SAND2016-4199C

Effect of surface roughness and wetting angle on permeability for geologic CO2 sequestration

Alec Kucala, Mario Martinez, Yifeng Wang and David Noble

Sandia National Laboratories

Albuquerque, New Mexico

May 12, 2016

Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

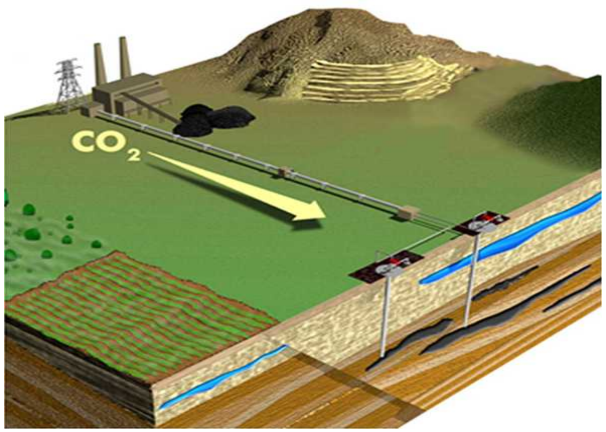
NNSA National Nuclear Security Administration

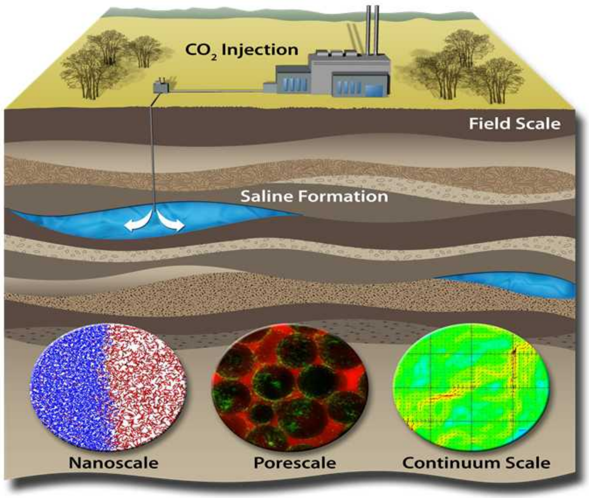
SAND2016???

