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Thermal retardation in porous media of macro-scale heterogeneity

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Quantifying advective heat transport in sedimentary aquifers is crucial for understanding processes and applications such as shallow geothermal systems, streambed flux estimation, and aquifer property assessment. Heterogeneous aquifers are ubiquitous and present significant challenges, as the substantial variability in hydraulic conductivity gives rise to preferential flow pathways, non-uniform temperature fronts, and enhanced thermal dispersion. This study systematically conducts direct numerical Monte-Carlo simulations using the Multiphysics Object-Oriented Simulation Environment (MOOSE) to analyze heat transport. We simulate the evolution of a heat plume generated by a borehole heat exchanger in a three-dimensional aquifer of heterogeneous hydraulic conductivity. We characterize the evolving heat plume by calculating dispersion coefficients and effective thermal retardation factors, defined as the ratio of the thermal front velocity to the seepage velocity, averaged over an ensemble of heterogeneous realizations. In addition, we consider varying degrees of heterogeneity and examine the role of the thermal Péclet number in influencing the effective thermal retardation factor.

Results show that for aquifers with homogeneous hydraulic conductivity, the effective thermal retardation factor matches the theoretically predicted apparent thermal retardation factor. However, in heterogeneous systems, the effective thermal retardation factor is significantly reduced compared to the apparent value during the initial phases of transport. This discrepancy becomes more pronounced with increasing thermal Péclet numbers. The reduction in the effective thermal retardation factor can be explained by preferential flow through high-conductivity zones and delayed heat diffusion into low-conductivity regions. We link this phenomenon to local thermal non-equilibrium (LTNE) effects occurring at the field scale. Our findings reveal insights into heat transport in hydraulically heterogeneous systems and highlight the importance of field-scale LTNE effects. Considering these effects in real-world applications, for example field tracer tests in heterogeneous streambeds or shallow geothermal energy use, could improve process understanding, predictions and optimized design.