

H4IJ-2205  
SAND2018-13795C

# Electrokinetic Methods for Permeability Characterization

Kristopher L. Kuhlman<sup>1</sup>, Melissa M. Mills<sup>1</sup>, Narayana R. Aluru<sup>2</sup>, Bwalya Malama<sup>3</sup>

<sup>1</sup>: Sandia National Laboratories, <sup>2</sup>: University of Illinois, <sup>3</sup>: California Polytechnic State University

2018 AGU  
Fall Meeting

Permeability ( $k_0$ ) is one of the most important and difficult-to-measure properties in tight porous media. Electrokinetics includes streaming potentials (SP) and electroosmosis (EO) that arise when an ionic fluid is in contact with solid with surface charge (the Electrical Double Layer - EDL).

SP arise from electric currents due the movement of ions when water flows (**water drags ions**). Similarly, EO is a pressure due to an electric field (**ions drag water**).

These two effects happen at every liquid-solid interface, but they are often ignored.

Pressure-driven water flow typically dwarfs the EO effect in permeable rocks, but in small pores pressure-driven flow becomes insignificant ( $\bar{u}_{max}$  is 1/pore size to 4th power). EO drives water independent of pore size.

## Steady Macro-scale Equations

At steady-state the driving forces (green and red) are linearly related to fluxes ( $\vec{J}_f$  and  $\vec{J}_e$ ). The SP and EO terms are off-diagonals where voltage creates flow or flow generates current.

Onsager originally showed the off-diagonal coupling coefficients must be equal, (e.g., Haase, 1990).

Putting fluxes into mass and charge balances leads to the  $K_S$  and  $K_E$  coefficients. Because  $L_{12} = L_{21}$ , these coefficients are related.

**Because  $L_{12} = L_{21}$ , independent measurements of  $K_S$  and  $K_E$  can be used to estimate the permeability,  $k_0$  (Pengra et al. 1999).**

$$\begin{aligned} \text{Fluid Volume Density} \quad \vec{J}_f &= -\frac{k_0}{\mu} \nabla p - L_{12} \nabla \psi \\ \text{Electric Current Density} \quad \vec{J}_e &= -L_{21} \nabla p - \sigma_0 \nabla \psi \end{aligned}$$

Darcy's Law      SP  
EO      Ohm's Law

$$\text{Pressure Diffusion} \quad \frac{1}{\alpha} \frac{\partial p}{\partial t} = \nabla^2 p + K_E \nabla^2 \psi$$

$$\text{Electrical Conduction} \quad 0 = K_S \nabla^2 p + \nabla^2 \psi$$

$$K_S = \frac{L_{12}}{\sigma_0} = \left[ \frac{V}{Pa} \right] \quad K_E = \frac{L_{21} \mu}{k_0} = \left[ \frac{Pa}{V} \right]$$

Streaming potential      Electroosmotic pressure

## Measuring $K_S$ and $K_E$

The streaming potential ( $K_S$ ) is easier to measure than the electroosmotic pressure ( $K_E$ ). It is easier to measure a small voltage or current than a small pressure or water flux.