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

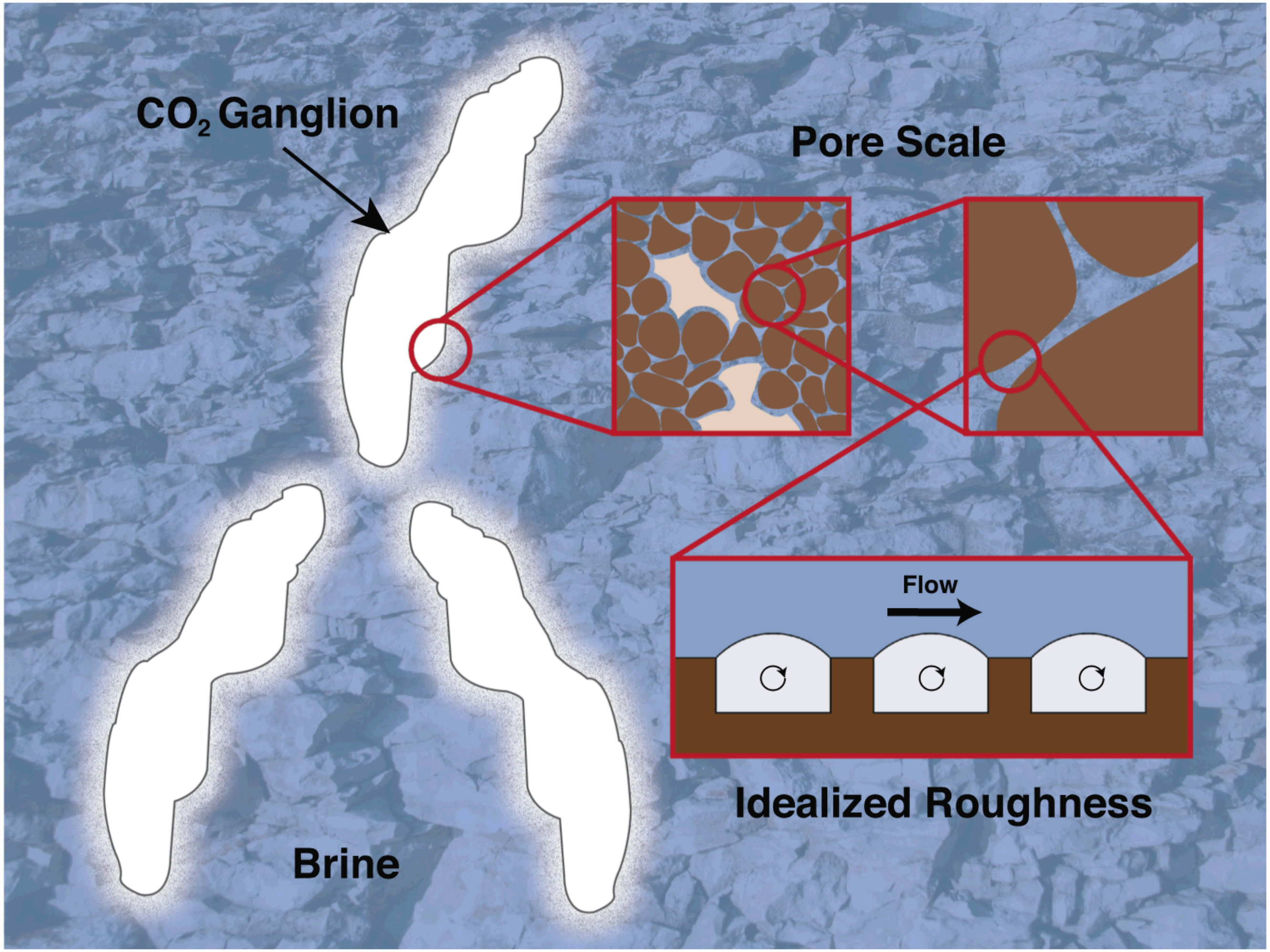
Introduction

- Injection of CO_2 into reservoir rocks is a promising strategy of reducing greenhouse gas emissions
- Modeling CO_2 migration and capillary trapping at the pore scale is important in predicting the permeability characteristics of reservoir rocks
- Heterogeneity at the pore scale can alter the permeability of the rock by introducing slip at the two-phase interface
- Use computational fluid dynamics to model the multi-phase flow through heterogeneous reservoir rock pores
- Extend models to account for wide range of working fluids (oil extraction, fracking, etc.)



