Measurement of Slip Flows in Nanofluidics & Rocks

Ye Tian, Xiangyu Yu, Yu-Shu Wu and Xiaolong Yin
yetian@mines.edu

Outline

- Background
- Experimental set up
- Results & Discussions
- Conclusions

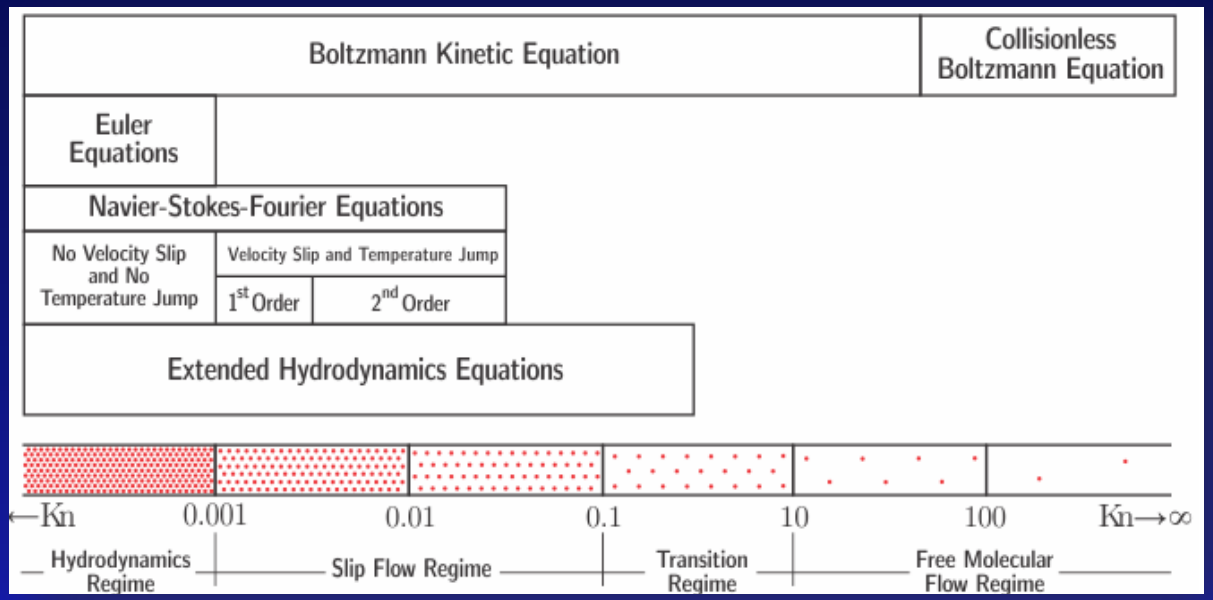
Background

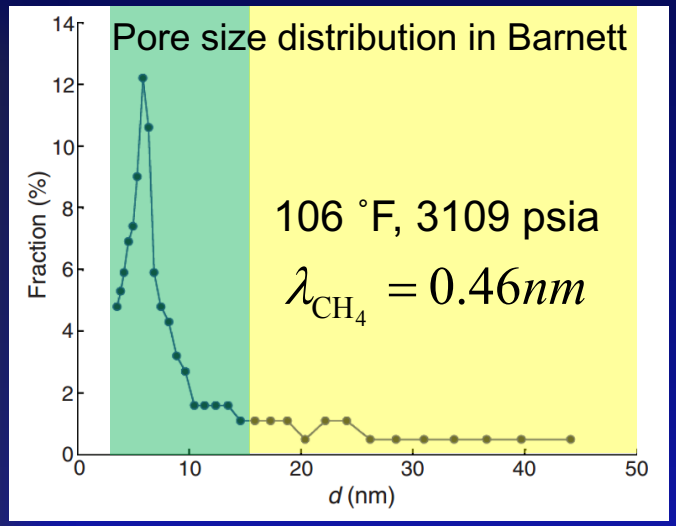
- Key parameters affecting gas flow regimes
- Knudsen number

$$Kn = \frac{\lambda}{L}$$

$$\lambda = \frac{\mu}{p}\sqrt{\frac{\pi RT}{2M}} \quad \text{or} \quad \lambda = \frac{k_B T}{\sqrt{2}\pi d^2 p}$$

Characteristic length (Pore size r)





