PS A Modified Gas Expansion Method for Measurement of Shale Matrix Permeability and Relative Permeability*

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Search and Discovery Article #42419 (2019)**
Posted August 12, 2019

*Adapted from poster presentation given at 2019 AAPG Annual Convention and Exhibition, San Antonio, Texas, May 19-22, 2019
 DOI:10.1306/42419Peng2019

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Abstract

Matrix permeability is a key petrophysical parameter in reservoir evaluation and simulation. However, measurement of this parameter still remains problematic for unconventional reservoirs. One of the biggest challenges lies in the influence of fractures, which can be artificially induced and are ubiquitous in almost all shale plug samples. Inclusion of fractures in measurement and data interpretation can lead to overestimation of shale-matrix permeability. In this study, new experimental and data analysis procedures are developed for more accurate measurement of shale matrix permeability based on a previous work (Peng and Loucks, 2016). The new experimental procedures also allow fast pressure equilibrium and takes 15-60 minutes, which is less time than that compared to other methods such as pulse-decay or steady-state methods. Permeability and porosity values under confining pressure are obtained from quantitative analysis on measured pressure-decay curve for oven-dried samples. The influence of fractures on matrix porosity and permeability is quantified and excluded. Reliability and consistency of the measurement results are confirmed through multiple means, including analytical solution back-calculation, numerical modeling, and multiple measurements for similar samples but with different plug diameters. Because the influence of fractures is explicitly excluded in the data analysis, the new method is also more flexible regarding sample conditions – even broken plug samples with fractures can be used in this method. This is another advantage of the new method given the difficulty in obtaining “intact” plugs because of the fissility of shale. The newly developed method can thus serve as a fast yet reliable technique for “real” shale matrix permeability measurement. Measurement results for 50+ shale samples with detailed lithofacies information will be presented.

References Cited

Peng, S., and B. Loucks, 2016, Permeability Measurements in Mudrocks Using Gas-Expansion Methods on Plug and Crushed-Rock Samples: Marine and Petroleum Geology, v. 73, p. 299-310. doi.org/10.1016/j.marpetgeo.2016.02.025

Peng, S., B. Ren, and M. Meng, 2019, Quantifying the Influence of Fractures for More Accurate Laboratory Measurement of Shale Matrix Permeability using a Modified Gas Expansion Method: SPE Reservoir Evaluation & Engineering, Formation Evaluation, SPE-195570-PA, 12 p. doi.org/10.2118/195570-PA

A Modified Gas Expansion Method for Measurement of Shale Matrix Permeability and Relative Permeability

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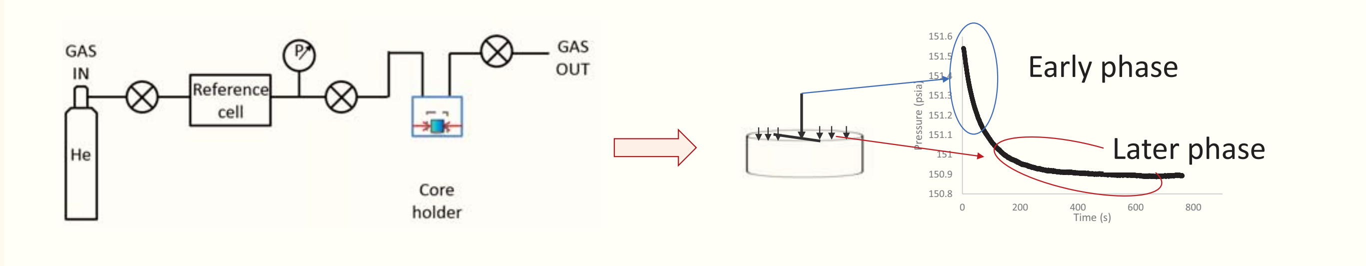
Problem statement and motivation

- Shale matrix permeability is important to identify:
  - 1) sweet spots; 2) source of high water cut
- However, the correlation between oil/gas production and permeability data is vague
- What causes the vague correlation?
  - Inconsistent/inaccurate measurement of shale matrix permeability
  - Influence of fractures: the biggest challenge
  - A lack of measurement on relative permeability
- Objectives:
  - Develop a method that is more accurate and reliable
  - Specifically a method that can quantify and exclude the influence of fractures
  - Can be used for relative permeability measurement

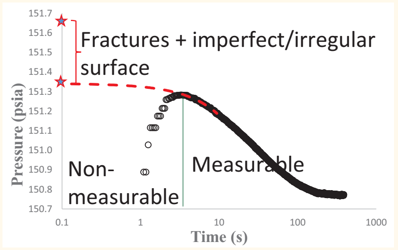
A modified gas expansion (MGE) method



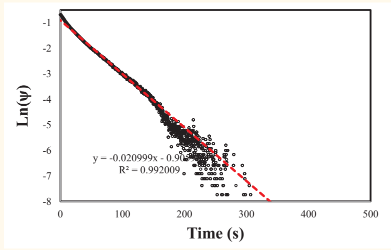
- Problems in our previous study (Peng and Loucks, 2016):
  - Influence of fractures still existed: permeability increased with the plug diameter
  - A lack of validation of the analytical solution
- Further modifications
  - Shorter plug length: 5-7 mm, leading to a faster experiment (30-60 min)
  - More accurate porosity measurement
  - Modification and validation of the analytical solution
  - Calibration using numerical modeling
  - Multiple measurements: 1-inch vs. 1.5-inch plugs