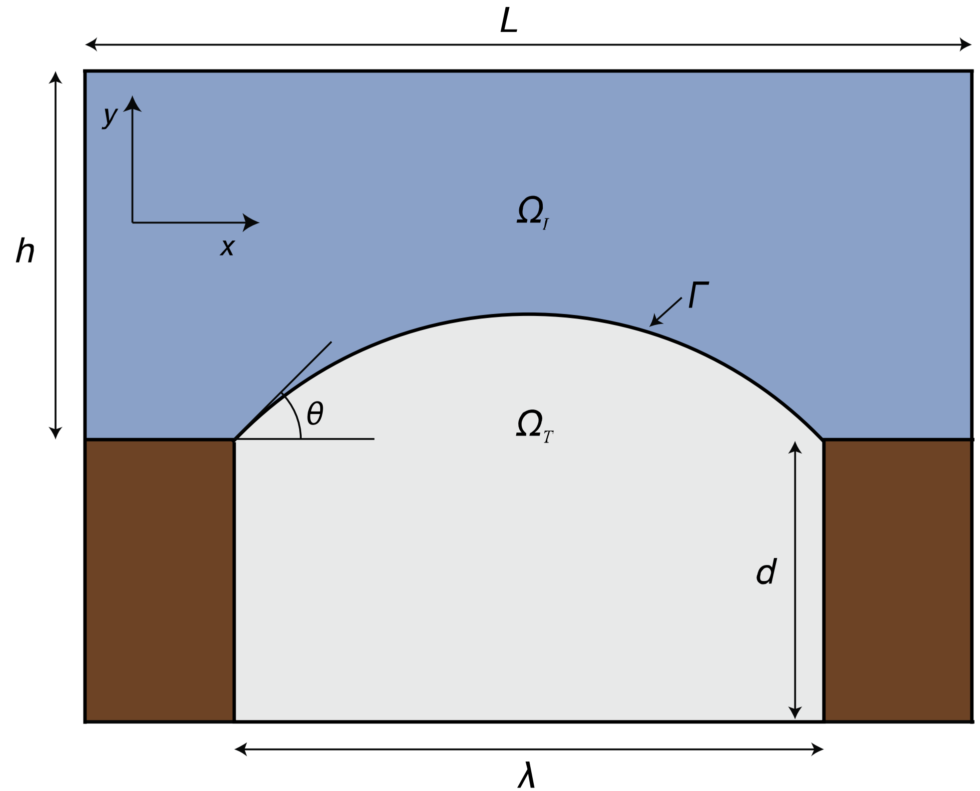


Conceptual Model

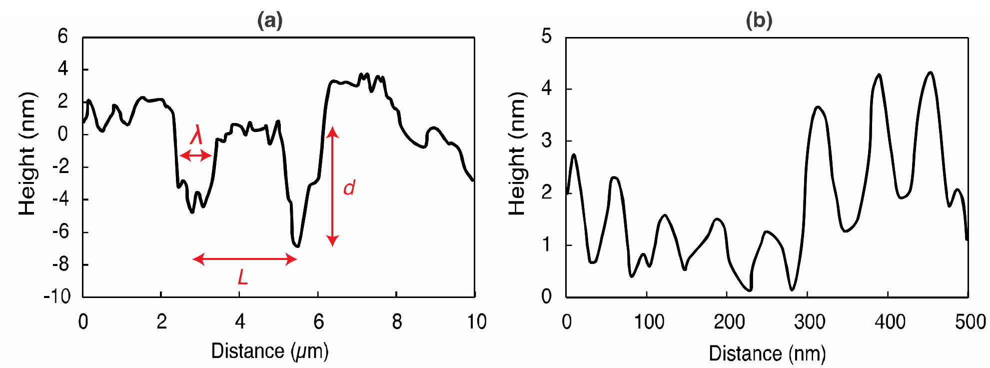


Flow Geometry and Case Descriptions

- Injection of fluid through a pressure gradient (periodic Poiseuille flow)
- Injected fluid slips at the two-phase interface, another fluid is trapped in a "pit" in the pore
- Investigate how viscosity and geometry affects the slip at the interface, measured as an effective permeability of the flow (K_E)
  - Change contact angle (θ)
  - Change spacing of pit $(\varphi = \lambda / L)$
  - Change roughness $(\beta = d / h)$
  - Change viscosity of fluids $(\mu_R = \mu_I / \mu_T)$



Flow geometry



Computational Model

- Utilize finite elements to discretize Navier-Stokes equation
- Arbitrary Lagrangian-Eulerian (ALE) method used to compute surface tension and enforce boundary conditions
- Solved using Sierra multi-physics suite at SNL[1]