Sakhee-Pour & Bryant, 2012; Wang, 2014

Background

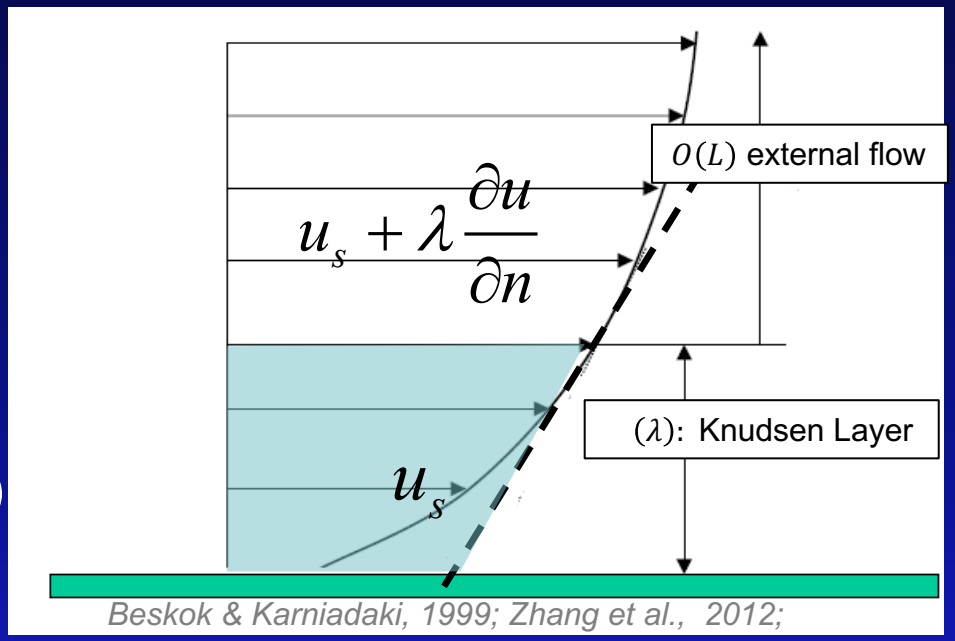
- Slip flow model
  - 1st order model (Kn<0.03)

$$u_s = \frac{1}{2}\left[u_s + \lambda\frac{\partial u}{\partial y} + \sigma u_w + (1-\sigma)\left(u_s + \lambda\frac{\partial u}{\partial y}\right)\right] \Rightarrow u_s - u_w = \frac{2-\sigma}{\sigma}\lambda\frac{\partial u}{\partial n}$$

  - 2nd order model (Kn<0.2)

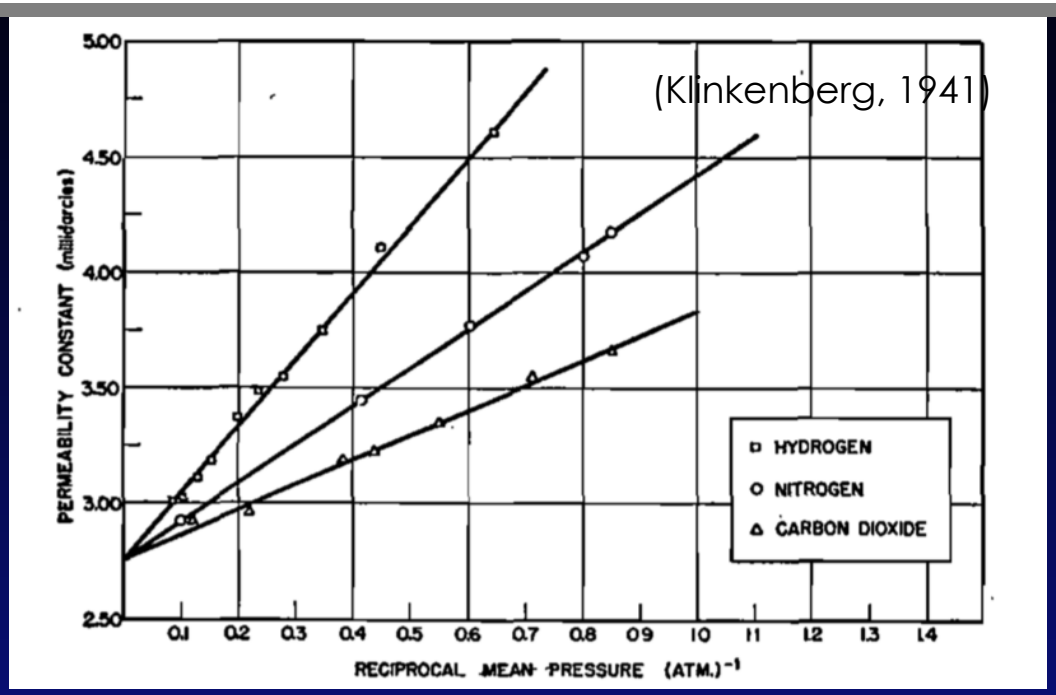
$$u_s - u_w = c_1\lambda\left(\frac{\partial u}{\partial n}\right) - c_2\lambda^2\left(\frac{\partial^2 u}{\partial n^2}\right)$$

σ is the fraction of molecules that reflects diffusely
or Tangential Momentum Accommodation Coefficient (TMAC)



