Stochastic Particle Method (SPM): A Lagrangian Modeling Framework to Study CO_2 Sequestration in Subsurface Formations

ABSTRACT

Computational Method

- A Lagrangian approach to solve phase transport in porous media
- A particle represents a phase (physical particles)
- Particles can carry various properties such as composition
- It is different from deterministic particle methods such as SPH
- Saturation is a local statistical property
- Physical particle evolution is approximated by a stochastic process
- Motivation: natural modeling framework for complex processes

Applications

Numerical simulation framework for CO_2 sequestration in subsurface formations. The problem involves complex non-equilibrium processes:

- Dissolution of CO_2 in brine
- Chemical reactions
- Trapping of CO_2

SPM is a rigorous frame-work that can deal with non-equilibrium phenomena based on

- Statistical information from pore scale physics
- Joint PDFs, correlation time and length scales

MATHEMATICAL MODEL AND SOLUTION ALGORITHM

Validation for 2-Phase Darcy Flow: An Example of a Stochastic Model

Phase indicator (particle property) $s^* = \begin{cases} 0 & \text{if particle is of phase } 0 \\ 1 & \text{if particle is of phase } 1 \end{cases}$ Saturation of phase 0: a statistical quantity $S = 1 - \langle s^* \rangle$

Phase transport equation $\frac{\partial S}{\partial t} + v_{tot} \cdot \nabla f(S) = \nabla C \nabla S + \nabla D \nabla S$ v_{tot} -total velocity

$C(S)$ -capillary dispersion coefficient $D(v_{tot})$ -pore scale dispersion coefficient

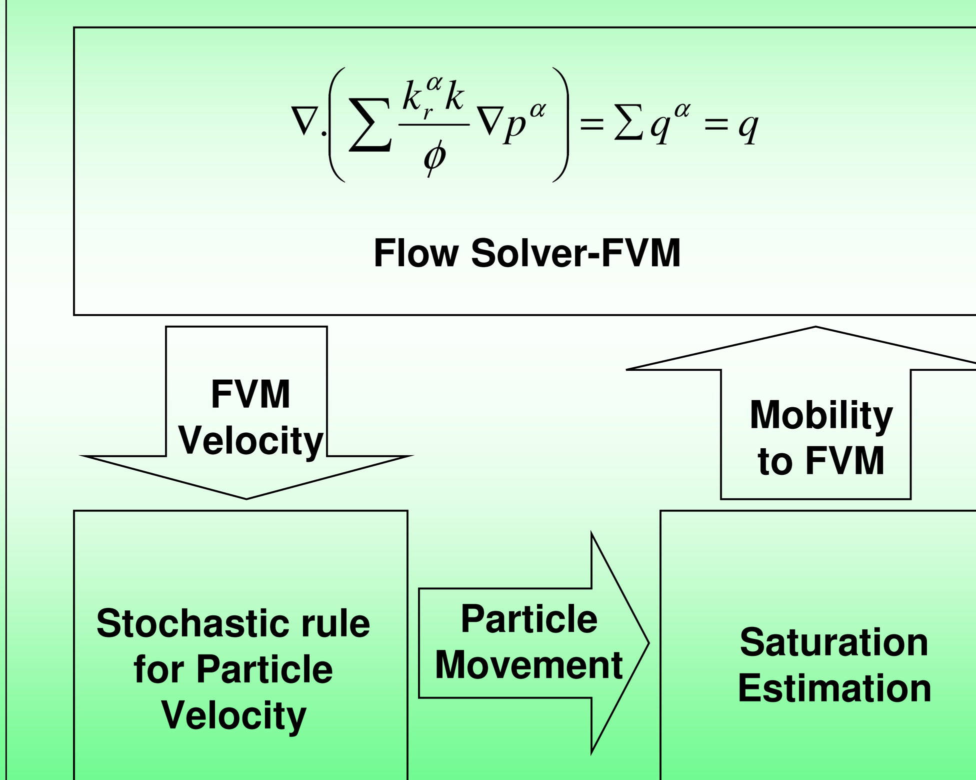
Consistent stochastic rule for particle displacement

$$dx^* = \begin{cases} v_{tot}\frac{f(S)}{S}dt + \frac{C(S)}{S}\nabla S dt + \sqrt{2D(v_{tot})dt}\,\xi + D'(v_{tot})\nabla S dt & s^* = 0 \\ v_{tot}\frac{f(1-S)}{1-S}dt - \frac{C(S)}{1-S}\nabla S dt + \sqrt{2D(v_{tot})dt}\,\xi + D'(v_{tot})\nabla S dt & s^* = 1 \end{cases}$$