Navier-Stokes Equation

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

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

Interface Boundary Conditions

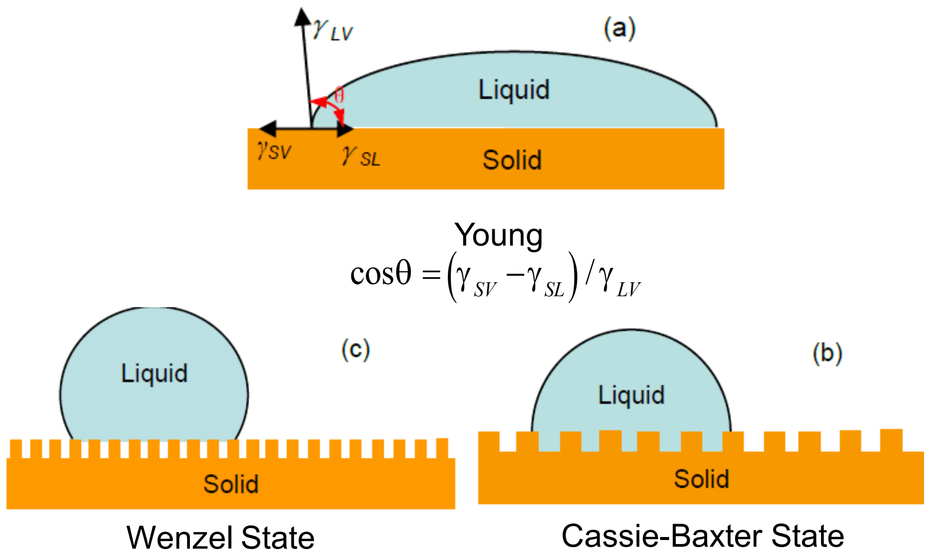
$$[\mathbf{u}]_{\Delta} = 0, \qquad \mathbf{x} \in \Gamma$$ ***(impermeability)***

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

1. P. Notz, S. R. Subia, M. M. Hopkins, H. K. Moffat, and D. R. Noble, Aria 1.5: User Manual, SAND2007-2734 (Sandia National Laboratories, Albuquerque, NM, 2007)

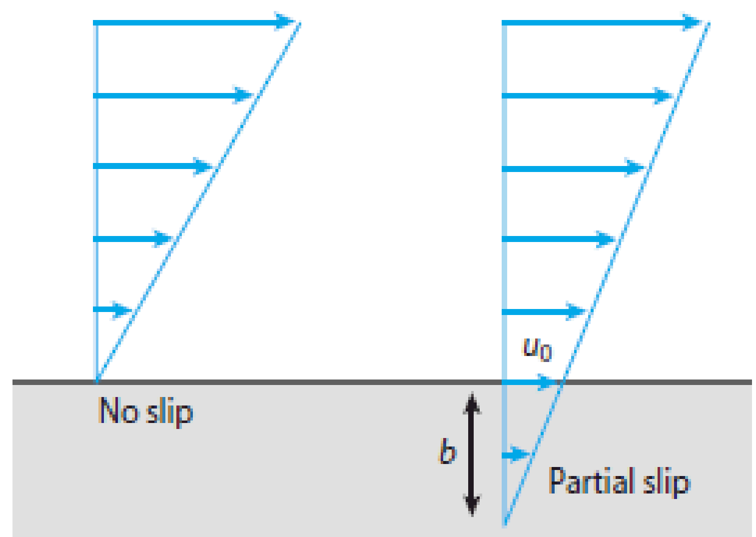
Fluid Slip and Permeability

- Surface roughness can change the contact angle between the liquid, gas and solid
  - Wenzel State[1]
  - Cassie-Baxter State[2]
  - Introduces slip flow at the liquid/gas interface in the vicinity of the surface roughness
- Slip length (velocity) can change depending on surface roughness and fluid configuration



$$u_w = b \left|\frac{\partial u}{\partial y}\right|_w$$ **Slip length**

$$K_S = \frac{h^2}{4}\left(\frac{1}{3} + \frac{b}{b+h}\right)$$ **Permeability of channel with slip**



1. Wenzel, R. N. (1936). Resistance of solid surfaces to wetting by water. *Industrial & Engineering Chemistry*, *28*(8), 988-994.
2. Cassie, A. B. D., & Baxter, S. (1944). Wettability of porous surfaces. *Transactions of the Faraday Society*, *40*, 546-551.

