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Fluid Dynamics Model for Pore-Scale Wetting Phenomena

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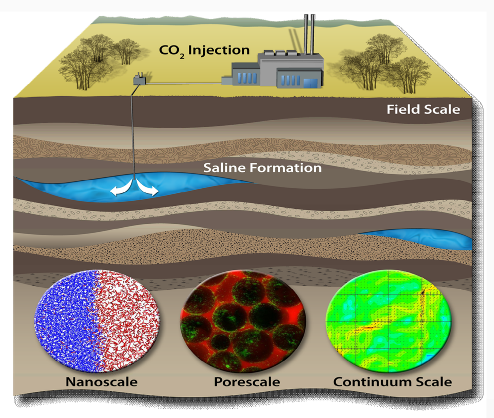
Introduction

Motivation

Moving Contact Line (MCL) problems are important to model the migration of wetting/non-wetting fluids through reservoir rocks.

Scientific Objective:
Understand and control *emergent behavior* arising from *coupled physics* in *heterogeneous geomaterials* associated with injection for CCS, especially at *intermediate length scales* (cm to m) where geologic variability plays a decisive role. Processes and strategies are based on mesoscale science from which non-equilibrium and emergent behaviors arise over a large range of time and length scales.

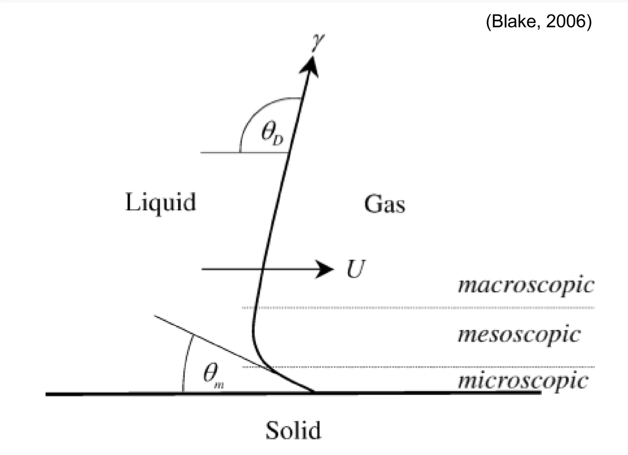


Contact Line Modeling

Moving Contact Lines

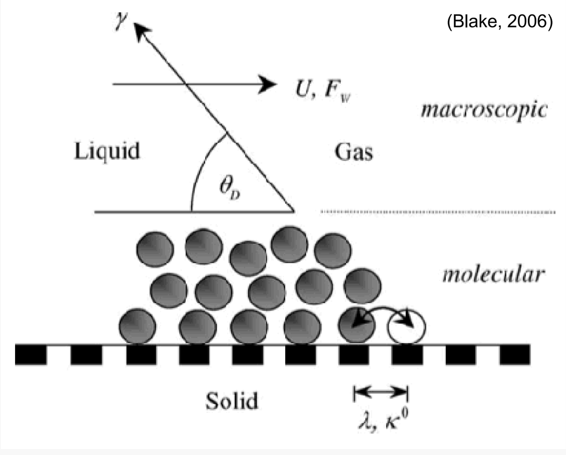
- Two immiscible fluids in contact with a solid surface in equilibrium form a static contact angle
- When this equilibrium is disturbed, the contact angle becomes dynamic and the contact line moves
- Must model relationship between contact angle and contact line velocity as the physics are poorly understood

Hydrodynamic Models



- Three length scales near the contact line: macroscopic, mesoscopic, and microscopic
- Changes in experimentally observed macroscopic dynamic contact angle is attributed to viscous bending of the interface in the mesoscopic region
- Microscopic angle is usually assumed as the static angle and velocity independent
- Voinov, 1976; Cox, 1989; Huh & Scriven, 1971.

Molecular Models



- Two length scales: macroscopic and molecular
- Contact line motion is determined by the statistical dynamics of the molecules at the molecular scale
- Driving force of contact line is proportional to the disturbed and equilibrium contact angles.
- Blake, 1969

Computational Model

Navier-Stokes Equation

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho(\mathbf{x}) \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = -\nabla p + \nabla \cdot \left(\mu(\mathbf{x}) \left(\nabla \mathbf{u} + \nabla \mathbf{u}^{\mathrm{T}} \right) \right)$$