ξ -random variable with normal distribution

NOTE: same concept can be generalized for more complex physics; e.g., non-equilibrium processes

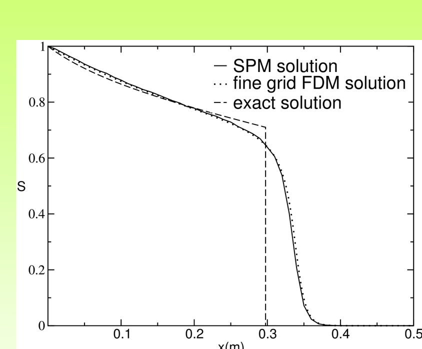
Algorithm



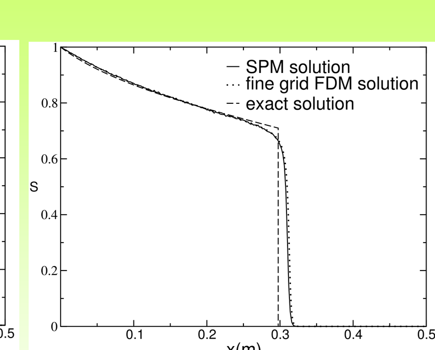
VALIDATION

1D Test Case: Buckely-Leverett Problem

Saturation of injected phase after t=0.25s for two grid spacings v_{tot}=1m/s, C=0.



D=0.01, dx=0.01

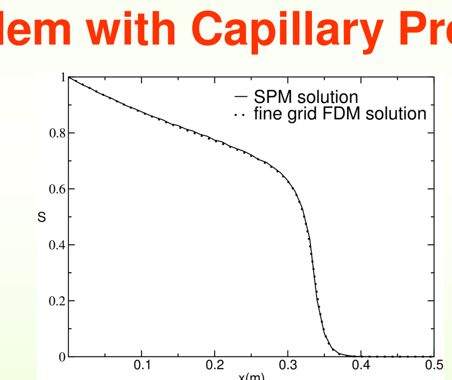


D=0.002, dx=0.002

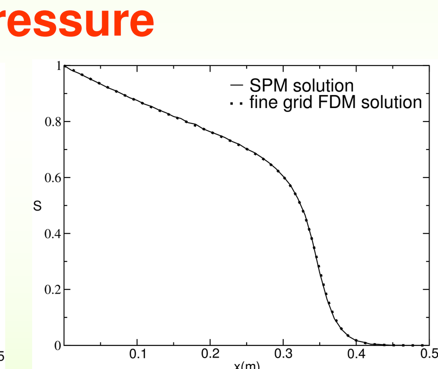
1D Test Case: Buckely-Leverett Problem with Capillary Pressure

Constant C

Saturation of injected phase after t=0.25s. D=0.001. dx=0.01.



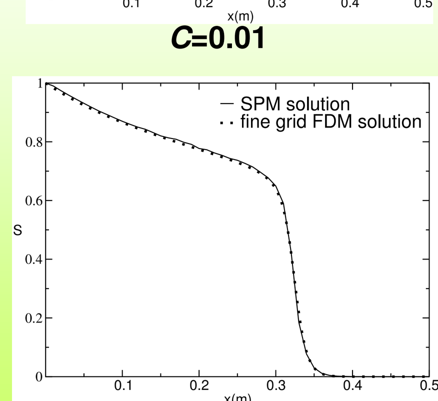
C=0.01



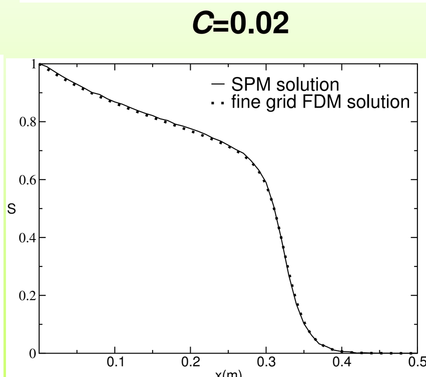
C=0.02

Non-constant C, $C(S) = \frac{C_0(1-S)^2}{S^2 + (1-S)^2}$

Saturation of injected phase after t=0.25s. D=0.001. dx=0.01.



