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Semi-Analytical Models of Fracture Dissolution Including Roughness and Interporosity Fluid Exchange

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Abstract

Fracture dissolution in carbonate rocks is of great interest for the applications of CO₂ geological storage and formation of conduits and caves in karst reservoirs. Taking into account the fracture roughness and interporosity fluid exchange between the fracture and the porous host rock, the classical cubic law for parallel-plate channels or Poiseuille's flow for tubes cannot describe the flow within the fracture's opening.

Reynolds number increases along the fracture as a result of the influx crossing the fracture walls. The wavy, irregular, nonparallel-plate shape of the boundaries affects the overall flow regime and the average flow model. The velocity field on the fracture boundaries possesses a slip and a normal component. The nonzero fluid velocity maintains the concentration gradient near the porous host rock and provides a fresh source of the solvent that facilitates dissolution.

The aim of this work is to point out the role of fracture roughness and the flux of fluid through the walls on fracture dissolution. The model of flow in a single fracture with permeable wavy walls is coupled to transport of dissolved calcite. The asymptotic solutions of the steady-state Navier-Stokes equations with slip boundary condition are used to determine the velocity field in the fracture opening. The case of parallel-plate wavy fractures is considered. The inflow through the walls increases the Reynolds number along the fracture and results in local flow instabilities and formation of reverse flow. The local instabilities arise in relatively higher Reynolds numbers in parallel-plate wavy fractures than in cylindrical wavy fractures. The corrections result from the effect of the inflow through the walls and the irregular geometry of channel. Asymptotic solutions to the reactive transport of the dissolved calcite in the acidified brine are derived for rate-limited reactions with a low Damkohler number and high Peclet number. The role of the fracture's walls corrugations, fractures aspect ratio, various surface roughness shapes, and the interporosity fluid exchange between the fracture and host rock on the fracture dissolution is investigated.