Background

- Klinkenberg effect
  - observed *k=F(1/p)*
  - *converge to liquid k at high p*



$$\frac{k_a}{k_\infty} = \frac{Q}{\lim\limits_{Kn\to 0} Q} = 1 + \frac{b}{\bar{p}}$$

$$\frac{Q}{\lim\limits_{Kn\to 0} Q} = 1 + CKn\frac{2-\sigma}{\sigma}$$

$$\Rightarrow b = CKn\frac{2-\sigma}{\sigma}\bar{p} \xrightarrow{Kn=\lambda/r} b = C\frac{2-\sigma}{\sigma}\frac{\mu}{r}\sqrt{\frac{\pi RT}{2M}}$$

From 1st Oder slip model

b is not *p*-dependent for 1st order slip model.

b is a function of *p* for 2nd order slip model.

Background

- Slip flow model and Modified Darcy's law

$$b = C\frac{2-\sigma}{\sigma}\frac{\mu}{r}\sqrt{\frac{\pi RT}{2M}}$$

C is a function of geometry
C=4 for tubular flow; i.e. Pore-throat
C=6 for planar flow; i.e. fractures
(Wang, 2014)

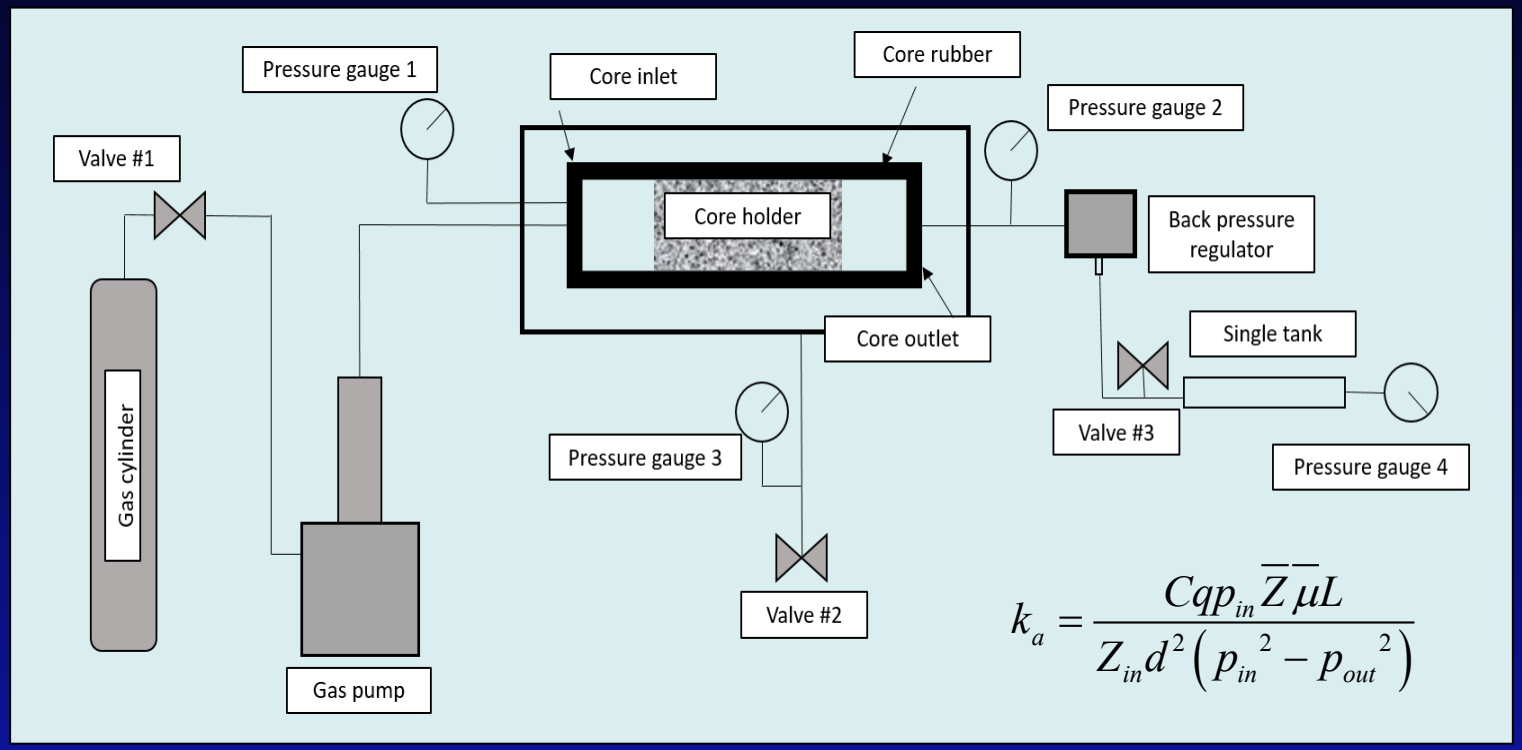
Gas flow model is critical for reservoir evaluation/simulation.

