Upscaling gas permeability in tight-gas sandstones

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Abstract

Klinkenberg-corrected gas permeability (k) estimation in tight-gas sandstones is essential for gas exploration and production in low-permeability porous rocks. Most models for estimating k are a function of porosity ( ), tortuosity (τ), pore shape factor (s) and a characteristic length scale (lc). Estimation of the latter, however, has been the subject of debate in the literature. Here we invoke two different upscaling approaches from statistical physics: (1) the EMA and (2) critical path analysis (CPA) to estimate lc from pore throat-size distribution derived from mercury intrusion capillary pressure (MICP) curve. τ is approximated from: (1) concepts of percolation theory and (2) formation resistivity factor measurements (F = τ/). We then estimate k of eighteen tight-gas sandstones from lc, τ, and   by assuming two different pore shapes: cylindrical and slit-shaped. Comparison with Klinkenberg-corrected k measurements showed that τ was estimated more accurately from F measurements than from percolation theory. Generally speaking, our results implied that the EMA estimated k within a factor of two of the measurements and more precisely than CPA. We further found that the assumption of cylindrical pores yielded more accurate k estimates when τ was estimated from concepts of percolation theory than the assumption of slit-shaped pores. However, the EMA with slit-shaped pores estimated k more precisely than that with cylindrical pores when τ was estimated from F measurements.

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BACKGROUND

Factors affecting gas permeability in tight media

- Connectivity
- Pore-throat size distribution
- Slip flow and Knudsen diffusion
- Tortuosity
- Porosity
- Pore shape geometry
- Gas characteristics

Theoretical upscaling techniques

- Bundle of capillary tubes approach
- Effective-medium theory (EMA)
- Critical path analysis (CPA)
- Perturbation theory
- Volume averaging method
- Mean-field theory
- Renormalization group theory
- …

PURPOSES AND ASSUMPTIONS

Objectives

- ✓ To evaluate the EMA's reliability to estimate the Klinkenberg-corrected gas permeability k from pore-throat size distribution, tortuosity, and porosity.
- ✓ To estimate k from pore-throat size distribution and electrical conductivity measurements.
- ✓ To compare EMA results to those obtained from critical path analysis in tight-gas sandstones.

Assumptions

- ❑ Pores are cylindrical or slit-shaped.
- ❑ The influence of pore pressure on k in our samples is small because all permeability measurements were Klinkenberg-corrected.
- ❑ Contact angle is about 140° for mercury.
- ❑ The air-mercury interfacial tension is 485 mN/m.

MATERIALS AND METHODS

Hydraulic and electrical conductances

	Hydraulic flow	Electrical flow
Cylindrical	$g_h = \frac{\pi r^4}{8\mu l}$	$g_e = \sigma_f \frac{\pi r^2}{l}$
Slit-shaped	$g_h = \frac{b w^3}{12\mu l}$	$g_e = \sigma_f \frac{b w}{l}$

The effective-medium approximation (EMA)

An upscaling technique from statistical physics appropriate in homogeneous and relatively heterogeneous porous rocks.

Cylindrical pores: $k = \frac{\phi}{8\tau_h} \frac{r_{he}^4}{\langle r_b^2 \rangle}$ and $\frac{\sigma_b}{\sigma_f} = \frac{\phi}{\tau_e} \frac{r_{ee}^2}{\langle r_b^2 \rangle}$ → $k = \frac{1}{8} \frac{\sigma_b}{\sigma_f} \frac{r_{he}^4}{r_{ee}^2}$

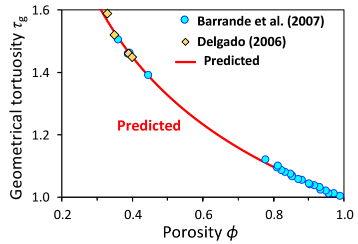
Slit-shaped pores: $k = \frac{\phi}{12\tau_h} \frac{w_{he}^3}{\langle w_b \rangle}$ and $\frac{\sigma_b}{\sigma_f} = \frac{\phi}{\tau_e} \frac{w_{ee}}{\langle w_b \rangle}$ → $k = \frac{1}{12} \frac{\sigma_b}{\sigma_f} \frac{w_{he}^3}{w_{ee}}$