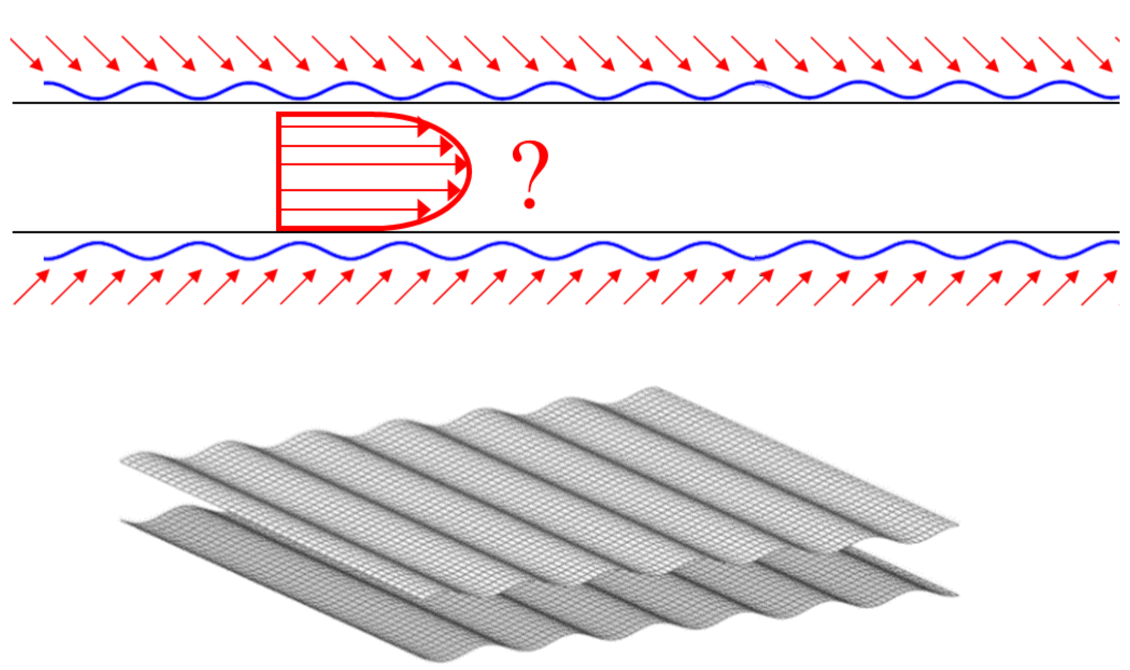


Figure 1. Schematic of a fracture with sinusoidal wavy walls

Problem Formulation

The flow in the fracture is described by a complete set of Navier-Stokes equations, while the flow in the porous rock will be described by Darcy's law. The exchange between the fracture and porous rock is ensured by applying the no jump boundary conditions on normal component of flux, slip condition on tangential velocity, and pressure jump on the interface of conduit and porous rock using Beavers-Joseph-Saffman boundary condition. The influx is highly dependent on the geometry of the interface between the conduit and the porous host rock. This dependence will be taken into account by using the Modified Beavers-Joseph-Saffman boundary condition.

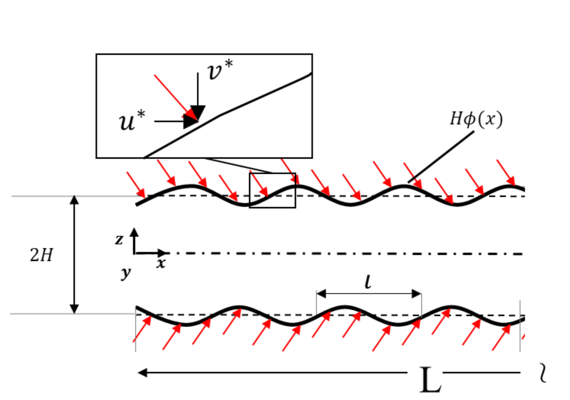


Figure 2. Interporosity fluid exchange between fracture and porous rock is influenced by the fracture wall roughness

Flow Equations and Solute Transport

Flow equations

$$\omega \frac{\partial u}{\partial x} + \frac{\partial v}{\partial z} = 0,$$

$$Re\left(\omega u \frac{\partial u}{\partial x} + v\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \left[\omega^2 \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z}\right],$$

$$Re\left(\omega u \frac{\partial v}{\partial x} + v\frac{\partial v}{\partial z}\right) = -\frac{1}{\omega}\frac{\partial p}{\partial z} + \left[\omega^2 \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial z^2}\right].$$

Boundary conditions:

$$1 = \int_0^{\varphi(0)} u(0,z)dz,$$

$$\left.\frac{\partial u}{\partial z}\right|_{z=0} = 0, \quad v\Big|_{z=0} = 0, \quad u\Big|_{z=\varphi(x)} = \omega u^*, \quad v\Big|_{z=\varphi(x)} = -\omega v^*.$$

Two small parameters $\omega = \frac{H}{L}, \quad \varepsilon = \frac{\ell}{L}$

Chemical dissolution

$$r = kS_r\left(1-\left(\frac{Q}{K_e}\right)^\theta\right)^\eta a_{H^+}^n,$$

$$k = k_1 a_H^+ + k_2 a_{H_2CO_3} + k_3.$$

$$CaCO_3 + H^+ \overset{k_1}{\Leftrightarrow} Ca^{2+} + HCO_3{}^-$$

$$CaCO_3 + H_2CO_3 \overset{k_2}{\Leftrightarrow} Ca^{2+} + 2HCO_3{}^-$$

$$CaCO_3 \overset{k_3}{\Leftrightarrow} Ca^{2+} + CO_3{}^{2-}$$

Solute transport

$$\frac{\partial c_i}{\partial t} + (\boldsymbol{u}\cdot\nabla)c_i = \nabla\cdot D_m \nabla c_i.$$

Method

Asymptotic solution

The solution will be searched in the form of a double asymptotic series expansion with respect to

$$\mathcal{F}(x,z) = \mathcal{F}_0(x,z) + \omega\mathcal{F}_1(x,z) + \omega^2\mathcal{F}_2(x,z) + \cdots,$$

$$\mathcal{F} = (u,v,p)$$

Two-scale formulation

The small-scale variable $y = x/\varepsilon$ is used to represent the two-scale oscillations of the wall geometry.

