

MODELLING THE TRANSPORT OF PARTICULATE SUSPENSIONS AND FORMATION DAMAGE DURING THE DEEP INJECTION OF CARBON DIOXIDE

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INTRODUCTION

Numerical models which can predict well injectivity decline are useful in the operations of planning, design, and maintenance related to carbon dioxide injection.

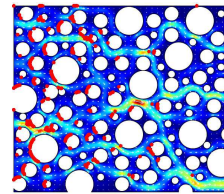
Fluid dynamics of solid particulate suspensions in permeable media is one of the major factors recognized to impact deep wells injectivity. The invading liquid-like supercritical CO₂ phase can contain significant concentrations of fines generated in-situ during well completion operations or desiccation phenomena. Suspended solids can plug the pores leading to significant formation damage and permeability reduction in the vicinity of the injection well.

This phenomena is less studied in the carbon dioxide storage field which is still in its infancy. Experience and practical knowledge from other fields (geothermal reservoir engineering, deep-well injection of hazardous liquid wastes) need to be updated to the specifics of deep CO₂ disposal.

OBJECTIVES

- Develop a theoretical framework and conceptual model to predict CO₂ injectivity decline at the core and field scales.
 - Provide a practical simulation tool for design and interpretation of laboratory experiments.
 - Guide a parametric sensitivity analysis study to highlight injectivity dependence on the CO₂ fluid characteristics, thermo-physical properties of the fines-CO₂ mixture, initial permeability of the host rocks, initial well damage, and the flow rate and/or the bottom-hole injection pressure.
- The real challenge of this project is to define where the most important changes will occur within the reservoir and how the CO₂ injectivity will evolve in time.**

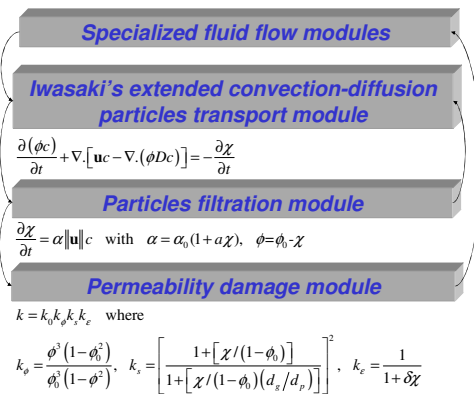
PORE-SCALE DYNAMICS



- This figure illustrates the complexity of particle flow dynamics, as calculated by a Stokesian approach at the pore scale, where three grain size distributions are considered.
- The highest velocity norms are plotted in red and lowest ones in blue.

Injected particles (small red circles) are tracked along the flow lines until they get stuck on pores boundaries. As injection proceeds, accumulation of small mass particles plug some of the pores along the mainstream channels. This process will in turn change the flow field and redistribute particle packets elsewhere.

MODEL PHYSICS & STRUCTURE



NUMERICAL METHODS

- The computational domain is meshed with quadratic Lagrange finite elements (FE).
- The non-linear coupled FE equations set is solved fully implicitly with an affine invariant form of the damped Newton method. Whereas the sub-linear iterative process is solved with the GMRES Krylov based technique.
- For high flow rates the particles transport equation becomes strongly hyperbolic. A streamline upwind Petrov-Galerkin (SUPG) shock capturing technique can simultaneously damp out oscillations and prevent overshoots and undershoots close to discontinuities.

