Center for Phase Equilibria and Separation Processes

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Coupling Miscible Flow and Geochemistry for Carbon Dioxide Flooding into North Sea Chalk Reservoir

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Introduction CO_2 Flooding

- **CO_2 flooding of oil reservoir can potentially enhance oil recovery significantly. At the same time, injected CO_2 could be captured during this process.**

- **CO_2 flooding is characterized by complex phase behavior and geochemical reactions**

- **The mineral dissolution and precipitation chages the porosity and permeability.**

- **The reservoir simulators for CO_2 flooding and the geothermal simulators for CO_2 sequestration usually have different focuses**

Introduction Why COMSOL

- **COMSOL Multiphysics offers multi-functionality (Including both transport and geochemical reaction)**

- **The interface is friendly to user. The model can be easily modified to solve other problems.**

- **Different application modes are suitable for complex problems.**

Aim of the Study

- **Test the performance of COMSOL Multiphysics in simulating enhanced oil recovery (EOR) process by comparing results with analytical solution**

- **Investigate how to simulate CO_2 flooding including both three-phase flow and geochemical reaction by using COMSOL Multiphysics**

Numerical Tests   Gas Flooding

- In gas flooding, component separation happens while flowing. The transfer of components between flowing phases strongly influences displacement performance.

- Main Equations in 1-D for two component displacement

  Molar conservation

  $$\phi\frac{\partial}{\partial t}(S_g\rho_g x_{g,g}+S_o\rho_o x_{g,o})+\frac{\partial}{\partial x}(x_{g,g}\rho_g u_g+x_{g,o}\rho_o u_o)=0$$

  $$S_g + S_o = 1$$

  Darcy's law

  $$u_j = -\frac{kk_{rj}}{\mu_j}\frac{\partial P}{\partial x}, \; j = o, g$$

  $$u_j = f_j u = f_j(u_o + u_g)$$

Numerical Tests   Gas Flooding

- **By assuming that molar density of gas component is constant in two phases and introducing dimensionless parameters,**

$$\rho_{cg} c_{g,j} = \rho_j x_{g,j}$$

$$\tau = \frac{u_{inj} t}{\phi L}, \zeta = \frac{x}{L}, u_D = \frac{u}{u_{inj}}$$

Molar conservation becomes

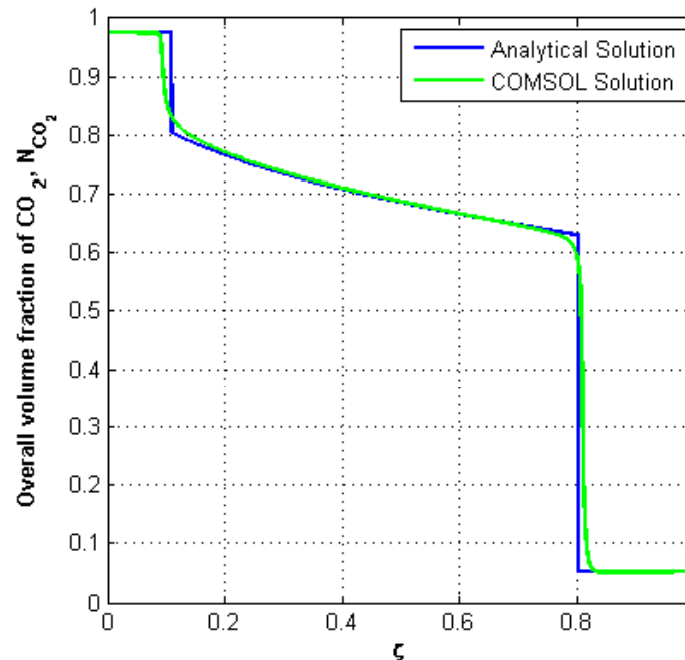$$\frac{\partial N_g}{\partial \tau} + \frac{\partial F_g}{\partial \zeta} = 0$$

$$N_g = S_g c_{g,g} + S_o c_{g,o} \qquad F_g = f_g c_{g,g} + f_o c_{g,o}$$

To compare with the analytical solution, constant pressure and velocity is assumed

$$c_{g,g} = 0.95 \qquad\qquad c_{g,o} = 0.2$$

Numerical Tests   Gas Flooding

- **By applying** $N_g(\tau,0)= 0.975$ $N_g(0,\zeta)= 0.2$ **and artificial diffusion**