Level Set Equation

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = 0$$

Interface Boundary Conditions

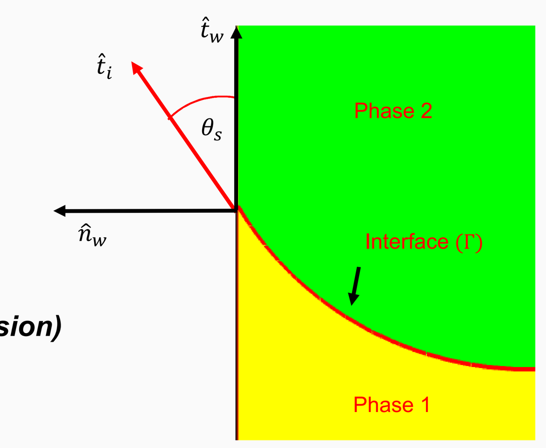
$$[\mathbf{u}]_{\Delta} = 0, \qquad \mathbf{x} \in \Gamma \qquad \textit{(continuity)}$$

$$\left[-p\mathbf{I} + \mu(\mathbf{x}) \left(\nabla \mathbf{u} + \nabla \mathbf{u}^{\mathrm{T}} \right) \right]_{\Delta} \cdot \hat{\mathbf{n}} = -\gamma \kappa \hat{\mathbf{n}}, \qquad \mathbf{x} \in \Gamma \qquad \textit{(surface tension)}$$

Wetting Line Model

$$\int_{\zeta^{n+1}} \sigma \left(\cos(\theta_s) \mathbf{t}_w + \sin(\theta_s) \mathbf{n}_w \right) \cdot \mathbf{w}_i d\Gamma$$

$$\int_{\Gamma_w^{n+1}} \frac{\mu}{\beta^*} \left(\mathbf{u}_w - \mathbf{u}^{n+1} \right) \cdot \mathbf{w}_i d\Gamma$$



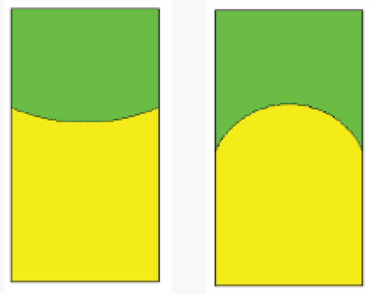
Finite Element Method (FEM) is used to model the interface dynamics

- Conformal decomposition FEM (CDFEM) uses the level-set method to model two-phase interface
- CDFEM allows for a sharp-interface between the immiscible phases, providing exact location of the contact line
- Contact line model determined completely by equilibrium properties (must fit a slip coefficient)

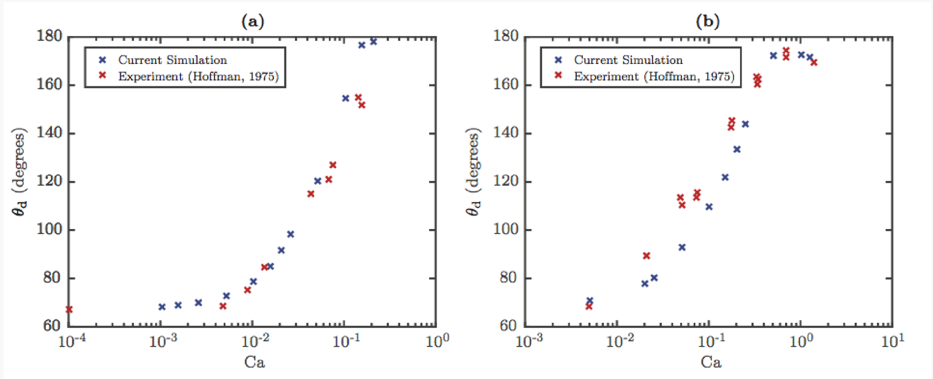
Verification & Validation

Capillary Injection

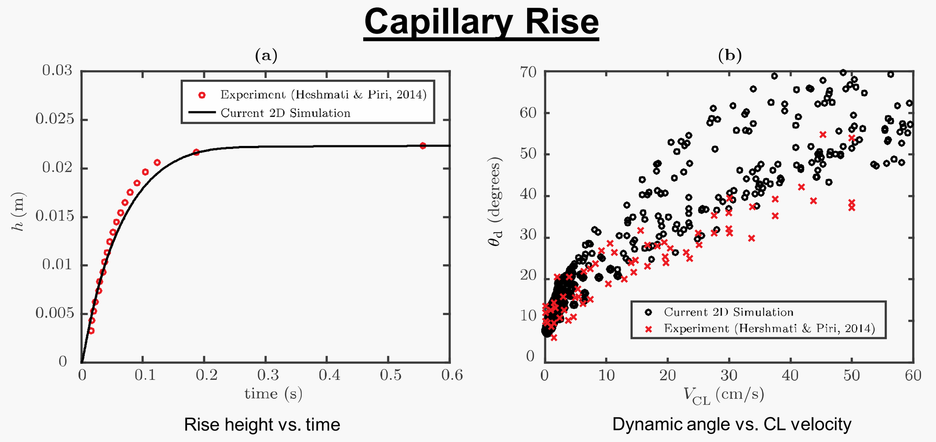
Ca = 5.2e-3 (low) | Ca = 4.4e-2 (high)



