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Biofilm growth in heterogeneous porous media: pore-scale modeling and anomalous transport analysis

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Biofilms are complex microbiome in extracellular polymeric substances that regulates the biological environments in porous media. The phenomenon of solute anomalous transport can be induced from the evolution of biofilm which dynamically alters the pore structure, the hydrophobicity, and the hydrological-biogeochemical processes in the pore space. So far, few study has pay attention to scaling the regime of biofilm-induced anomalous transport through numerical modeling and simulation. In this study, an in-house developed solver BioFOAM, based on the micro-continuum theory and the Darcy-Brinkman-Stokes equation, was developed to simulate pore-scale solute transport of fluid flow and biofilm growth. Parameter sensitivity analysis were then conducted to investigate the effects of the substrate concentration (c), the Monod kinematic parameter (ks), and the growth rate (μ) on transport properties. Finally, anomalous transport regimes were quantified via breakthrough curves under different Reynolds (Re), Peclet (Pe) and Damköhler (Da) numbers. Results revealed that (1) the biofilm growth process significantly altered the flow velocity field by reshaping the pore structure and forming recirculation zones. These behaviors resulted in the evolution of solute transport pathways in heterogenous porous media. (2) The parameter c, ks, and μ demonstrate different sensitivities towards biofilm growth processes. The growth rate was the most sensible parameter. The biomass density, the averaged porosity and permeability varied significantly even at the value of 10^{-6}. The Monod kinematic parameter showed a clear dividing region from 10^{-3} to 10^{-4}. When ks was below 10^{-4}, the biomass density accumulated while the porosity and permeability decreased. When ks was larger than 10^{-3}, the biofilm growth was invalid. The substrate concentration was not sensitive for biofilm accumulation. (3) The nondimensional number Da was useful in analyzing anomalous transport regimes, while the variation of Re and Pe did not bring much difference to the breakthrough curves. For the case of biofilm growth on a single grain, the valid anomalous breakthrough regime was within the Da from 0.018 to 0.054. When Da was below 10^{-3} or above 10^{-1}, the anomalous breakthrough phenomenon disappears. For the case of biofilm growth in heterogenous porous media, the valid anomalous breakthrough regime was within the Da from 2.5×10^{-4} to 3×10^{-3}. When Da was as small as 1.5×10^{-4}, the anomalous breakthrough phenomenon disappears. When Da was as large as 6×10^{-3}, the numerical experiment received numerical error. In general, when the Da number was within the anomalous transport regime, the characteristic time decreased and the tails stretched longer as the increase of the Da number. This study provides a specific modeling case to analyze the biofilm-induced anomalous transport regimes, which can be regarded as a comparative effort to theoretical studies on the scaling of anomalous transport regimes.

Participation

In-Person

References

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