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Numerical Investigation of Microbially Induced Calcite Precipitation as a Leakage Mitigation Technology

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Abstract

In this work we investigate the performance of a numerical model for microbially induced calcite precipitation predicting the reduction of permeability over time due to biomineralization under reservoir pressure in sandstone cores. Although the model was previously validated with experiments in sand columns under atmospheric pressure, its calculations are consistent with experimental data towards the final half of the experiment, if the implemented porosity permeability relation is fitted to the final experimental porosity and permeability. The initial reduction of permeability is underestimated by the model, indicating an inconsistency between model and experiment. Calculated and measured porosity are nearly identical.

Keywords: reactive transport, numerical simulation; calcite precipitation; biofilm; leakage mitigation; carbon dioxide sequestration geochemistry

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1. Introduction

Reliable technologies and engineering measures to prevent leakage from reservoirs in case of unexpected problems is crucial for both safety and efficiency of carbon capture and storage (CCS). One of the possible sealing technologies is mircobially induced calcite precipitation (MICP). Bacteria, calcium and other reactants are injected into the rock, were the metabolism of the bacteria alters the geochemistry resulting in a super saturation of calcite. The subsequent calcite precipitation reduces or even completely clogs the pore space, minimizing possible leakage pathways.

Experiments in sand-filled columns [1] and rock cores [2] show that it is possible to control the distribution of the precipitated calcite through the column as well as to reduce the permeability of a fractured rock due to mineralization. A model describing the relevant processes of MICP has been developed and validated using the experimental data of the sand column experiments [1].

Recently, MICP experiments were conducted under reservoir-like pressure conditions at 7 MPa using a large fractured sandstone core [2] as well as small 5.08 cm long and 2.54 cm diameter cores of the same sandstone [3]. In this work, the existing model is used to simulate a small sandstone core experiment to find out if the model is able to describe MICP under more realistic conditions, including reservoir-like pressure and a consolidated porous medium.

Nomenclature

φ	porosity
φ_0	initial porosity
φ_b	volume fraction of biofilm
φ_c	volume fraction of calcite
φ_{crit}	critical porosity at which the intrinsic permeability becomes zero
K	intrinsic permeability
K_0	initial intrinsic permeability

2. Methods and Results

The two-phase multi-component reactive transport model used for simulation is the same as described in [1]. It is implemented in the numerical framework of DuMu^x [4]. Geometry and properties of the porous medium as well as the boundary conditions were adapted to match the conditions of the high-pressure, rock-core experiment. Table 1 shows the main differences in the porous media, injection and geometry parameters between the new sandstone core experiment [3] and the sand-filled column experiments, which were used to validate the model in [1].

Table 1. Differences between experiments used for validation of the model and the experimental setup considered in this paper.

Experiment(s)	Length	Pressure at effluent	Molar ratio of injected calcium to urea	Biofilm resuscitation events	Initial porosity φ_0	Initial permeability K_0
Sand columns [1]	61 cm	0.1 MPa	3.7 Ca/Urea	When appropriate	0.4	1.8 – 2.3x 10^{-10} m²
High-pressure core [3]	5.08 cm	7 MPa	1 Ca/Urea	After each calcium injection	0.18	3.7x 10^{-14} m²

Figure 1 shows a sketch of the simulation domain with the used grid of 4 cells with the boundary conditions. At the left, there is a periodically changing injection of different aqueous media according to the experimental injection scheme. The injected media are equivalent to those in [2]. Top and bottom are Neumann no-flow boundaries. The outlet on the right hand side is implemented as a Dirichlet boundary. For this boundary all values are set to the initial value except for substrate and oxygen, which are set to zero. The simulation domain is set twice as long as the experimental core in order to avoid boundary effects.