But can we use 1st order slip model to modify Darcy's law?

When should we switch to 2nd order slip model?

Experimental set up

- Gas flow in rocks

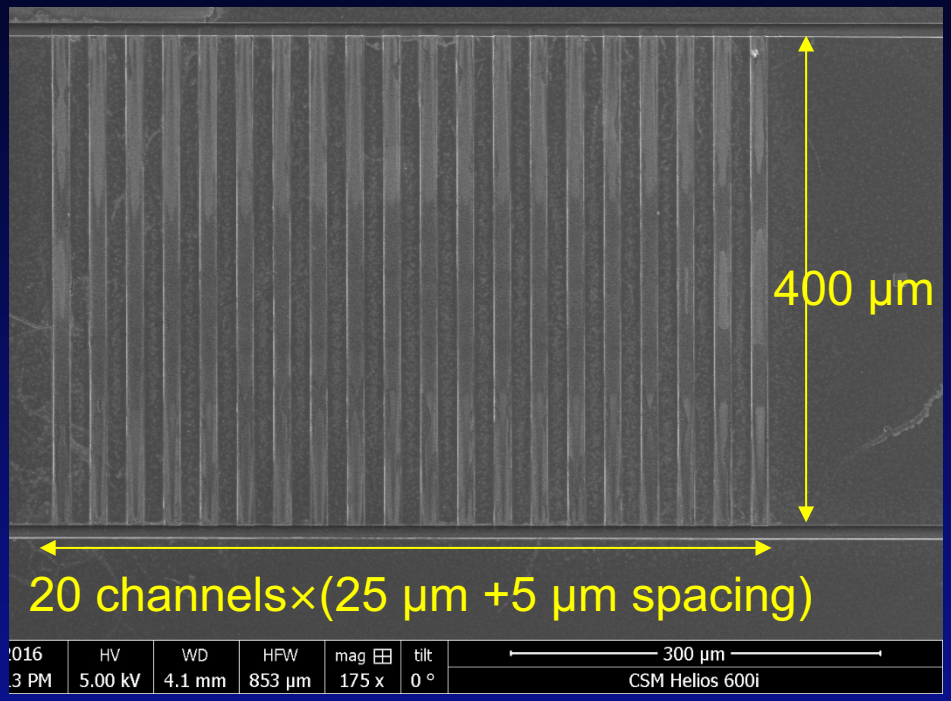


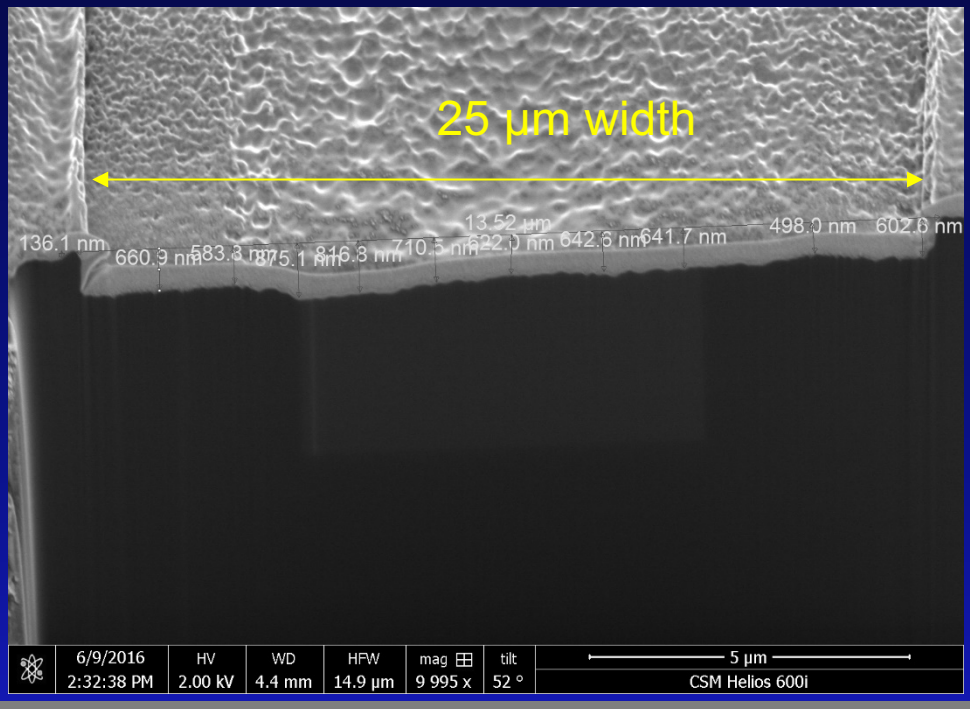
$$k_a = \frac{C q p_{in} \overline{Z} \overline{\mu} L}{Z_{in} d^2 \left(p_{in}^{\ 2} - p_{out}^{\ 2} \right)}$$