Effective Permeability and Slip

$$u_w = b \left|\frac{\partial u}{\partial y}\right|_w$$ **Slip length**

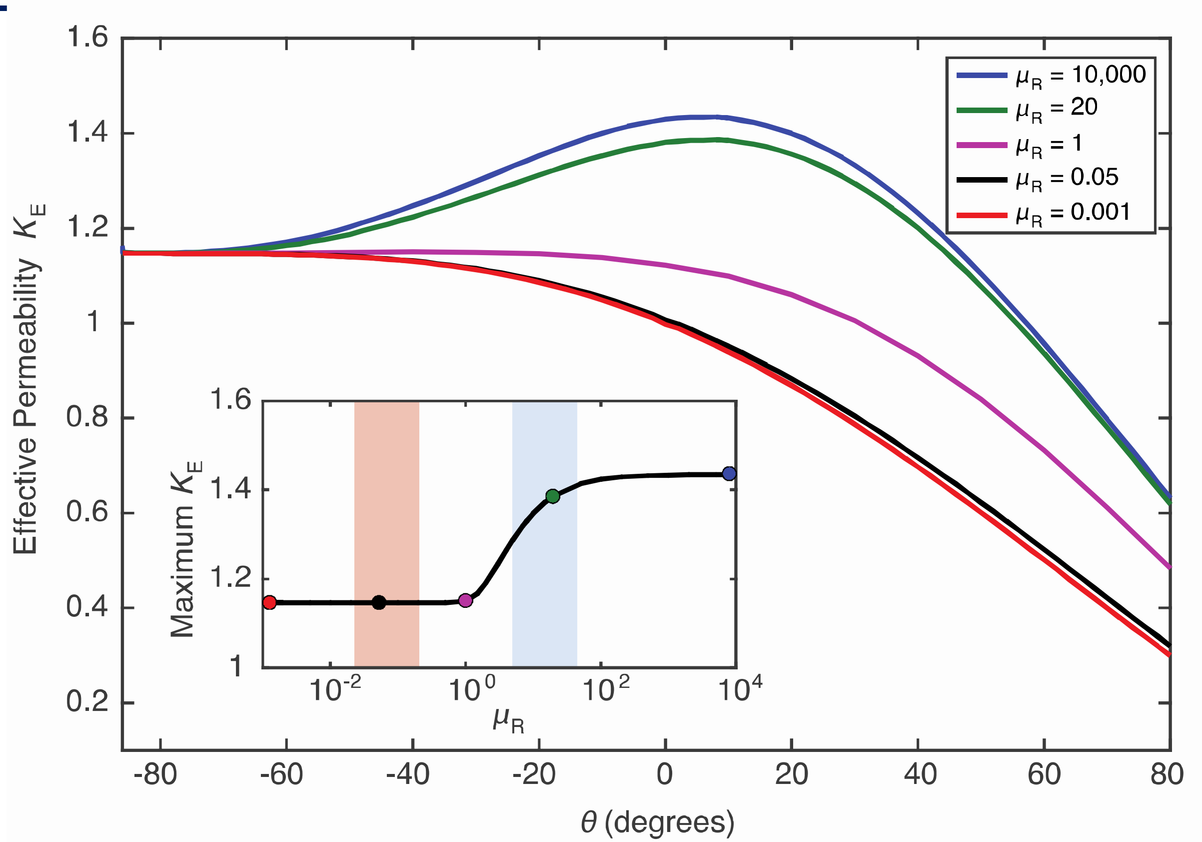
$$K_S = \frac{h^2}{4}\left(\frac{1}{3} + \frac{b}{b+h}\right)$$ **Permeability of channel with slip**

$$K_{NS} = \frac{h^2}{12} \qquad b = 0$$ **Permeability of channel without slip**

