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Vorticity and upscaled dispersion in 3D heterogeneous porous media

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Modeling flow in porous media is relevant for many environmental, energy and industrial applications. From an environmental perspective, the relevance of porous media flow becomes evident in subsurface hydrology. In general, flow in natural porous media is creeping, yet the large variability in the hydraulic conductivity values encountered in natural aquifers leads to highly heterogeneous flow fields. This natural variability in the conductivity field will affect both dilution rates of chemical species and reactive mixing. A physical consequence of this heterogeneity is also the presence of a various localized kinematical features such as straining, shearing and vorticity in aquifers, which will influence the shape of solute clouds and its fate and transport. This work aims in fundamentally characterizing the vorticity field in spatially heterogeneous flow fields as a function of their statistical properties in order to analyze the impact on transport processes. In our study, three-dimensional porous formations are constructed with an ensemble of N independent, non-overlapping spheroidal inclusions submerged into an homogeneous matrix, of conductivity K_0. The inclusions are randomly located in a domain of volume W and are fully characterized by the geometry of spheroid (oblate or prolate), their conductivity K (random and drawn from a given probability density function f_κ), the centroid location $\bar{x}$, the axes ratio e, the orientation of the rotational axis (α_1, α_2) and the volume w. Under the assumption of diluted medium, the flow problem is solved analitically by means of only two parameters: the conductivity contrast $\kappa = K/K_0$ and the volume fraction $n = Nw/W$. Through the variation of these parameters of the problem, it is possible to approximate the structure of natural heterogeneous porous media. Using a random distribution of the orientation of the inclusions, we create media defined by the same global anisotropy $f = I_z/I_x$ but different micro-structure (inclusion's type and shape). The purpose of this work is to study how different micro-structures impact the vorticity. The analysis is carried on for a binary medium, as a function of conductivity contrast κ, and for heterogeneous ensemble of inclusions with a lognomal distribution of κ, as a function of heterogeneity degree $\sigma^2_{\ln\kappa}$. Inclusion's type and shape have a great influence on the vorticity field: in media defined by the same volume fraction and anisotropy degree, thinner inclusions yield more vorticity, therefore the smaller is e the greater is the vorticity. This effect is more evident if inclusions are more conductive, due to flow focusing effects. We demonstrate that the statistical anisotropy of the medium plays an important role: the smaller is the statistical anisotropy ratio, the higher is the vorticity produced by the mixture of inclusions. Furthermore, considering heterogeneous mixture of inclusions, it is showed that vorticity growths with increasing the variance of the conductivity contrast distribution. In addition to analyzing the rotational properties of the spatially variable flow field, we illustrate how the global vorticity of the medium affects solute transport. This is achieved by evaluating the upscaled dispersion coefficients.