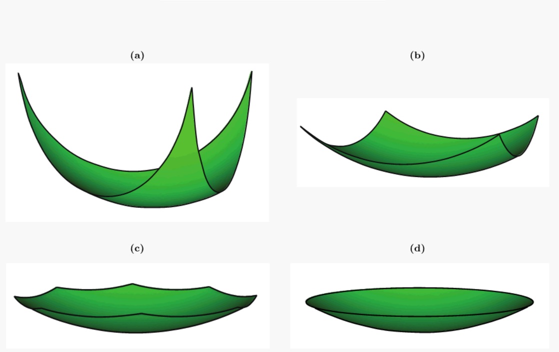
Sancitizer 405 ($\theta_s = 67°$) | Amdex 760 ($\theta_s = 69°$)



Capillary Rise

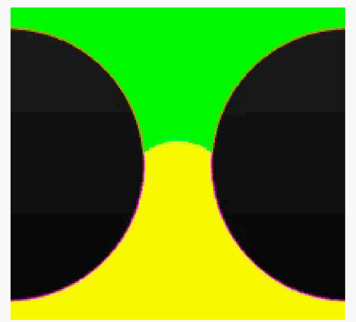


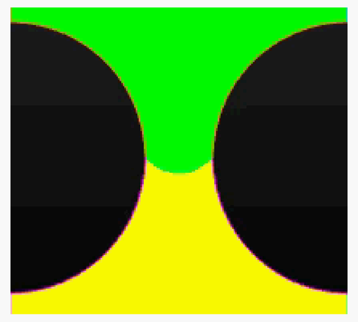
3D Interfaces



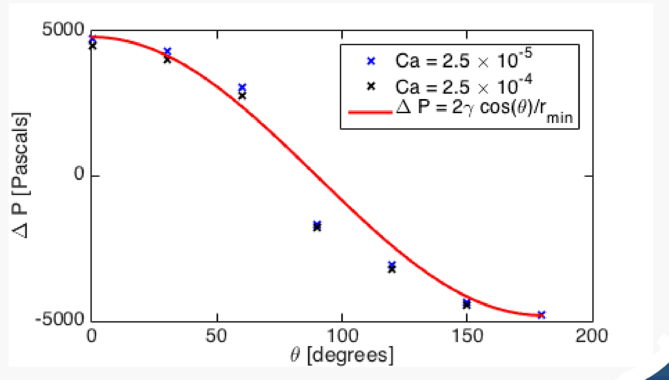
Flow Through a Pore Throat

$\theta = 150°$ (non-wetting) | $\theta = 30°$ (wetting)





