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Radial Continuous Time Random Walks for Non-Fickian Solute Transport under Forced Flow Conditions and Different Heterogeneity Scenarios

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Solute transport in heterogeneous porous media is characterized by features that do not conform to advection-dispersion models characterized by equivalent transport parameters. This has been observed in tracer experiments under forced and natural flow conditions. Key questions are (i) how non-Fickian solute transport can be quantified under radial flow conditions, and (ii) how different heterogeneity sources of non-Fickian behavior manifest in non-Fickian radial transport models. In order to approach these questions, we develop a radial continuous time random walk (CTRW) formulation for the quantification and interpretation of non-Fickian solute transport under forced flow conditions and different heterogeneity scenarios. The derived radial CTRW approaches model anomalous behavior induced by heterogeneous flow distributions and mobile-immobile mass transfer processes (matrix diffusion). We start by establishing a general CTRW framework in radial coordinates on the basis of the random walk equations for radial particle positions and times. The evolution of solute concentration is governed by a non-local radial advection-dispersion equation. Unlike in CTRWs for uniform flow scenarios, particle transition times here depend on the radial particle position, which renders the CTRW non-stationary. We then derive radial CTRW implementations that (i) emulate non-local radial transport due to heterogeneous advection, (ii) model multirate mass transfer (MRMT) between mobile and immobile continua, and (iii) quantify both heterogeneous advection in a mobile and mass transfer between mobile and immobile regions. We analyze the transport signatures for the distinct CTRW models in terms of solute breakthrough curves and their dependence on the heterogeneity scenarios.