Comparison of analytical solution and COMSOL solution in gas flooding $\tau = 0.6$

Numerical Tests Polymer Flooding

- **In polymer flooding, polymer is added to water to increase its viscosity so as to mobilize more oil. However, the polymer can be adsorbed on rock surface, and the decreasing concentration of polymer in water will affect the flow of water phase**

- **Main Equations in 1-D**

  Transport equations

  $$\phi \frac{\partial S_w}{\partial t} + u \frac{\partial f_w}{\partial x} = 0$$

  $$\phi \frac{\partial}{\partial t}(S_w c + c_s) + u \frac{\partial}{\partial x}(f_w c) = 0$$
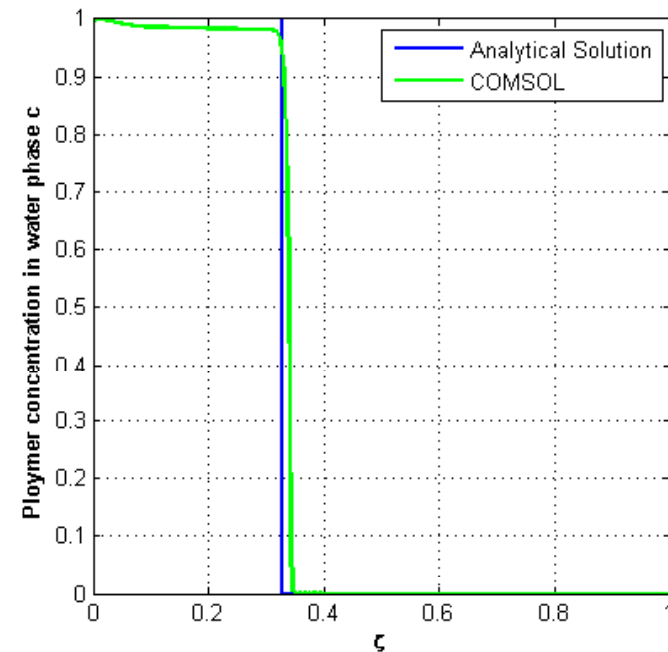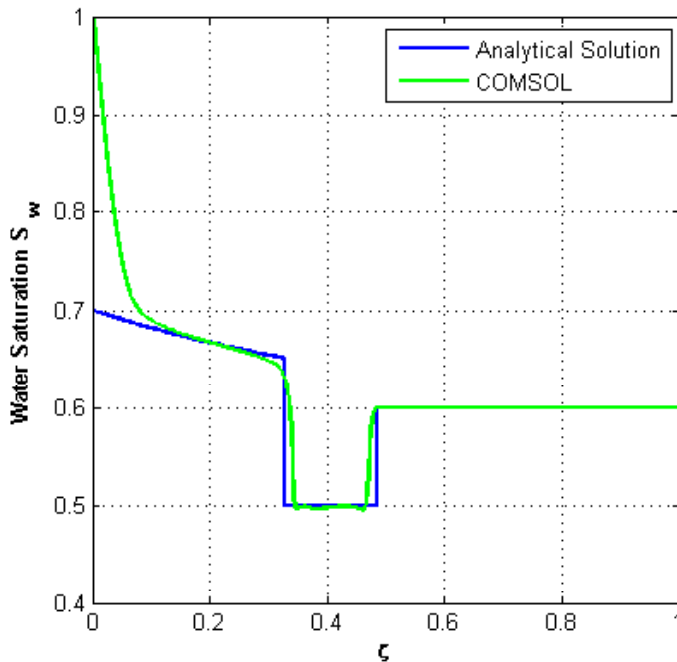
  Fractional flow equations

  $$f_w = \frac{k_{rw}}{k_{rw} + k_{ro}\mu_w/\mu_o} \qquad \begin{aligned} k_{ro} &= (1 - \psi)^2 (1 + 2\psi) \\ k_{rw} &= 0.25\psi^2 \end{aligned} \qquad \psi = \frac{S_w - S_{wr}}{1 - S_{or} - S_{wr}}$$