Capillary Pressure Curve

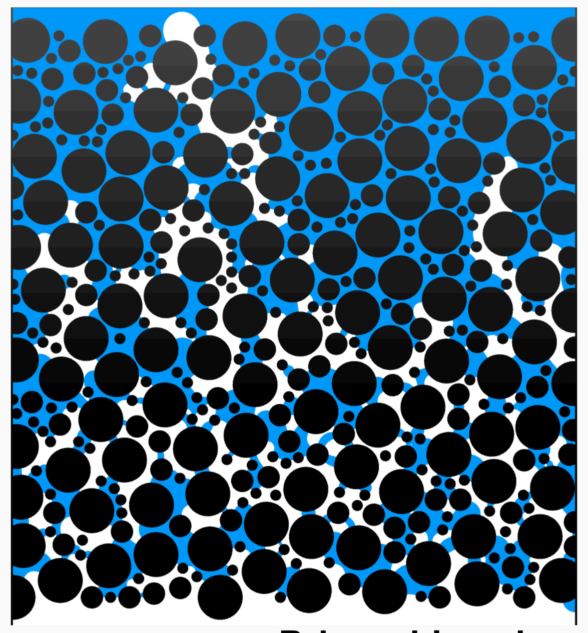


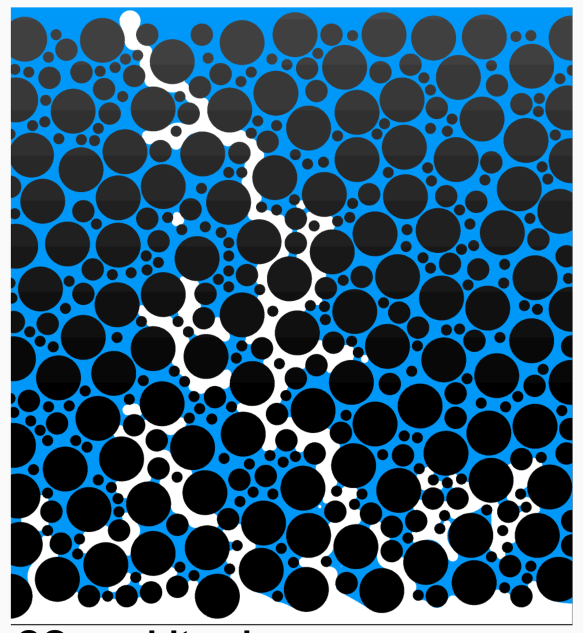
Model Applications for GCS

Drainage in Disordered Media

Capillary Number, Ca $= 1 \times 10^{-5}$

Weakly Wetting ($\theta_S = 80°$) | **Strongly Wetting ($\theta_S = 0°$)**

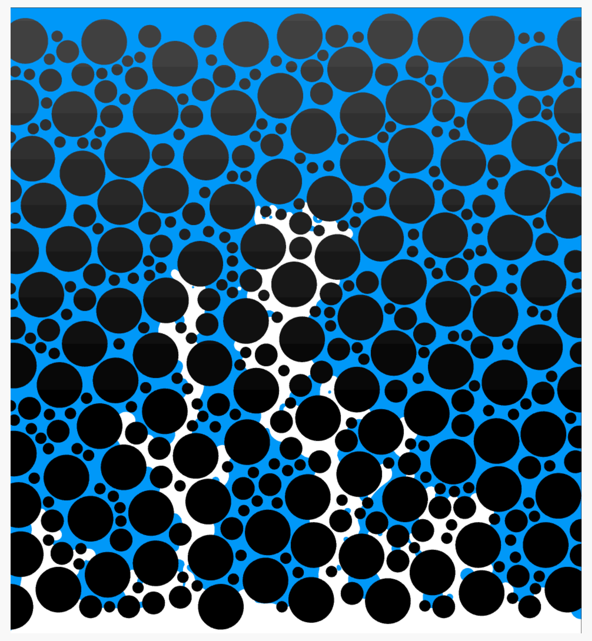


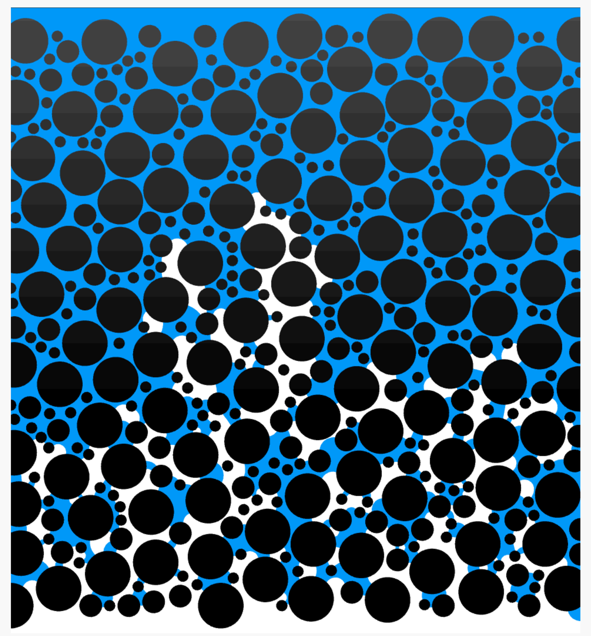


Brine – blue phase | **CO_2 – white phase**

Wetting Angle $\theta = 80°$ (Weakly Wetting)

Capillary Number, Ca $= 1 \times 10^{-4}$ | **Capillary Number, Ca $= 1 \times 10^{-5}$**





Brine drainage by CO_2 injection

- Wetting model captures viscous and capillary fingering configurations
- At fixed capillary number, increased brine wettability promotes fingering, lowers final saturation (lower sweep efficiency)
- For weakly wetting brine, increasing capillary number promotes viscous fingering

Concluding Remarks

- Improvement in MCL models can be used to accurately predict CO_2 migration in reservoir rocks
- CO_2 saturation profiles influenced on static wetting properties of the reservoir
- Mixed-wettability within a pore-network may impact sweep efficiency

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