$$K_E = \frac{K_s}{K_{NS}} = 1 + \frac{3b}{b+h}$$ **Effective permeability**

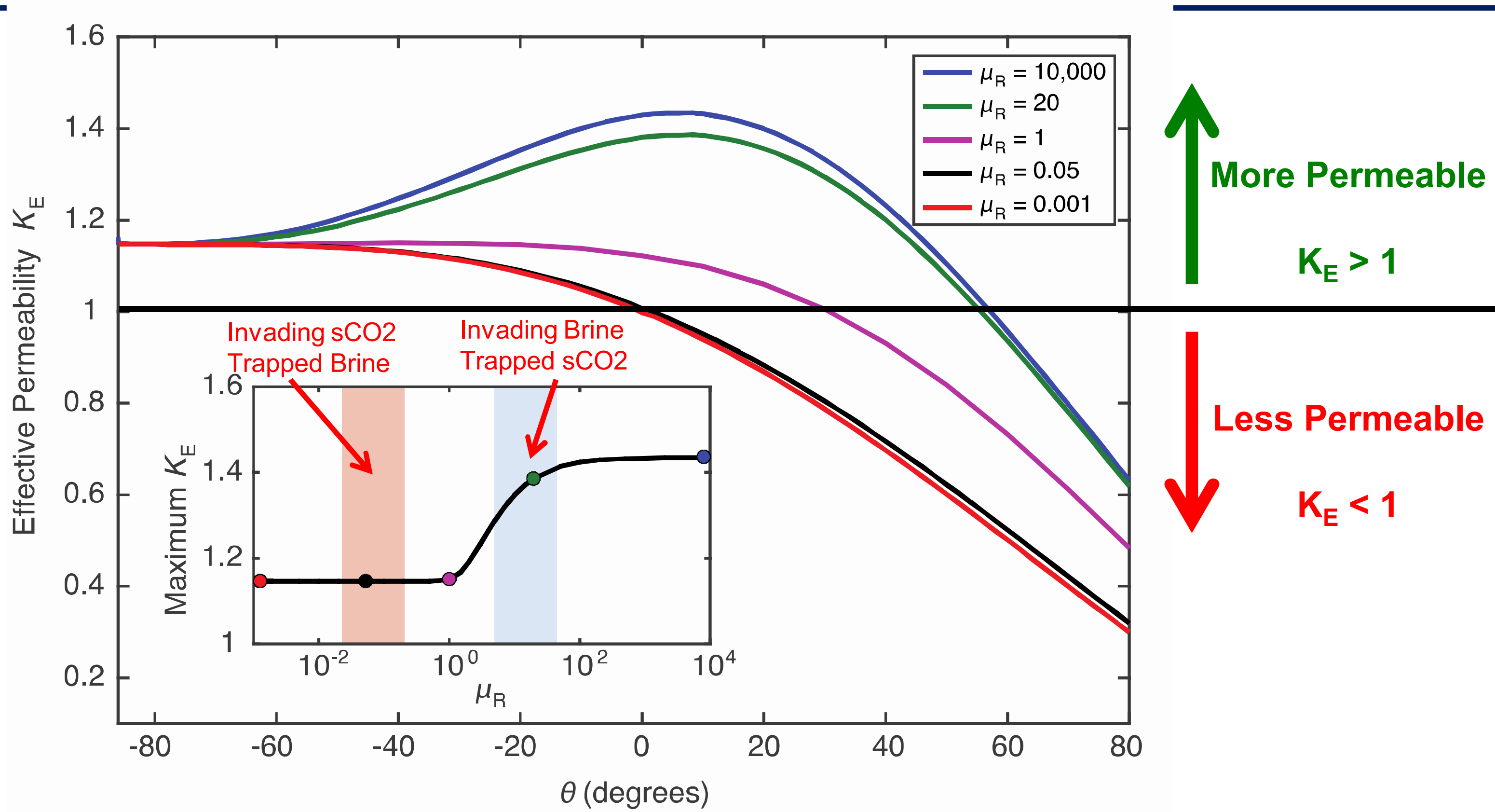
- Effective permeability measures the relative importance of slip to the bulk flow of the channel
- $K_E = 1$
  - b << h
  - b = 0
- K < 1 when b<0
- K > 1 when b>0