  Water viscosity $\quad \mu_w = \mu_w^0 (1 + \beta c) \quad$ **Langmuir Adsorption** $\quad c_s = \frac{NKc}{1 + Kc}$

Numerical Tests   Polymer Flooding

- **By applying** $\tau = 0: \quad S_w = 0.6, \quad c = 0 \text{ g/liter}$
  $\zeta = 0: \quad S_w = 1.0, \quad c = 1.0 \text{ g/liter}$ **and artificial diffusion**

Comparison of analytical solution and COMSOL solution in Polymer flooding $\tau = 0.4$

Modeling of CO_2 flooding   Description

- When CO_2 is injected into oil reservoir, three phases are present: oil, CO_2 and water. The water phase contains ions and dissolved CO_2. The mineral reaction is,

$$CO_2(aq) + H_2O + CaCO_3(mineral) \Longleftrightarrow Ca^{2+} + 2HCO_3^-$$

Assumptions:

1. This process is isothermal;
2. Only CO_2 is dissolved in water;
3. Chemical reaction has no influence on the molar density of water phase;
4. No capillary pressure is considered;
5. Molar density of single component in the different phases is same

Modeling of CO$_2$ flooding   Main equations

Oil component

$$\frac{\partial}{\partial t}(\phi S_o \rho_o) + \frac{\partial}{\partial x}(u_o \rho_o) = 0$$

CO$_2$ component

$$\frac{\partial}{\partial t}(\phi S_g \rho_g + \phi S_w \rho_w x_{CO_2,w}) +$$
$$\frac{\partial}{\partial x}(u_w \rho_w x_{CO_2,w} + u_g \rho_g) = -R_m$$

Water component

$$\frac{\partial}{\partial t}(\phi S_w \rho_w x_{H_2O,w}) +$$
$$\frac{\partial}{\partial x}(u_w \rho_w x_{H_2O,w}) = -R_m$$

Calcium component

$$\frac{\partial}{\partial t}(\phi S_w \rho_w x_{Ca^{2+},w}) +$$
$$\frac{\partial}{\partial x}(u_w \rho_w x_{Ca^{2+},w}) = R_m$$

Neutrality condition

$$2x_{Ca^{2+},w} = x_{HCO_3^-,w}$$

Molar fraction

$$x_{CO_2,w} + x_{Ca^{2+},w} + x_{HCO_3^-,w} + x_{H_2O,w} = 1$$

Saturation

$$S_w + S_g + S_o = 1$$

Porosity

$$\frac{\partial(1-\phi)\rho_m}{\partial t} = -R_m$$

$$R_m = S_w k_m A_m (1 - \frac{a_{CO_2,b}^{-1} a_{Ca^{2+},b} a_{HCO_3^-,b}^2}{K_{sp}})$$

Since velocity can be expressed by Darcy's law as function of pressure, eight unknowns and eight equations