1. Pre-stressed for 2-3 days with 25% higher than expected effective stress
2. Gas injection with constant inlet pressure and controlled back pressure
3. Steady-state measurement

Experimental set up

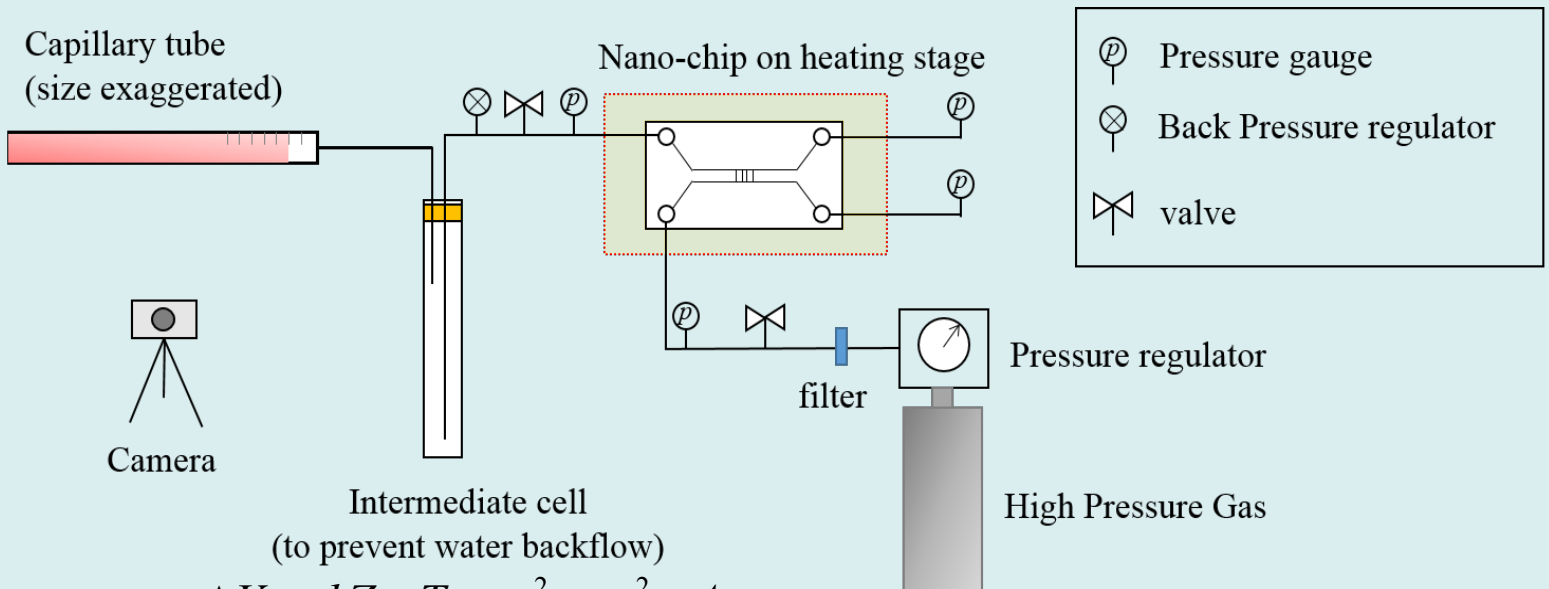
- Nanofluidics





