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Reactive transport in fractured porous media

L. Jasinski^a, J.-F. Thovert^b, V.V. Mourzenko^b, P.M. Adler^a

^aUPMC-Sisyphe, tour 46, 4 Place Jussieu, 75252 Paris Cedex 05

^bInstitut PPRIME - CNRS, SP2MI, BP 30179, 86960 Futuroscope Chasseneuil Cedex

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Reactive flow through geological formations can result from natural processes, such as chemical dissolution/precipitation in diagenesis or karstification, or be due to human intervention, provoked as in acidization for increasing a well productivity, or accidental in CO₂ sequestration. The description of the injection of a reacting fluid from a well, the quantitative analysis and prediction of the improvements or damages caused to the well itself and to its immediate surroundings are a subject of high interest.

The simultaneous account of the flows through the matrix rock and through the fractures that it contains is a challenging problem, due to the wide range of associated space and time scales. It is addressed here by direct numerical simulation, in a discrete fracture model. The coupled system of equations to be solved includes the descriptions of the fluid flow, of the solute transport by convection and diffusion/dispersion and of the chemical reactions, on the Darcy scale in the porous matrix and in the fracture network. In addition, constitutive equations are required for the evolution of these two structures, such as evolution laws for permeability and reactivity as functions of porosity.

An unstructured tetrahedral mesh of the fractures and of the porous matrix is built in the first place. Then, Darcy's equations are discretized and solved in a finite volume formulation. These two steps have been described in earlier works, which are summarized in [1]. Examples are shown in Fig.1. The simulation of the evolution of the solute concentration is the most difficult point. A time implicit, non linear flux limiting scheme was implemented to avoid numerical diffusion. First-order dissolution/deposition reactions can take place, both in the matrix and the fractures, which modify their porosity and aperture. This in turn modifies the flow field which has to be continuously updated during the simulations. The effective properties such as the permeability, diffusivity and reactivity coefficients are modeled as functions of the local matrix porosity and fracture aperture.

Simple model situations have been considered for validation purposes or to illustrate some physical points. In particular, it is shown that even when the matrix permeability is small convective matrix/fracture exchanges can still widely exceed diffusive ones and strongly affect the solute transport and its residence time distribution. Finally, simulations of passive and reactive solute transport have been performed in large samples containing fracture networks, percolating or not. Various parameters have been systematically investigated, including the fracture transmissivity σ' , the flow regime characterized by Péclet numbers in the fractures and matrix (Pe_m , Pe_f), and the Damköhler numbers of the reaction process in the matrix and fractures. The passive transport behavior and the effect of the gradual clogging of the fractures and/or matrix pore space in the case of precipitation are analyzed.

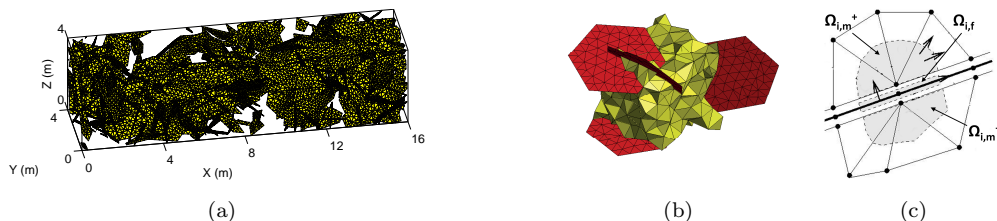


Figure 1: A fracture network meshed by unstructured triangles (a). Meshing of the matrix by unstructured tetrahedra (b). Triple control volume around a fracture node for the finite volume formulation (c).

Examples of concentration fields in the matrix and fractures are shown in Fig.2 for a pulse injection of passive solute in a long rod in different regimes. Typical concentration profiles are shown in Fig.3 for a continuous injection of reactive solute in such a rod. At early times (a), the solute front progresses but decreases in magnitude due to deposition. However, deposition does not yet cause significant changes in the medium properties and a nearly steady profile is reached. Due to strong convective exchanges between matrix and fractures, the solute carried by the fractures is transferred in the surrounding matrix and the two concentration profiles are only slightly shifted. Later (b,c), clogging becomes significant, the flow rate decreases and the concentration profiles recede. The recession is more pronounced in the matrix, since it is clogged along the fractures which prevents the solute to reach it.

