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Computational Physics of Flow Through Porous Media: Permeability Scaling

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The advent of high-performance computers and advanced fluid dynamics simulation codes allows the Navier-Stokes equations to be solved in realistic three-dimensional pore spaces. As a result it is possible to perform computational experiments on virtual and real porous media that are equivalent in accuracy to physical experiments while yielding unprecedented levels of detail about the resulting flow fields. We will discuss a set of simulations that are aimed at understanding the dynamical basis behind empirical estimates of permeability like the Kozeny equation and related power law models. The Kozeny equation states that the permeability of a porous medium is proportional to the product of porosity with the square of mean hydraulic radius. A Kozeny-type equation is a more general function of porosity and/or hydraulic radius that estimates permeability, in this case a power law. Since its introduction in 1927, the Kozeny equation has been widely applied, but with mixed results. We present computational evidence that the Kozeny equation is most accurate when applied to samples of porous media that fall in a range of porosities between 0.3 - 0.7. In general, the Kozeny equation does not apply to low or high porosity media, and it is less accurate than power law alternatives at all levels of porosity including 0.3 - 0.7. Specifically, we compare estimates of permeabilities based on the Kozeny equation to estimates obtained from three Kozeny-type power laws. Since we produce the entire velocity field within explicit an pore space, we also are able to observe individual streamlines and calculate their tortuosities. We compute statistics of streamline lengths and corresponding breakthrough curves. Based on these microscopic statistics we observe that streamlines fall into two classes: (1) normal streamlines of particles that remain near their neighbors throughout the flow field, i.e., streamlines with low Lyapunov exponents, and (2) streamlines with high Lyapunov exponents that exhibit chaotic behavior by swiftly moving away from their initial neighbors.

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