameters'uncertainty by Bayesian inference. These parameter values (and their uncertainties) are then used to evaluate the first four spatial moments of the internal concentration distribution, representing the temporal evolution of total mass (0th), centre of mass (1st), variance (2nd), skewness (3rd) and kurtosis (4th). Unique to this study, the predicted moments are compared to their experimental counterparts, which have been estimated from 4D solute concentration measurements obtained by Positron Emission Tomography (PET) imaging.

We demonstrate that PET can be used to precisely measure the spatial moments of the solute concentration and that these present unique features depending on the rock type. We show that for BS the spatial moments are insensitive to flow rate when plotted as a function of pore volumes injected (PVI). However, for the two carbonate rocks, they feature a flow rate dependency, due to the presence of microporosity and vugs, which introduce porous regions of virtually stagnant flow - where transport is largely dominated by diffusion. For the two carbonate samples, both 0th and 1st moment yield earlier breakthrough, and greater tailing of the solute mass with increasing flowrate. The 2nd moment takes much larger values for KL and EB than BS, indicating greater spreading of the tracer pulse and less mixing due to the larger contrasts in activity between the immobile and mobile zones. This is further exacerbated at higher flowrates. For BS, the 3rd and 4th moments prior to breakthrough take constant values at 0 and 3, respectively, indicating that the tracer plume is normally distributed. Yet, lower values are observed for the carbonates, reflecting an evolving skewness of the tracer plume during transport.

Participation

In-Person

References

- Kurotori, T., Zahasky, C., Benson, S.M. and Pini, R., 2020. Description of chemical transport in laboratory rock cores using the continuous random walk formalism. Water Resources Research, 56(9), p.e2020WR027511.

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