Effective hydraulic and electrical pore sizes are determined from the following EMA governing equation:

$$\int_{g_{min}}^{g_{max}} \frac{(g_e - g)}{g + (Z/2 - 1) g_e} f(g) dg = 0$$

As a first-order approximation, the following geometrical tortuosity model may be used to approximate τ_e and τ_h with the geometrical tortuosity τ_g (Ghanbarian et al., 2013):

$$\tau_g = \left(\frac{L_e}{L_s}\right)^2 = \left[\frac{\phi - \phi S_c + (C/L_s)^{\frac{1}{\nu}}}{1 - \phi S_c}\right]^{2(\nu - \nu D_{opt})}$$



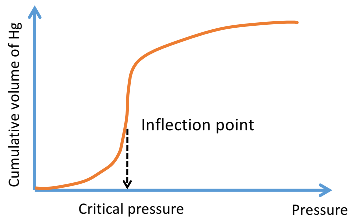
Critical path analysis (CPA)

Another upscaling technique from statistical physics appropriate in heterogeneous porous media with broad pore-throat size distribution.

Cylindrical pores: $k = \frac{2^{-y}}{8} \frac{\sigma_b}{\sigma_f} r_c^2$

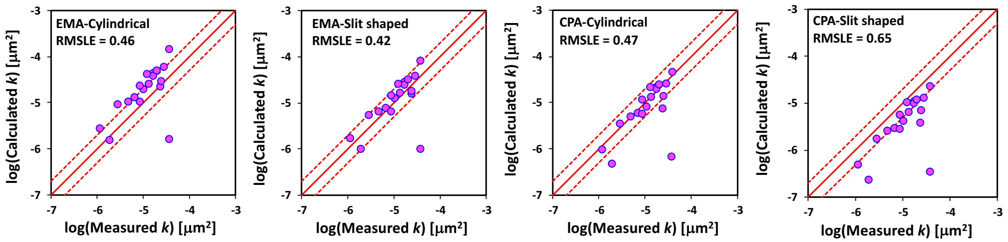
y = 0.74 (Skaggs, 2011)

Slit-shaped pores: $k = \frac{3^{-y}}{12} \frac{\sigma_b}{\sigma_f} w_c^2$

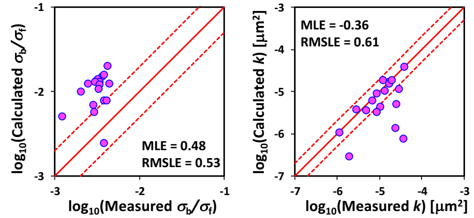


RESULTS

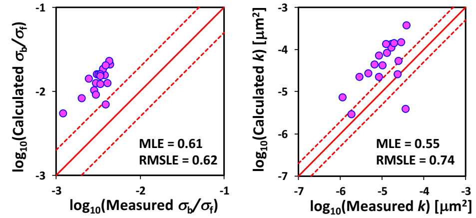
The eighteen tight-gas sandstones used in this study were cut from whole cores retrieved from a tight-gas sandstone formation located in East Texas. In all samples, gas permeability was measured using the transient pulse technique at a net confining stress of 2500 psi and corrected by extrapolating to infinite pressure using the *Klinkenberg* method.



Estimating σ_b/σ_f and k via EMA from MICP, porosity and tortuosity assuming that pores are cylindrical



Estimating σ_b/σ_f and k via EMA from MICP, porosity and tortuosity assuming that pores are Slit-shaped



CONCLUSION

- ❑ EMA with slit-shaped pores estimated k slightly more precisely than CPA with cylindrical pores, although both method estimations were mainly within a factor of two of the measurements.
- ❑ Depending on input parameters and upscaling methods, the assumption of cylindrical pores could yield more accurate σ_b/σ_f and k estimates than the assumption of slit-shaped pores and vice versa.

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