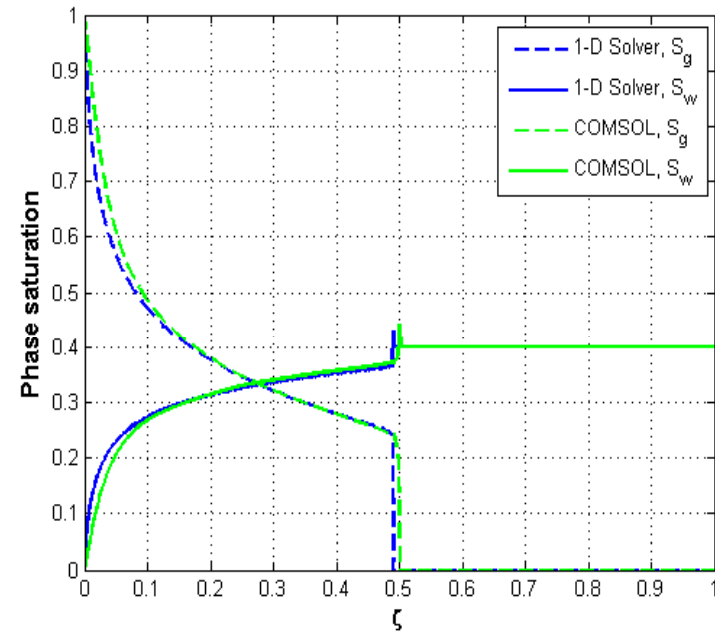# Modeling of CO$_2$ flooding Solution Methods

- **Different approaches: simultaneous solution method, sequential iterative approach (SIA), and sequential non iterative approach (SNIA)**
- **SNIA approach from TOUGHREACT**
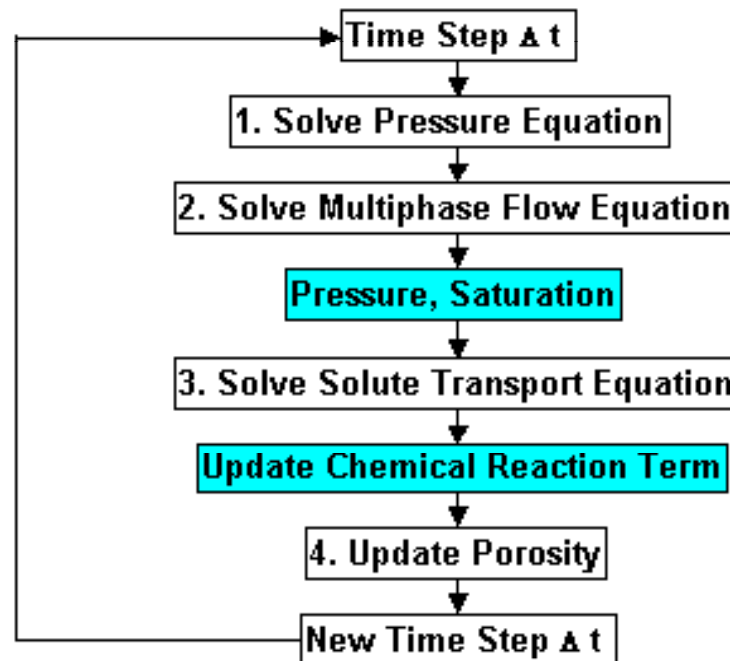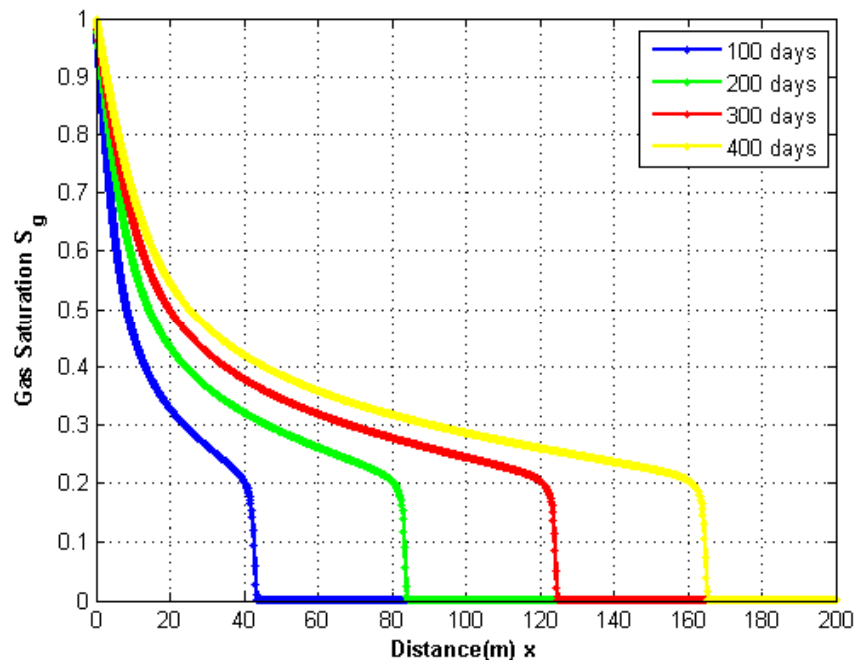
Modeling of CO$_2$ flooding **Using COMSOL**