References

- [1] Adler P.M., J.-F. Thovert, V.V. Mourzenko, *Fractured porous media*, Oxford University Press, 2012.

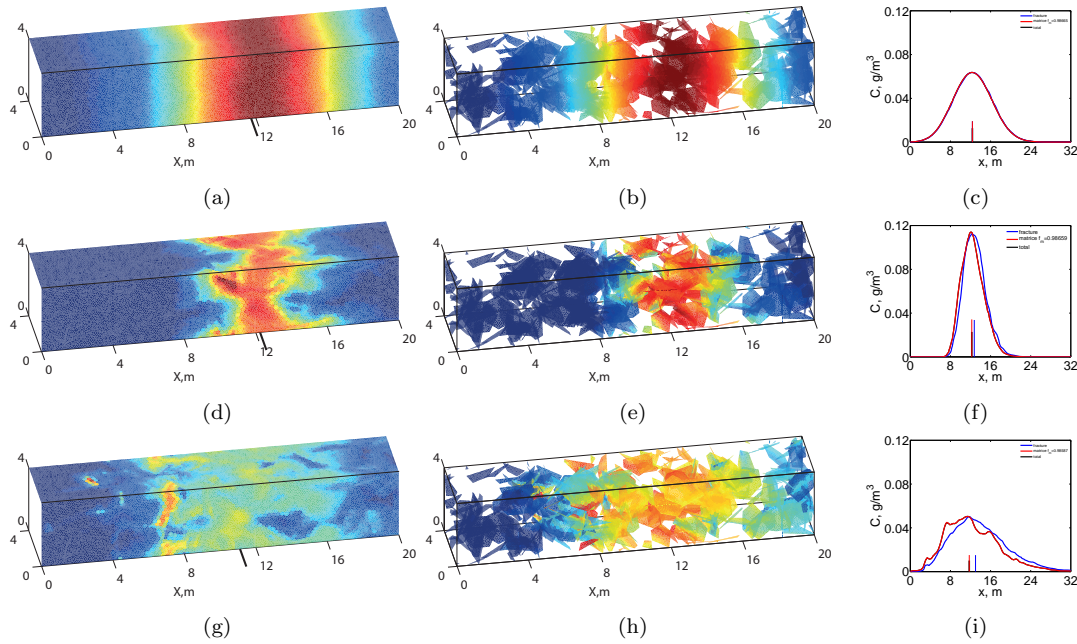


Figure 2: Transport of a pulse of passive solute injected at $x = 0$ in a fractured porous matrix. Concentration at the rod walls in the matrix (left), in the fractures (middle), and in average over the cross section (right). The rows correspond to different regimes, $Pe_m=1$ and $\sigma'=1$ (top), $Pe_m=100$ and $\sigma'=1$ (middle), $Pe_m=100$ and $\sigma'=10$ (bottom). The concentration fields are captured at identical mean travel distances in all cases.

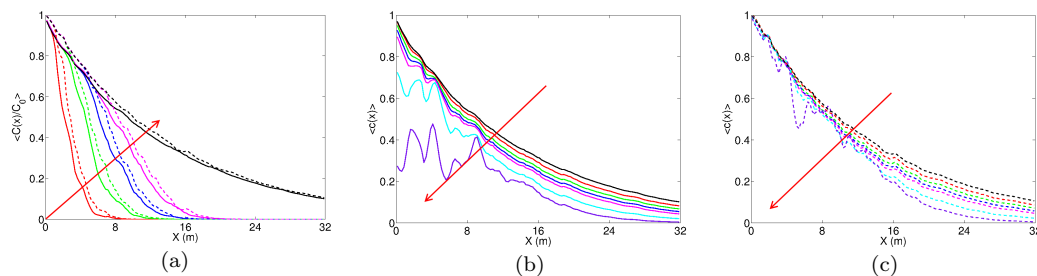


Figure 3: Continuous injection at $x = 0$ of a reactive solute in a rod of fractured porous matrix. Mean concentration profiles at successive times. The arrows show the evolution for increasing times. (a) early times in the matrix (—) and fractures (---); (b) late times, in the matrix; (c) late times in the fractures.