Experimental set up

- Gas flow in nanofluidics



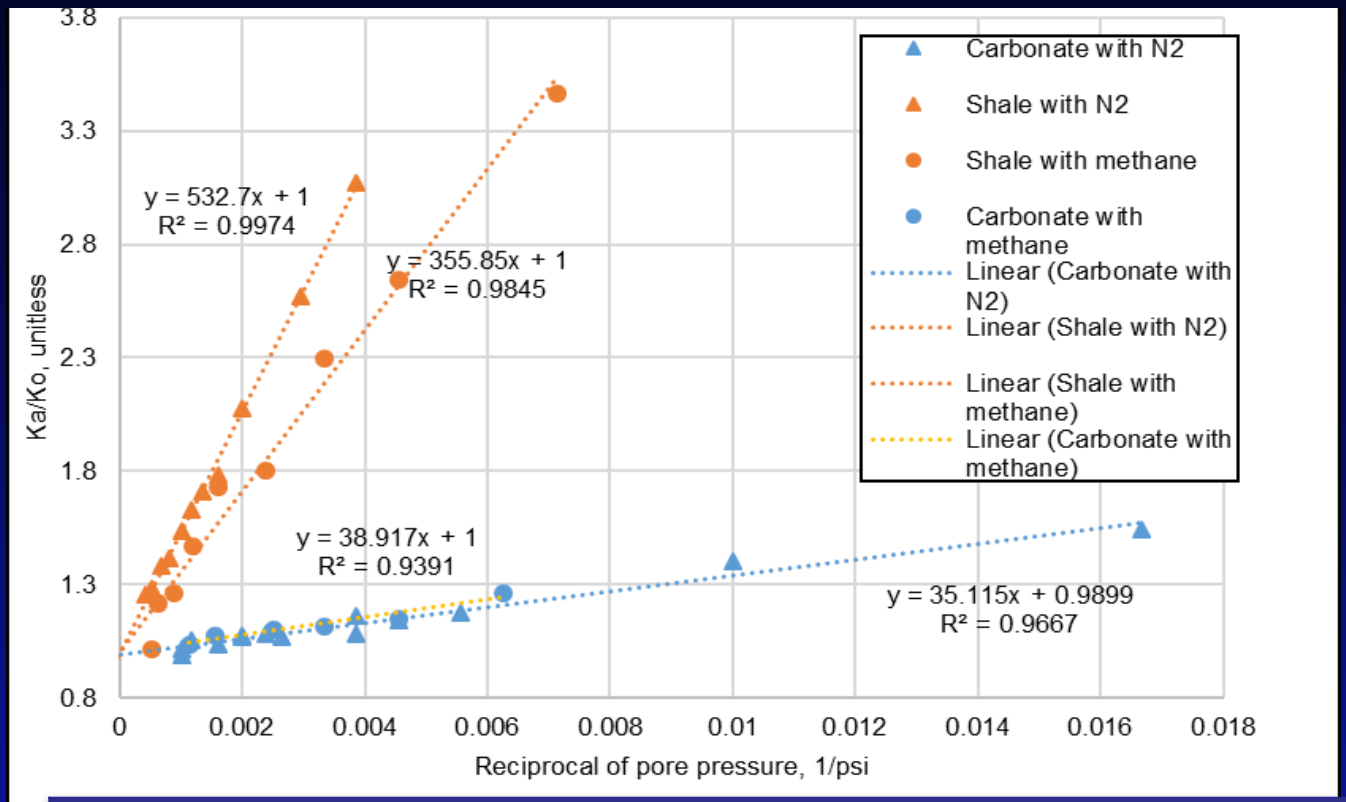
$$\frac{\Delta V}{\Delta t} = \frac{kZ_{\text{atm}}T_{\text{atm}}}{\bar{p}T}\,\frac{p_{\text{in}}^2 - p_{\text{out}}^2}{2\mu Z}\,\frac{A_{\text{channel}}}{L_{\text{channel}}}$$