$$\frac{\partial f}{\partial x} = \frac{\partial \tilde{f}}{\partial x} + \frac{1}{\varepsilon}\frac{\partial \tilde{f}}{\partial y}$$

$$f(x,z) = \tilde{f}(x,y,z)|_{y=x/\varepsilon}$$

Mapping to parallel plane geometry

$$(x,z) \longrightarrow (x,\zeta), \qquad \zeta = z/\phi(x),$$

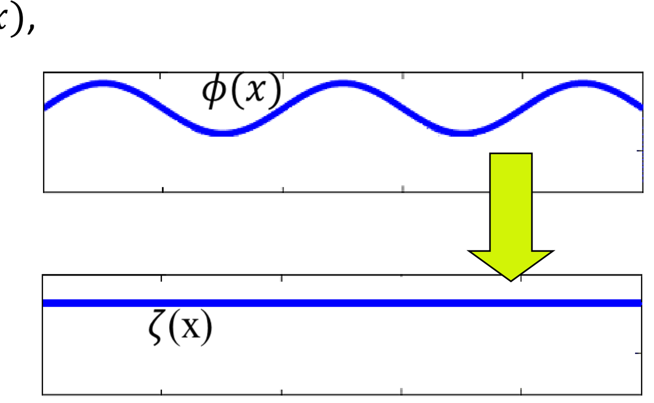