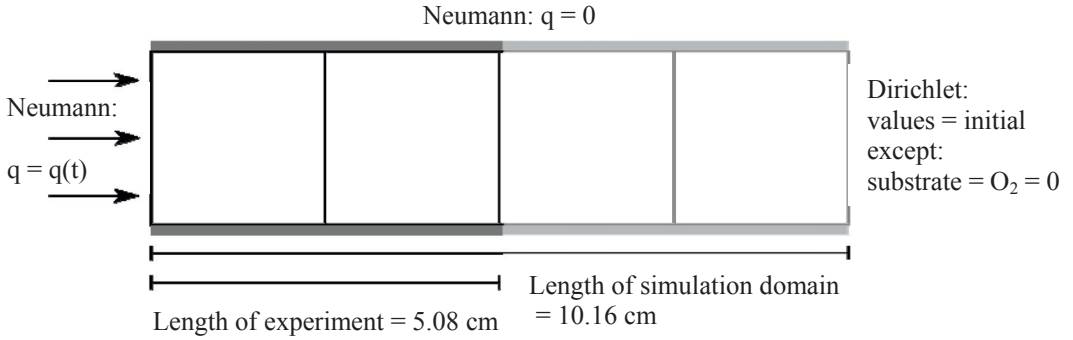

Fig. 1. Sketch of the domain, boundary conditions and the grid used for simulation

After simulation of the experiment, the simulated permeability was reduced by a factor of roughly 2, whereas the experimental permeability was reduced by a factor of about 10. The implemented relation of porosity to permeability is of a Kozeny-Carman like type:

$$\frac{K}{K_0} = \left(\frac{\varphi - \varphi_{crit}}{\varphi_0 - \varphi_{crit}} \right)^3 , \text{ with} \tag{1}$$

$$\varphi = \varphi_0 - \varphi_b - \varphi_c . \tag{2}$$

In the original model, validated against experiments in sand columns, φ_{crit} has been set to zero [1]. Considering that the permeability of a consolidated sandstone rock may tend to zero before its porosity

does, a second simulation was run with a value of $\varphi_{crit} = 0.108$, fitted using the measured final porosity and permeability. In Figure 2, the permeabilities of both simulations are compared to the permeability calculated from the measured pressure drop during injections in the experiment. For the simulation with the fitted critical porosity, the simulated permeability fits quite well to the experimentally measured data after a time of 500 hours. The initial drop in measured permeability is not matched by any simulation.

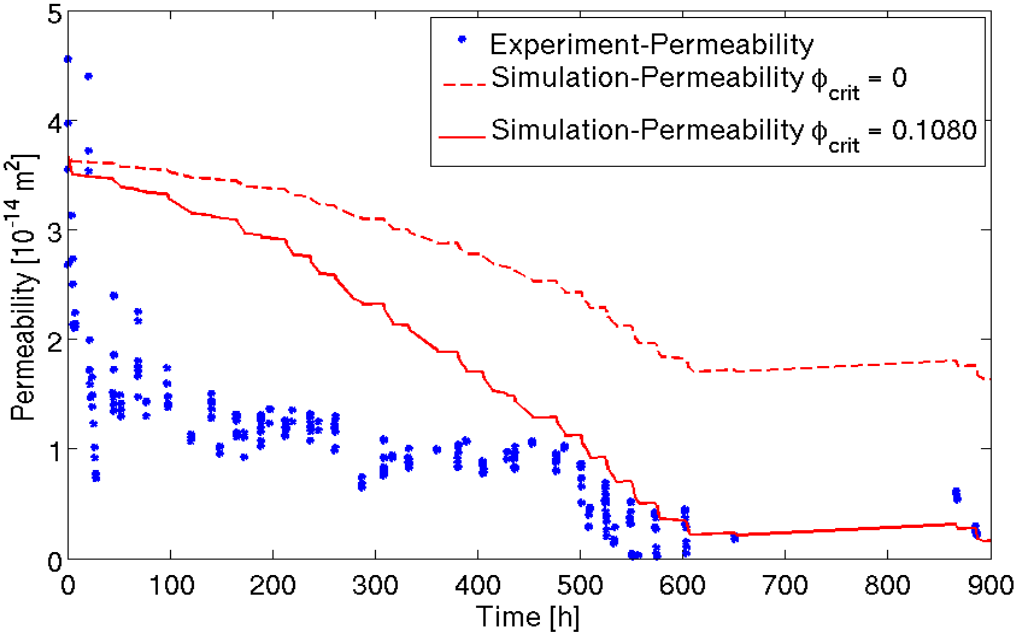

Fig. 2. Comparison of measured (blue stars) and simulated permeability (red lines) over time. The dashed line represents the permeability as calculated in the original model as described in [1], where as the solid one shows the permeability after fitting φ_{crit} in equation (1) to the experimental data.