1. Leakage test for 2-3 days
2. Gas flow with controlled inlet and back pressure
3. Steady-state measurement

Results & Discussions

- Gas flow in rocks

$$b = C\frac{2-\sigma}{\sigma}\frac{\mu}{r}\sqrt{\frac{\pi RT}{2M}}$$

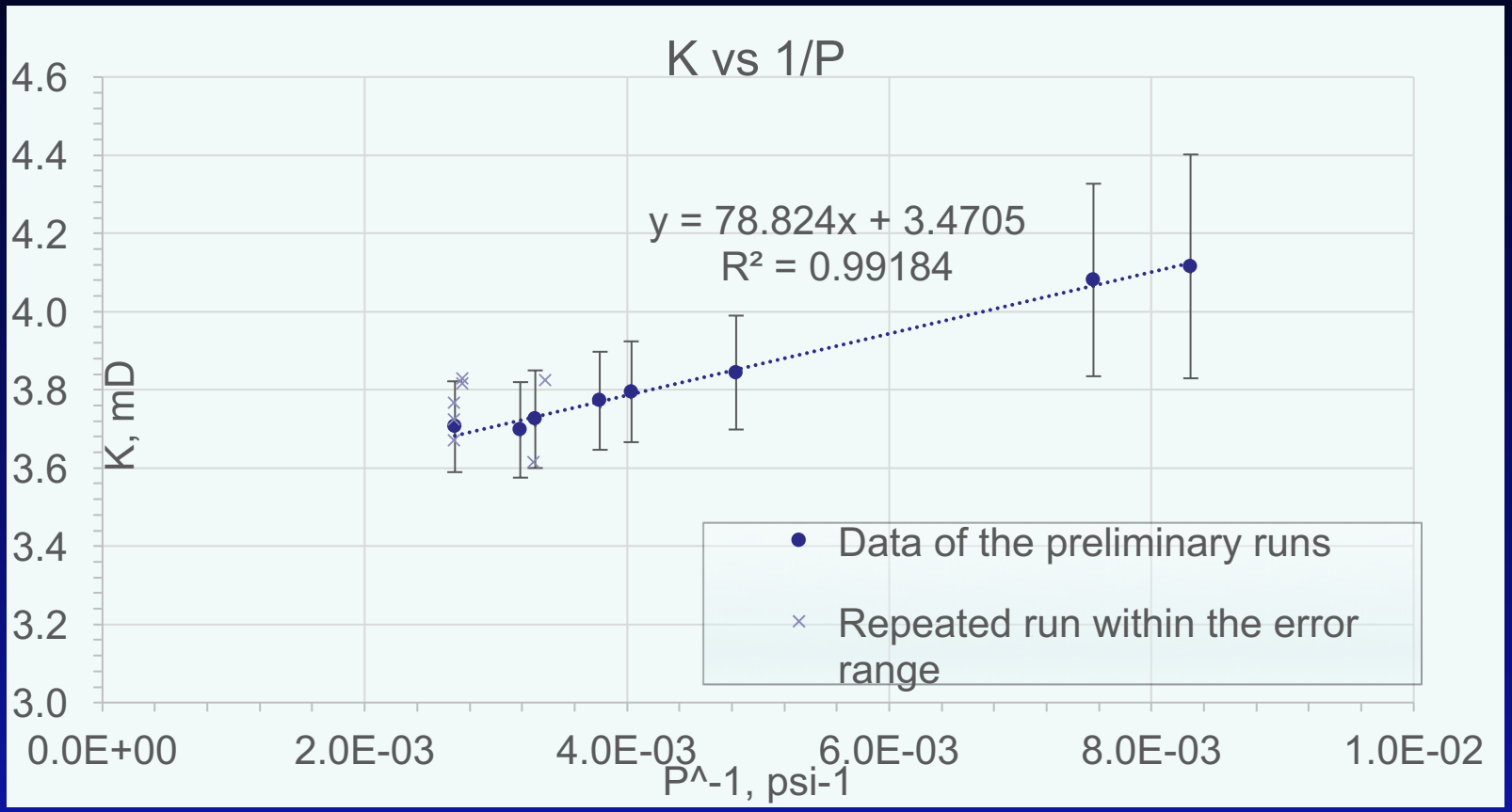


- Increasing Molecular weight should reduce slip factor.
- Carbonate $b_{N2}<b_{CH4}$. But for shale $b_{N2}>b_{CH4}$
- Adsorption may reduce actual pore size for shale.

	Formation	Intrinsic permeability	slip factor	Correlated pore size
Shale	Niobrara	0.124 μD (CH4) 0. 152 μD (N2)	355.9 psi (CH4) 532.7 psi (N2)	18 nm (N2) 27 nm(CH4)
Carbonate	Wisconsin	17.6 μD (CH4) 16.3 μD (N2)	38.9 psi (CH4) 35.1 psi (N2)	273 nm (N2) 246 nm (CH4)