Figure 3. Mapping the wavy geometry to parallel-plane geometry

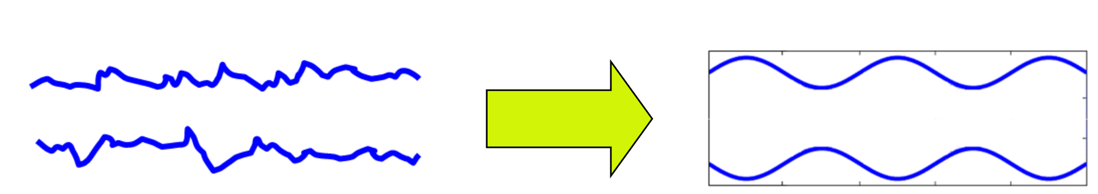
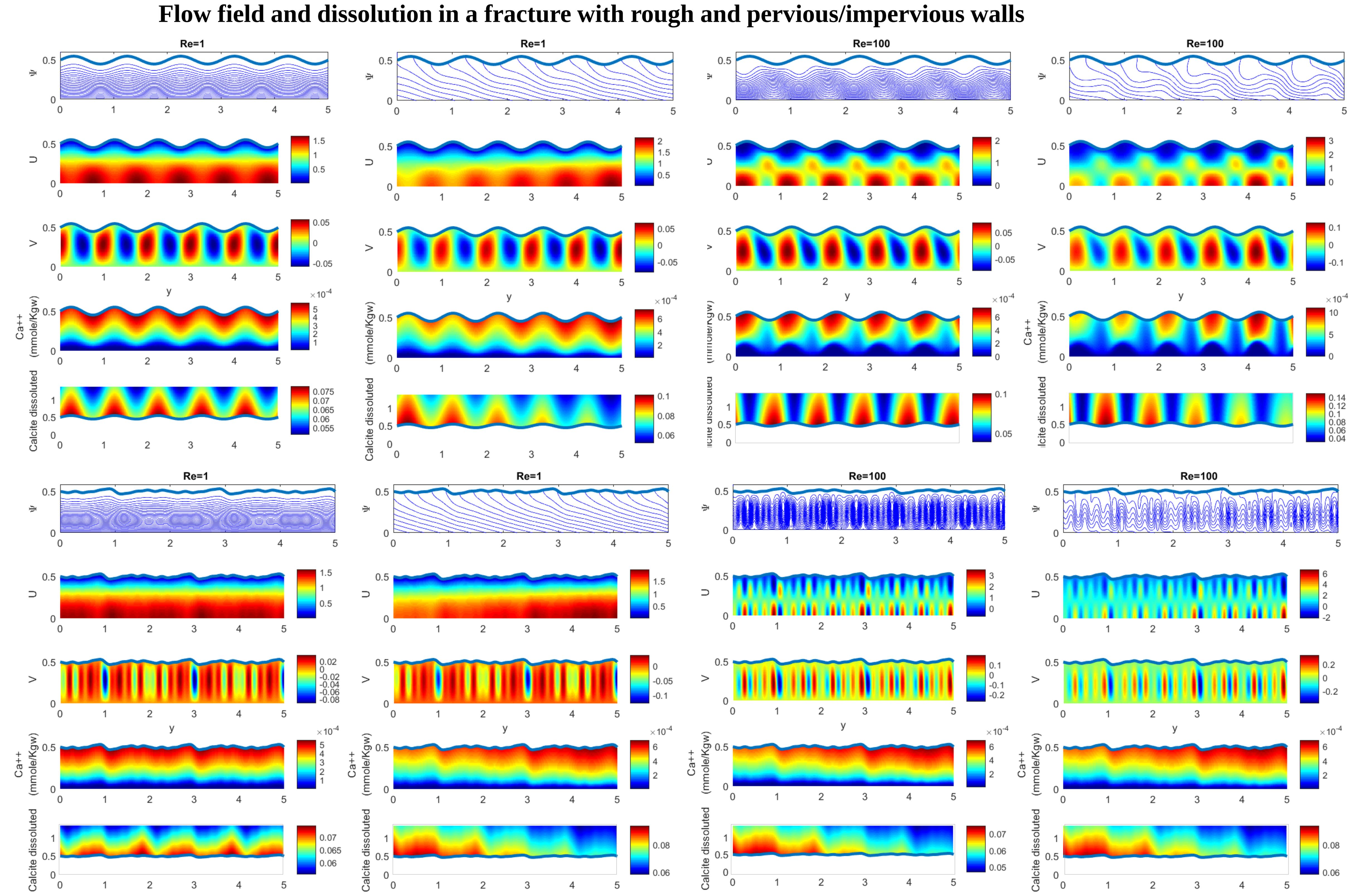
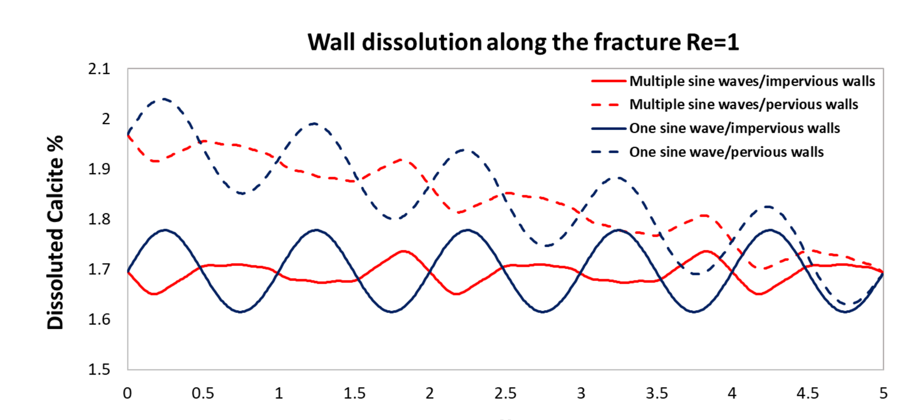


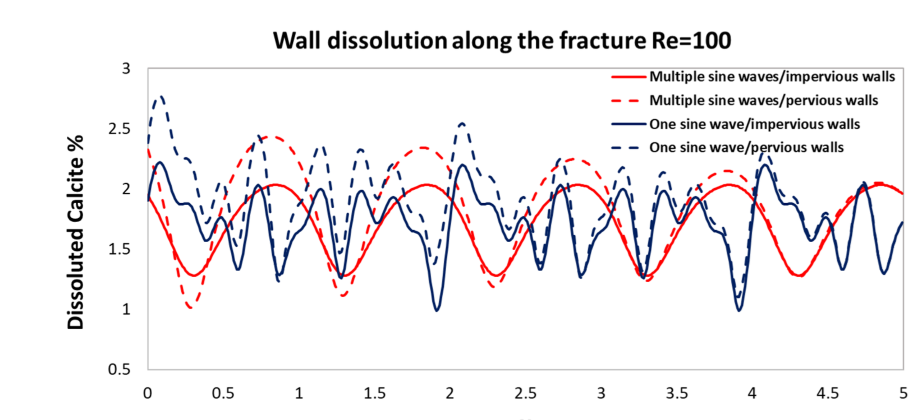
Figure 4. Microstructure of fracture surface roughness given by a piecewise continuous function