Effective Permeability on fluid properties



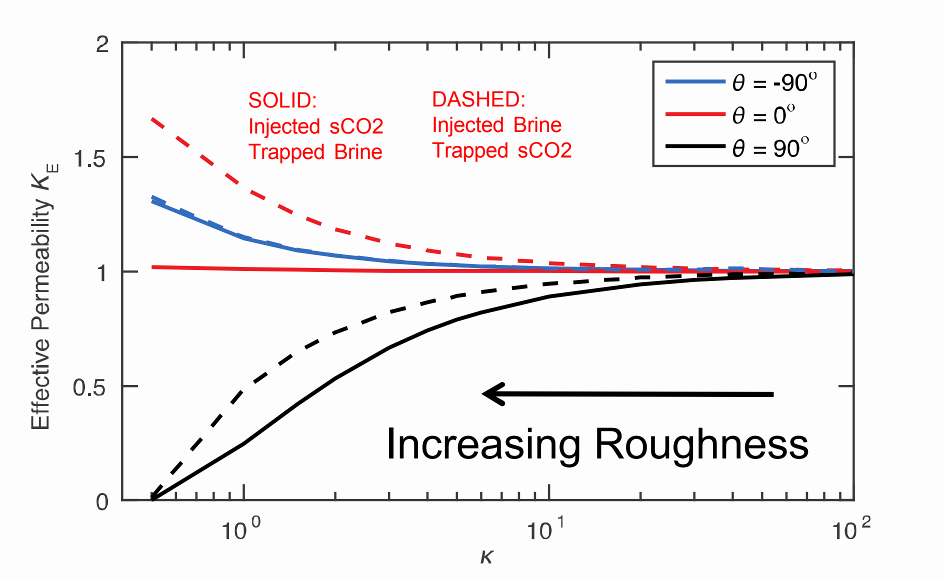
- Contact angle has large effect on permeability (slip) of the flow
  - Local maxima in K_E when $\mu_R > 1$
  - When $\mu_R < 1$ increasing contact angle decreases permeability
- Decreasing viscosity ratio lowers permeability of flow for all contact angles
  - Approaches a rigid wall solution as $\mu_R \to 0$
  - For zero contact angle and low viscosity ratio, K_E = 1 (rigid wall solution)

Effective permeability on fluid properties



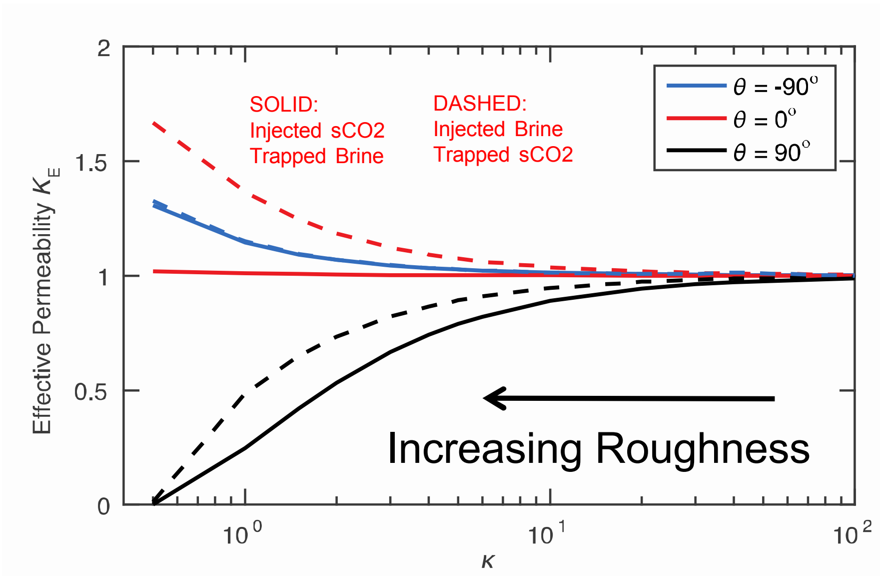
- Contact angle has large effect on permeability (slip) of the flow
  - Local maxima in K_E when $\mu_R > 1$
  - When $\mu_R < 1$ increasing contact angle decreases permeability
- Decreasing viscosity ratio lowers permeability of the pore for all contact angles
  - Approaches a rigid wall solution as $\mu_R \rightarrow 0$
  - For zero contact angle and low viscosity ratio, K_E = 1 (rigid wall solution)