C_0=0.01



C_0=0.02

2D Test Case: Quarter-Five Spot Configuration

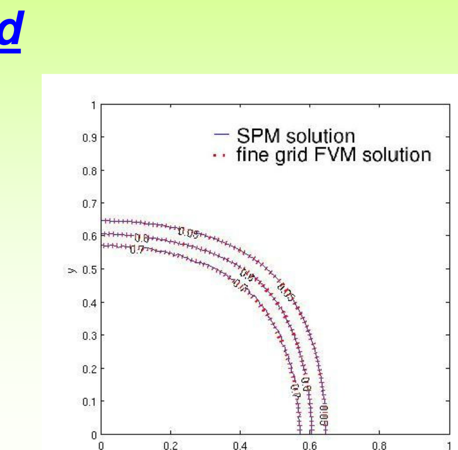
Homogeneous Permeability Field

Simulation results after 0.25 PVI

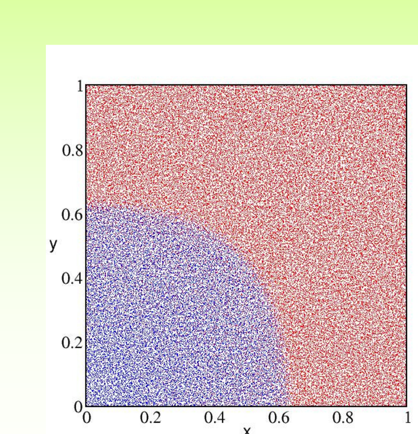
Grid =100*100

In the scatter plot, blue particles are injected in the domain initially filled with red particles.

D=0.01 v_{tot} ,C=0



Saturation contours of injected phase



Scatter plot

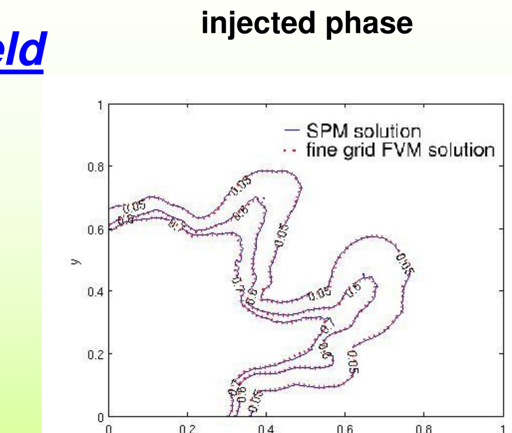
Heterogeneous Permeability Field

Simulation results after 0.25 PVI

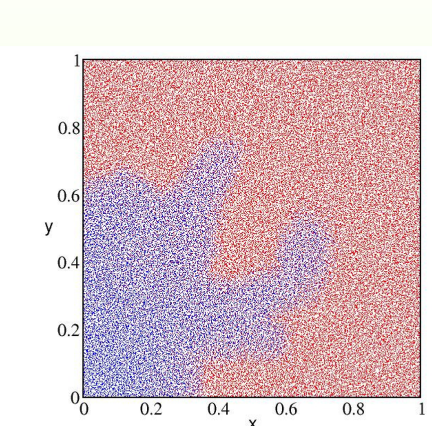
Grid =100*100

In the scatter plot, blue particles are injected in the domain initially filled with red particles.

D=0.01 v_{tot} ,C=0



Saturation contours of injected phase



Scatter plot

OUTLOOK

- Transporting particles with more complex rules that are consistent with the pore scale dynamics. The rules for particle movement can be provided by pore network simulations
- Using SPM for the problem of CO_2 sequestration in subsurface formations: A numerical tool to study complex processes; dissolution of CO_2 in brine, reaction, trapping etc.
- Extract effective models for finite volume simulator

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

M. Tyagi, P. Jenny, I. Lunati and H. A. Tchelepi

Institute of Fluid Dynamics