- **The equations for each stages are available in the paper. All equations are implemented into COMSOL by using the PDE Modes, the coefficient form and solved by the segeregated solver.**

- **A finite difference code for 3-phase immiscible or mscible flooding without chemical reaction is used to validate the model**
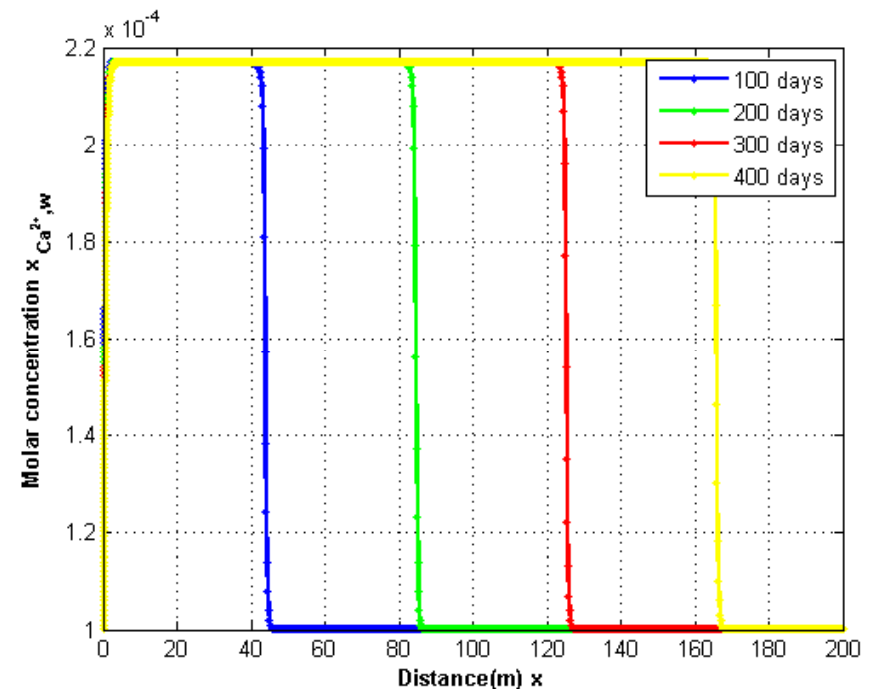