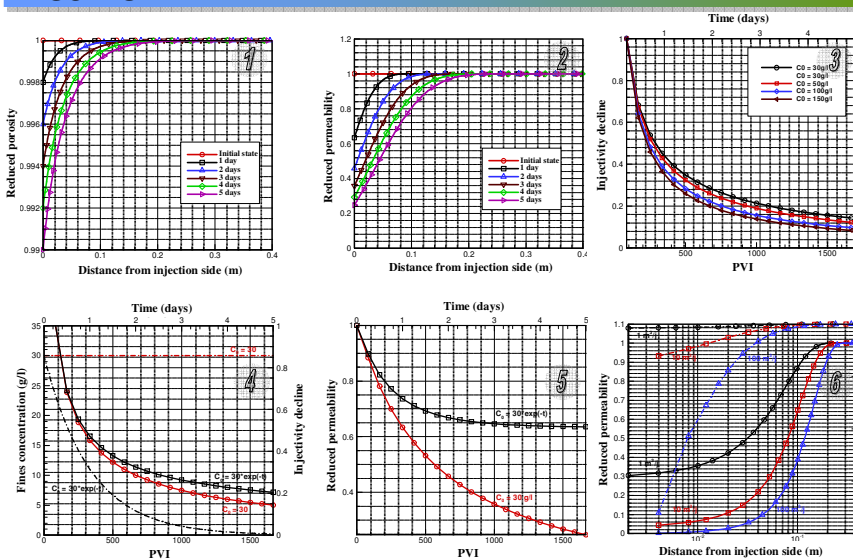
PROBLEM DESCRIPTION

We simulate the experimental conditions of a laboratory column having a length of 40cm, and a 5cm diameter. Supercritical CO₂ density and viscosity were calculated at initial conditions (T=72°C, P=153bars, S=30g/l) typical at the DOGGER geothermal reservoir of Paris basin (France). Other data are given in the following table:

Parameter	Value
k_0 : initial permeability	10 ⁻¹² m ²
ϕ_0 : initial porosity	0.15
μ_c : CO ₂ (sc) viscosity	5x10 ⁻⁴ Pa.s
ρ_c : CO ₂ (sc) density	501.5 Kg/m ³
e_0 : filtration coefficient	0.01 m ⁻¹
δ : damage factor	2
d_p : mean particles diameter	3 μm
d_p : mean pore diameter	500 μm
Q: injection flow rate	1 m ³ /d
C ₀ : particles concentration in injected CO ₂ (sc)	30 g/l
D: diffusion coefficient of particles	10 ⁻⁹ m ² /s

Model input data for the base case problem.

RESULTS

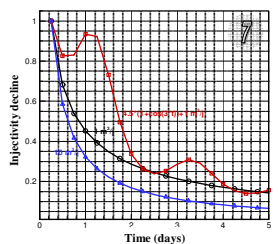


For the base case experiment, only 1% of porosity reduction (Fig. 1) leads to more than 75% permeability loss (Fig. 2) after 5 days of continuous injection. Figure 3 presents the behaviour of well injectivity decline as a function of pore volumes injected (PVI) for increasing values of upstream injected fines concentrations. Figures 4 and 5 compare the effect of decaying injected fines with the base case experiment for the injectivity decline and the reduced permeability ratio, respectively. Finally, Figure 6 depicts the reduced permeability (solid lines), and the reduced porosity (dashed lines) for increasing values of injection flow rates (1, 10, and 100 m³/d).

RE-ENGINEERING CO₂ INJECTION

In this numerical experiment the injection flow rate follows a curve cycling between 1 and 10 m³/d.

A non obvious result is that the injectivity decline at flow rates much higher than 1m³/d (red curve) remains always higher than the injectivity decline with this constant base flow rate (black curve)!



This is just another demonstration example that carbon dioxide injection could be re-engineered in many ways. Numerical models have to play a major role in this upcoming challenges.

CONCLUSIONS & OUTLOOK

- High fines concentrations, a relatively low flow rate of injection, and low initial permeability, favour rapid injectivity loss as injection proceeds.
- The lab-scale CO₂ injectivity decline model presented in this work is being extended to include other physical-chemistry phenomena (grain size exclusion effect, particle detachment kinetics, Van-der-Waals and double layer electrostatic models, and chemical precipitation/dissolution reactions).
- Modelling particulate suspensions with high flow rates required for site-scale CO₂ disposal is challenging, because such phenomena is required only nearby the injector, but still depends on the far field pressure conditions. Coupling different physics in these domains is targeted.

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