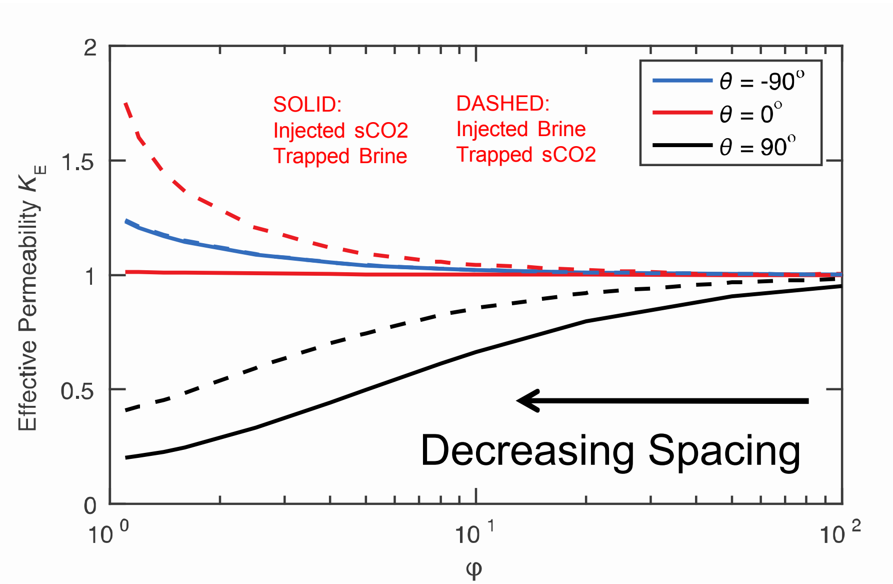
Effect of geometry on effective permeability



- As $\kappa \to \infty$, $K_E \to 1$ (rigid wall solution) for all contact angles
- Decreasing κ
  - Increases permeability for negative contact angles
  - Decreases permeability for positive contact angle (restricts flow)
- Roughness has a large effect on flow physics

Effect of geometry on effective permeability





- As $\kappa \rightarrow \infty$, $K_E \rightarrow 1$ (rigid wall solution) for all contact angles
- Decreasing κ
  - Increases permeability for negative contact angles
  - Decreases permeability for positive contact angle (restricts flow)
- Roughness has a large effect on flow physics

- As $\varphi \rightarrow \infty$, $K_E \rightarrow 1$ (rigid wall solution) for all contact angles
  - At slower rate than the roughness
- As $\varphi \rightarrow 1$
  - Increases permeability for negative contact angles
  - Decreases permeability for positive contact angle (restricts flow)
- Pit spacing has slightly weaker effect on flow spacing

Summary and conclusions

- Effective permeability is dependent on:
  - Viscosity ratio of the fluids
  - Protrusion angle
  - Pit depth
  - Pit spacing
- Influences on the migration of CO_2
  - Imbibition scenarios (invading brine) allow for wide range of self-lubricating regimes (b<0) and depending on geometry, large changes in permeability
  - Drainage scenarios (invading CO_2) more limited in maximum permeability, mostly impeded by trapped fluid interface
- Obtain geometrical parameters from experimental measurement of real rock pores.
- Results can be used to predict deviations in permeability (Darcy's law) of flows in rough pore bodies.
- This work was supported as part of the Center for Frontiers of Subsurface Energy Security, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award Number DE-SC0001114.