Results & Discussions

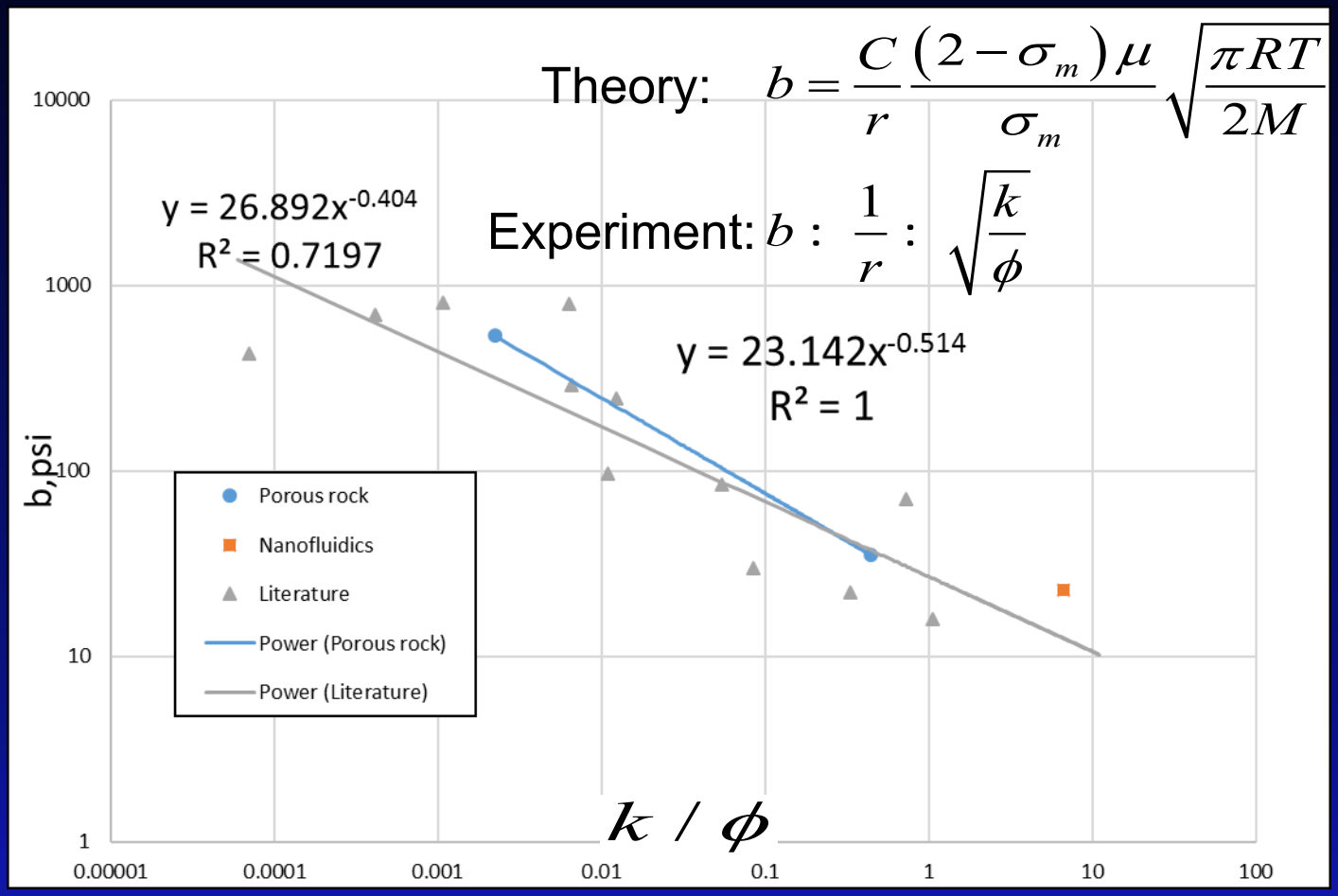
- Gas flow in nanofluidics



	Designed Depth	Effective Depth	Intrinsic K	Slip factor	TMAC
Nanofluidics	500 nm	284 nm	3.47 mD	18.01 psi	0.95

Results & Discussions

- Gas flow in nanoporous media



- Inverse scaling Validates 1st order Slip model in rock
- Rocks have less slip than nanofluidic perhaps due to surface roughness and pore tortuosity

Results & Discussions

- Summary

Different slippage factor of methane and nitrogen reflect:

- Interactions between pore wall and different gases;
- Adsorption effect in the pore;

In nanofluidics, data from one chip within 1st order slip.

- TMAC for methane is 0.95, consistent with literatures
- To validate TMAC by measuring gas flows in other depths i.e. 100 nm and 50 nm in the future

Conclusions

- The inverse scaling model shows that 1st order slip model can fundamentally cover slip flows in both rocks and nanofluidics.
- The slip factor is mainly controlled via pore size and gas properties.
- The Klinkenberg factors obtained from nanofluidic experiments indicated that rocks may have less slip than nanofluidic channels of the same dimension, due to surface roughness, pore tortuosity and adsorption

Many thanks to our sponsor Halliburton
Thanks for your attention.

All questions are welcome!

References

Arkilic, E.B., Schmidt, M.A. and Breuer, K.S., 1997. Gaseous slip flow in long microchannels. *Journal of Microelectromechanical systems*, *6*(2), pp.167-178.

Beskok, A. and Karniadakis, G.E., 1999. Report: a model for flows in channels, pipes, and ducts at micro and nano scales. *Microscale Thermophysical Engineering*, *3*(1), pp.43-77.

Colin, S., Lalonde, P. and Caen, R., 2004. Validation of a second-order slip flow model in rectangular microchannels. *Heat transfer engineering*, *25*(3), pp.23-30.

CHeller, R., Vermylen, J. and Zoback, M., 2014. Experimental investigation of matrix permeability of gas shales. *AAPG bulletin*, *98*(5), pp.975-995.

Niu, C., Hao, Y.Z., Li, D. and Lu, D., 2014. Second-order gas-permeability correlation of shale during slip flow. *SPE Journal*, *19*(05), pp.786-792.

Shen, Ching. *Rarefied gas dynamics: fundamentals, simulations and micro flows*. Springer Science & Business Media, 2006.

Sakhaee-Pour, A. and Bryant, S., 2012. Gas permeability of shale. SPE Reservoir Evaluation & Engineering, 15(04), pp.401-409.

Wang, L., 2014. *Simulation of slip flow and phase change in nanopores* (Doctoral dissertation, Colorado School of Mines. Arthur Lakes Library)

Wang, S., Lukyanov, A., Wang, L., Wu, Y.S., Pomerantz, A., Xu, W., Kleinberg, R., 2017. A Non-Empirical Gas Slippage Model for Low to Moderate Knudsen Numbers. Physics of Fluids, 29(1).

Zhang, W.M., Meng, G. and Wei, X., 2012. A review on slip models for gas microflows. Microfluidics and nanofluidics, 13(6), pp.845-882.