Results

Flow field and dissolution in a fracture with rough and pervious/impervious walls







Coupling Scheme

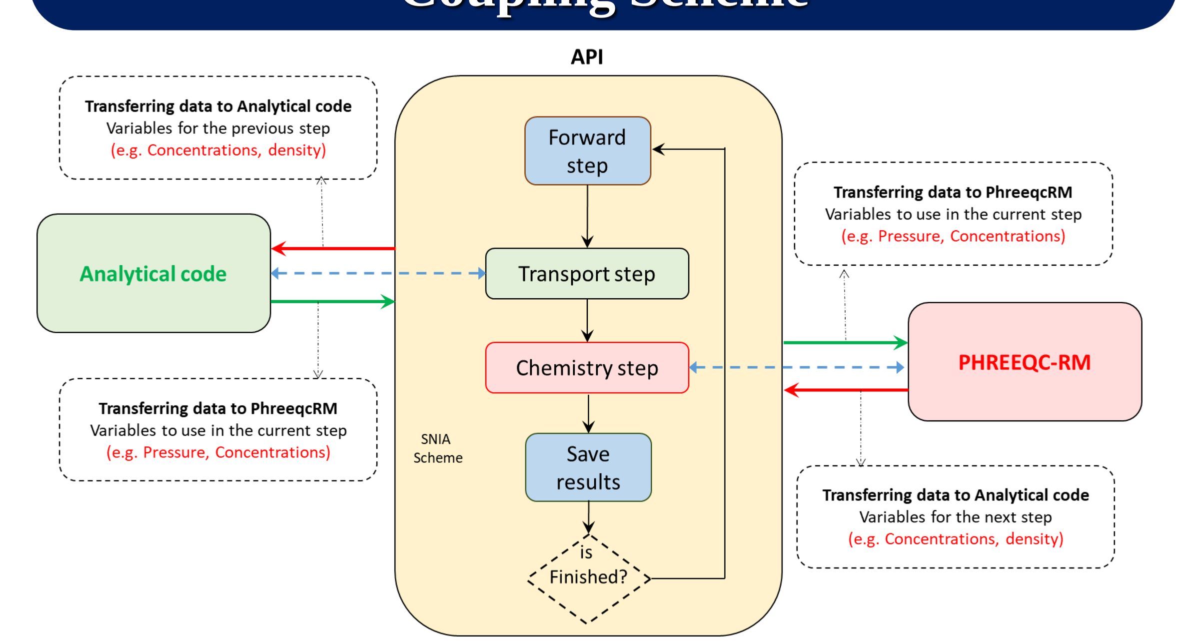


Figure 5. Flowchart showing the SNIA coupling scheme of analytical model and PHREEQCRM using an API. In each step, all the variables are transferred from the transport code to the geochemical code to be updated with the reaction data and then transferred back to transport code for the next step.

Conclusion

In this study, we performed pore-scale simulation of reactive transport in a single fracture with rough permeable walls embedded in porous medium. The semi-analytical solutions for fluid flow and transport in fracture is coupled to geochemical reactions taking place in the solid part of the wall. Different flow regimes and different roughness configurations are considered to investigate the fracture evolution. The results show the significant role of wall roughness and permeability on the fracture dissolution. These results cannot be captured by classical cubic law. First sine approximation of the wall roughness is determinative in wall dissolution. Higher Reynolds is expected to results in more significant wall dissolution. The flux through the walls maintains the nonzero velocity and improves the gradient of concentration. As a consequence the dissolution of pervious walls is higher than impervious walls.