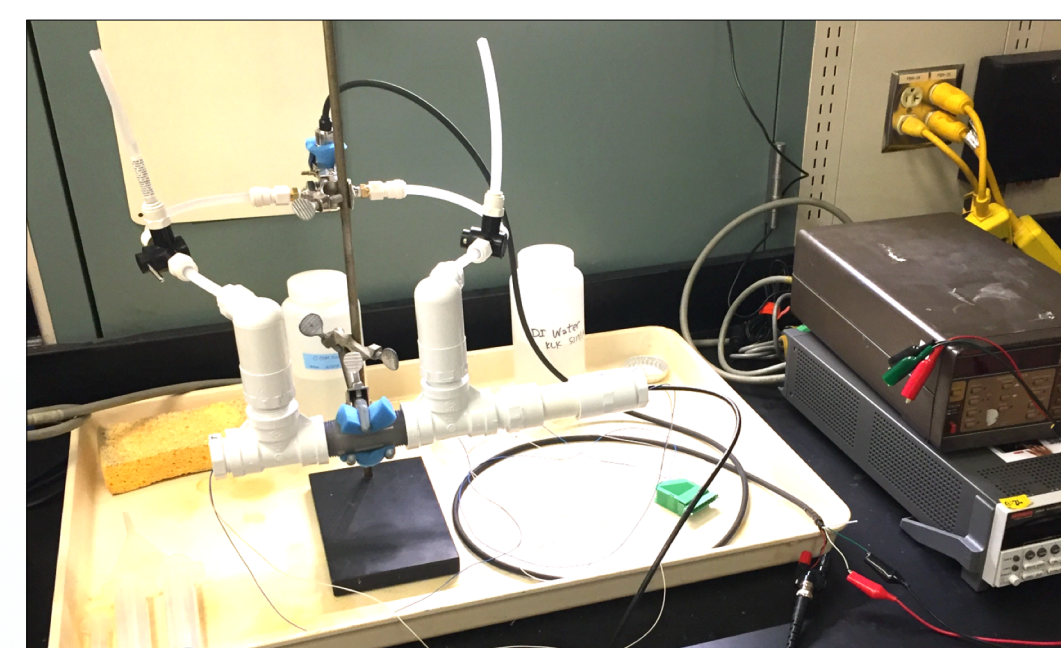
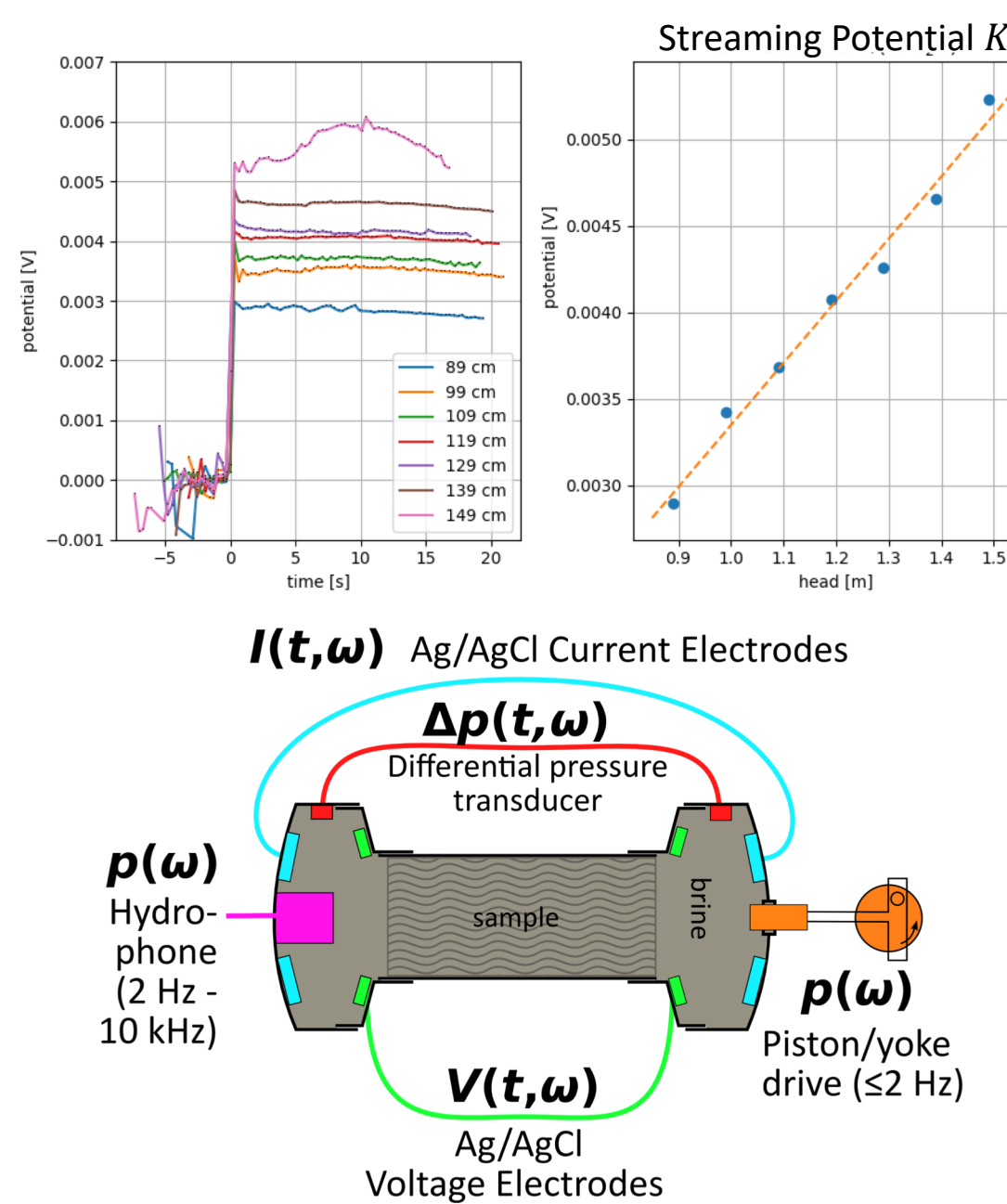
The device to estimate permeability is a modification of the approach taken by Pengra et al. (1999), with extension to lower-permeability media and transient electrokinetic phenomena (i.e., induced polarization – Revil & Florsch, 2010).

A differential pressure transducer is monitored through a frequency-specific amplifier to observe electroosmotic pressure at low frequency (<200Hz).

Current is applied and voltage is measured through sintered Ag/AgCl electrodes. Pressure is applied through a hydrophone or speaker.

Measuring  $K_S$  and  $K_E$ , we can estimate  $k_0 = \frac{\sigma_0 \mu K_S}{K_E}$

$p$	Fluid pressure [Pa]	$\alpha$	Hydraulic diffusivity [m/sec <sup>2</sup> ]
$\psi$	Electrostatic Potential [V]	$L_{12}, L_{21}$	Electrokinetic coupling constants [A/(Pa-m)]
$\mu$	Viscosity [Pa-sec]	$\bar{u}$	Pore fluid velocity [m/sec]
$k_0$	Fluid permeability [m <sup>2</sup> ]	$n_i$	Pore concentration [1/m <sup>3</sup> ]
$\sigma_0$	Electrical conductivity [S/m]	$D_i$	Diffusion coefficient [m/sec <sup>2</sup> ]



## Pore-scale Electrokinetic Simulations

Professor Narayana Aluru and Pikee Priya from University of Illinois are modeling the pore-scale physics (e.g., Probst, 1994) as part of the project to model SP and EO based on typical configurations of grains or fractures.

