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Inertial effects in channels with periodically varying aperture and impact on solute dispersion

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Contaminant transport in heterogeneous aquifers occurs mostly in the networks of intersecting channels. The sinusoidal channel geometry is relevant to transport moderately-disordered porous media, as well as (to some extent) to flow and transport in fractures with varying apertures. Here we investigate the spreading of a finite amount of solute entering such a channel of periodically-varying aperture.

In channels of uniform apertures (parallel plate), when solute buoyancy is negligible, the advection and diffusion processes eventually lead to the well-known asymptotic Taylor-Aris dispersion regime. After this asymptotic regime has been reached, the solute progresses along the fracture at the average fluid velocity, according to a one-dimensional longitudinal advection-diffusion process. The corresponding diffusive term features an apparent dispersion coefficient instead of the molecular diffusion coefficient. In many real applications the relevant channels do not have constant aperture. Prior works have shown that deviation from the parallel plate geometry can significantly alter the behavior, leading to relative increases or even decreases in the apparent dispersion. These studies assume small Reynolds number and thus that flow is governed by the Stokes equation. While this is very often a reasonable assumption, the Reynolds number can sometimes be of order unity or larger such that inertial effects are no longer negligible. Increased inertial effects lead to the presence of recirculation zones, which represent immobile regions that can have a significant impact on solute transport and in particular on the asymptotic dispersion. We address flow and geometry configurations for which inertial effects affect flow and transport. In these conditions, flow can no longer be predicted by analytical solutions. We compute the stationary velocity fields based on Navier-Stokes equations, using a numerical scheme based on a finite element analysis. The transport problem is then solved numerically by Lagrangian particle random walk simulations based on the Langevin equation. Depending on the geometry parameters (ie the aspect ratio of a cell and the relative amplitude of the aperture fluctuations) and on the Reynolds number, the size and the position of the recirculation zones vary. This phenomenon is not only responsible for longer residence times of the solute in these zones but also for higher velocities in the middle of the channel. At short times, this leads to unusual spreading patterns and oscillations in the velocity and apparent dispersion evolutions over time. At longer time, solute trapping is clearly visible in the recirculation zones. We characterize the asymptotic dispersion coefficient as a function of the geometry parameters, the Péclet number and of the Reynolds number. In our parameters range, a higher Reynolds number value systematically leads to an increase in the asymptotic dispersion coefficient. In tracer tests, higher apparent dispersion coefficient are often interpreted from the parallel plate model. This study shows that, at sufficiently high Reynolds number values, the channel uniform aperture inferred in that manner would be larger than the real mean channel aperture, the discrepancy arising from the effect of aperture variations.