Three-phase flooding without reaction $\tau = 0.2$

Modeling of CO$_2$ flooding Results

- **Simulation for reservoir scale flooding**
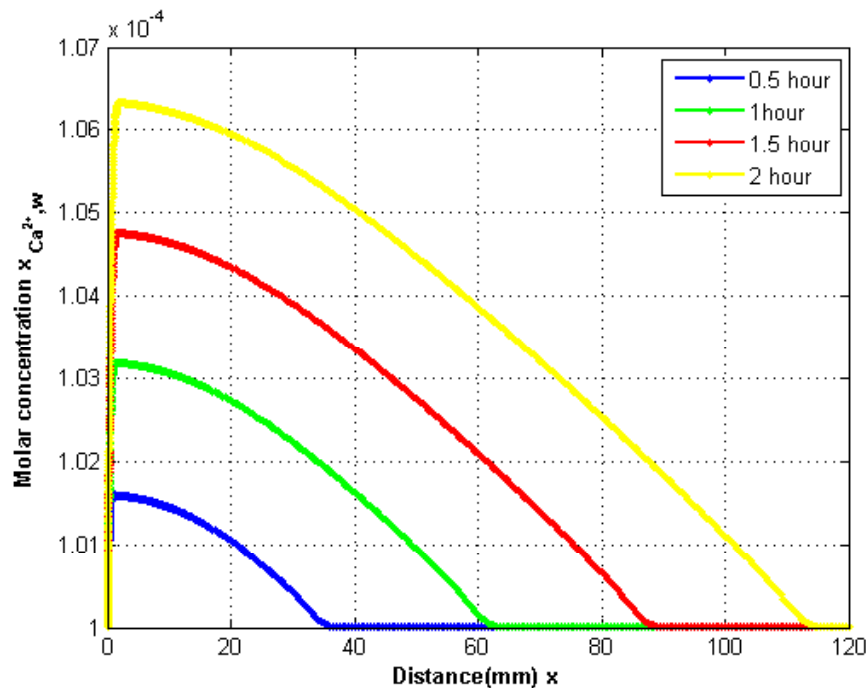- **Dissolution of calcite can be treated as equilibrium reactions**
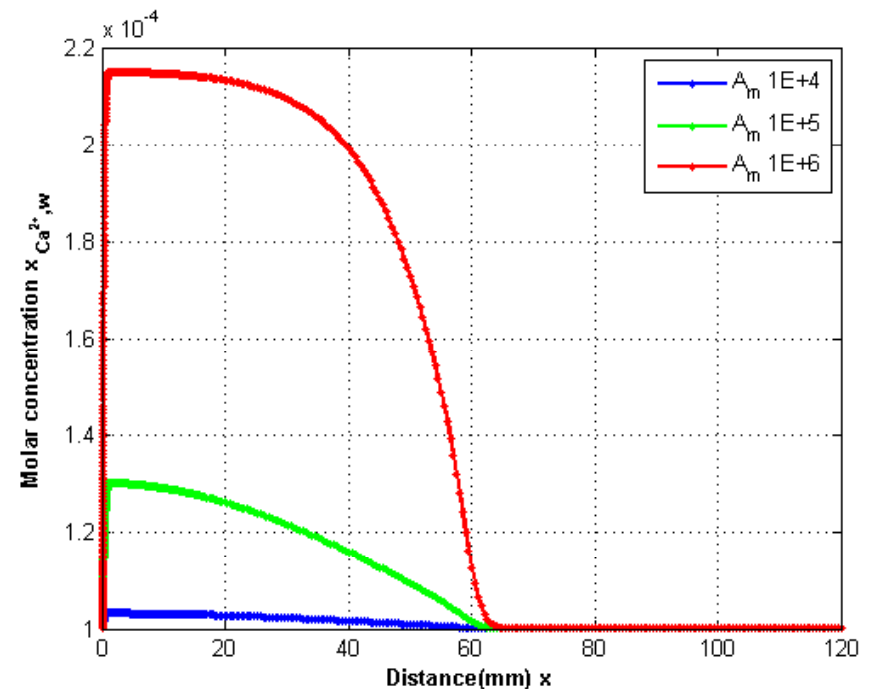

S_g **from 100 to 400 days**

$x_{Ca^{2+},w}$ **from 100 to 400 days**

Modeling of CO$_2$ flooding Results

- **Simulation for lab scale flooding**
- **The effects of reactive surface area** A_m **on** $x_{Ca^{2+},w}$

$x_{Ca^{2+},w}$ **from 0.5 to 2 hours**

Effect of A_m **on** $x_{Ca^{2+},w}$ **after 1 hour**

Conclusions & Future Plan

- Using SNIA, we have developed a model in COMSOL Multiphysics for miscible CO_2 flooding with dissolution reaction in the aqueous phase.

- COMSOL Multiphysics is able to provide reasonable results for this type of reactive transport problem by using the segregated solver.

- The model will be useful to study CO_2 flooding in chalk reservoir and CO_2 sequestration process. The phase equilibrium between CO_2 and oil can be added although it is not included by far.

- The geochemical model should be extended to include more reactions in order to simulate real CO_2 sequestration scenarios. Other solution method can also be tried in the future.

Acknowledgement

Thanks!