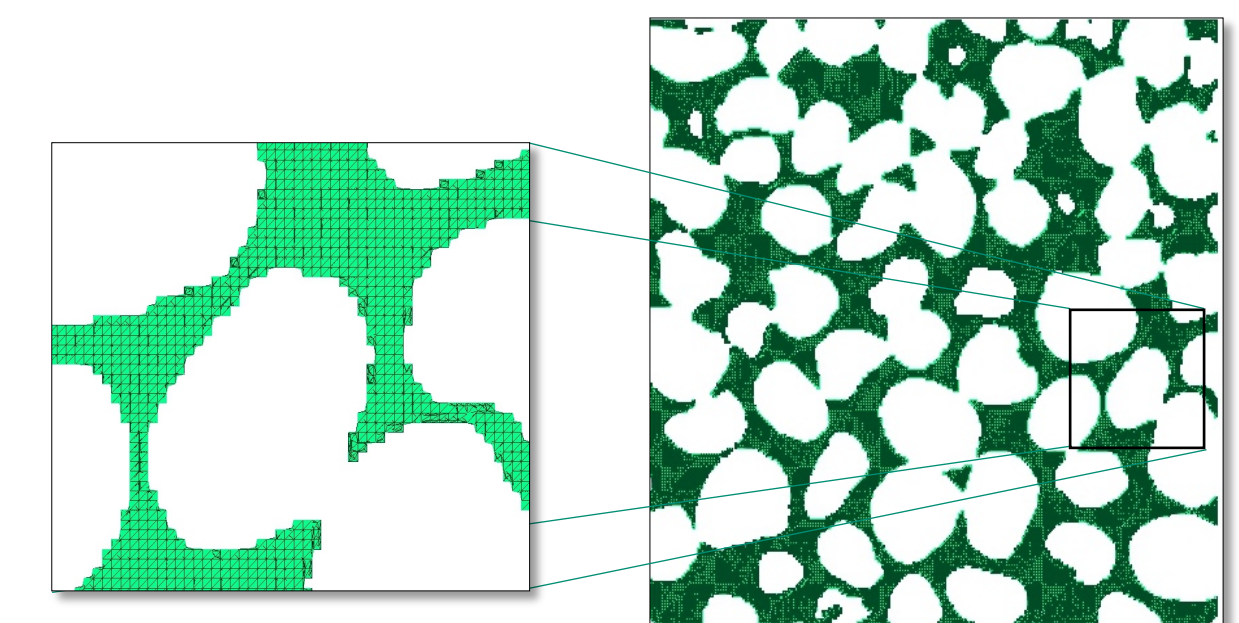
This upscaling seeks to investigate how appropriate are the macro-scale equations under general conditions:

- Saline brines
- Complex geometry
- Fracture networks
- Pore-scale heterogeneity

$$\begin{aligned} \text{Nernst-Planck} \quad \frac{\partial n_i}{\partial t} &= \nabla \cdot n_i \vec{u} - D_i \nabla^2 n_i - \sigma_0 \nabla^2 \psi \\ \text{Stokes Flow} \quad \rho \frac{\partial \vec{u}}{\partial t} &= -\nabla p + \nabla \cdot \mu \nabla \vec{u} - \rho \nabla \psi \\ \text{Poisson Excess Charge Redistribution} \quad \nabla^2 \psi &= \frac{\rho_f}{\epsilon} + \rho_b \end{aligned}$$

convection      diffusion      migration  
 $\nabla \cdot \vec{u} = 0$

Pore-scale simulations will consider coupled processes and typical geometry of porous and fractured media (digitalrockportal.org). The pore-scale modeling is utilizing the OpenFOAM multiphysics framework (openfoam.com).



## Project Goals

This research is part of a Sandia Laboratory Directed Research & Development (LDRD) project, with collaborations between CalPoly and University of Illinois. The Academic Alliance between Sandia and Illinois began in FY19. We are working to better understand of the appropriateness, uniqueness, and physical meaning of macro-scale properties in terms of micro-scale physics. Sandia and CalPoly are collaborating on analytical and numerical methods to more efficiently make predictions in field-scale problems.

## References

- Haase, 1990. *Thermodynamics of Irreversible Processes*, Dover.
- Pengra, Li & Wong, 1999. Determination of rock properties by low-frequency AC electrokinetics. *Journal of Geophysical Research*, 104(B12):29485-29508.
- Probst, 1994. *Physicochemical Hydrodynamics*. John Wiley & Sons, 2nd Ed.
- Revil & Florsch, 2010. Determination of permeability from spectral induced polarization in granular media. *Geophysics Journal International*, 181:1480-1498