Table 2 shows the volume fraction of calcite in the inlet and outlet half of the core, the average volume fractions of biofilm and calcite, and the resulting average porosity and permeability for each simulation and the experiment. Results of simulations with finer discretization, which are not shown here, are not significantly different from the 4-cell grid results.

Table 2. Comparison of simulated and measured volume fractions of calcite, average volume fraction of biofilm, average porosity and mean permeability at the end of the experiment. The experimental volume fraction of biofilm was calculated as $\varphi_b = \varphi_0 - \varphi - \varphi_c$, using equation (2).

	φ_c in the inlet half	φ_c in the effluent half	Average φ_c	Average φ_b	Average φ	Mean K
High pressure core experiment	0.035	0.039	0.037	0.006	0.137	2.4×10^{-15} m²
Simulation, $\varphi_{crit} = 0$	0.03355	0.02947	0.03151	0.01058	0.1379	16.3×10^{-15} m²
Simulation, $\varphi_{crit} = 0.108$	0.03353	0.02943	0.03148	0.01045	0.1381	1.6×10^{-15} m²

Decreasing simulation results with distance from the inlet for calcite were contrary to the experiment, where the outlet half of the core contained more calcite than the inlet half. Average volume fractions of calcite were lower for both simulations than for the experiment. However, in a control core 2.5 mg calcite were measured per g of sandstone [3], which yields an initial volume fraction of 0.002. Considering this initial calcite, the difference between simulated and experimental calcite was less than 10 % of the measured volume fraction of calcite.

Biofilm volume fractions were higher in the simulations, but the low volume fraction of biofilm of the experiment might be due to decay prior to porosity measurement, since porosity was not measured until weeks after the end of the experiment. Additionally, some biofilm might have been removed by detachment during the permeability measurements. Due to the fitted φ_{crit}, in the second simulation calculated shear stresses were increased as the permeability was reduced, which resulted in increased detachment of biofilm. The volume fraction of precipitated calcite decreased accordingly, since less biofilm produced less catalyzing enzymes. However, this decrease in biofilm and precipitated calcite for the simulation with the fitted φ_{crit} was very small. The average permeability for the simulations was calculated as a harmonic mean of the local permeabilities.

3. Conclusions

The model is capable of simulating MICP under reservoir-like conditions and an injection scheme different from the one used for validation of the model, as shown in Table 1. Only the simulated permeability deviated from the measured values for the direct implementation of the experimental setting in the existing model as it is described in [1]. By fitting the critical porosity in the Kozeny-Carman relation, the simulated permeability matched the measured for the last 400 hours of the experiment. For the first half of the experiment, there are processes occurring that cannot be described by the model's current implementation of the Kozeny-Carman relation.

We have a hypothesis which allows explaining the dramatic reduction of permeability during the first 100 hours of the experiment. Contrary to the implemented Kozeny-Carman relation, in reality relatively small volumes of biofilm and calcite precipitates might drastically reduce the permeability due to inhomogeneous distribution in the pore space. This inhomogeneity would change the shape of the pores or eventually clog pore throats shutting off possible flow paths. On the macro scale, this explanation is supported by a measured change in the pore-size distribution, which shows selective plugging of specific pore sizes [3].

4. Outlook

To show that MICP is a feasible as sealing technology for liquid storage reservoirs in the subsurface, further experiments need to be conducted. These experiments will include larger, more complex settings such as heterogeneous porous media, two-phase flow and such that cannot be simplified as one dimensional as the experiment in this work or in [1]. For the successful design of such experiments, modeling is an essential tool to determine in advance which setting is worth investigation. However, the high computational effort of the current model has to be reduced before complex simulations on a high-resolution grid can be simulated within rational time scales.

To get a better understanding of the permeability reduction due to MICP and test our hypothesis, we will perform additional micro model experiments with defined and known pore-size distributions. In those micro models the permeability and porosity can be measured continuously and non-destructively during MICP. With these porosity and permeability data sets, it will be possible to determine which

process leads to the initial decrease in permeability at the beginning of MICP. Once those processes are identified, the parameters of the appropriate constitutive relationship can be fitted by inverse modeling.

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