Data analysis and analytical solution validation

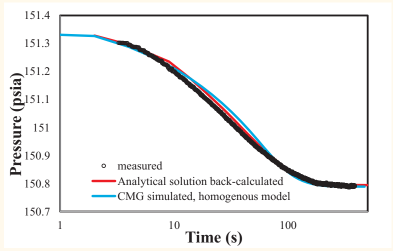
More accurate determination of porosity



Linear relationship with time



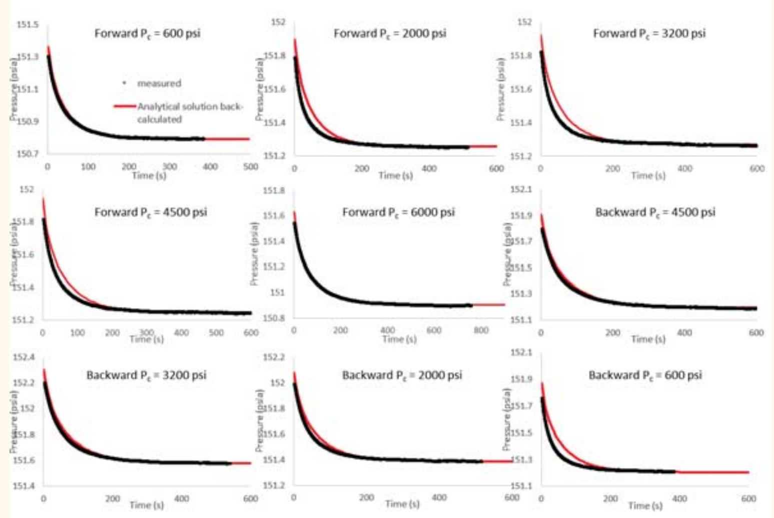
Validation of analytical solution & calibration with numerical simulation



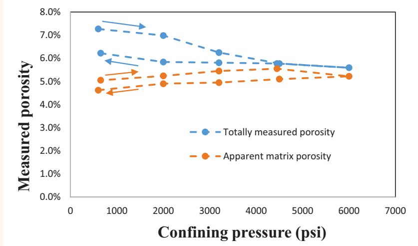
$$\phi \frac{1}{P}\frac{\partial P}{\partial t} = \frac{k}{\mu}\frac{\partial^2 P}{\partial z^2} \Rightarrow \psi = (P - P_0) - \left(\frac{P_{ai} - P_0}{1 + Lh}\right) = \frac{2h(P_i - P_0)\exp(-K\beta 1^2 t)}{L(\beta_1{}^2 + h^2) + h} \Rightarrow k = \frac{s}{\beta_1{}^2}\phi\mu\frac{1}{P}^{*}$$

*Please refer to references for the description of the symbols

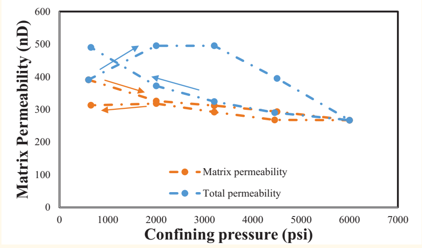
The change of fractures with confining pressure and the influence on porosity and permeability



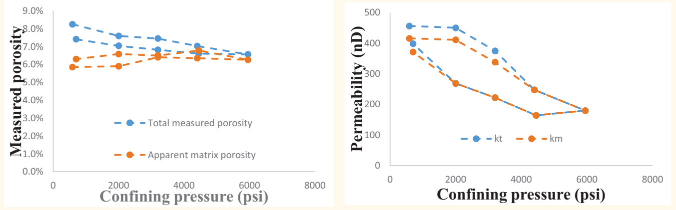
- Deviation of analytical solution back-calculated pressure-decay curve from measured curve indicates the change of fractures
- Fractures are compressed under confining pressure
  - Change from non-measurable to measurable
  - Measurable fractures add to porosity, and
  - Formed a higher-perm layer



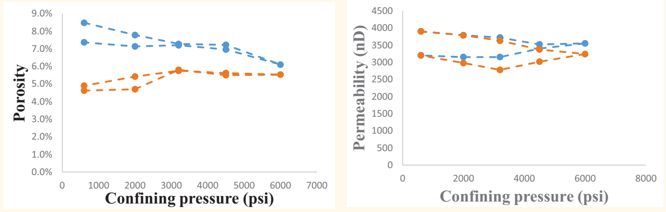
- Change of total measured porosity and apparent matrix porosity with confining pressure for sample an Eagle Ford sample.
- Arrows indicate the direction of decreasing or increasing confining pressure.



- The change of matrix permeability (k_m) and total measurable permeability (k_t) with confining pressure.
- Total measurable permeability is generally larger than matrix permeability.
- Arrows indicate the direction of decreasing or increasing confining pressure.



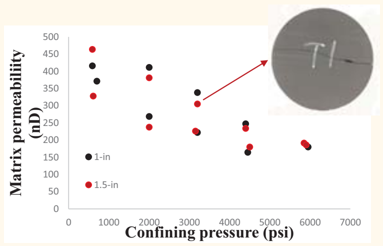
Sample-2 (Eagle Ford)



Sample-3 (Wolfcamp)

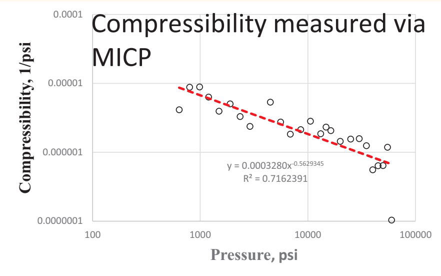
- Influence of fractures exists for all samples, but the influence varies

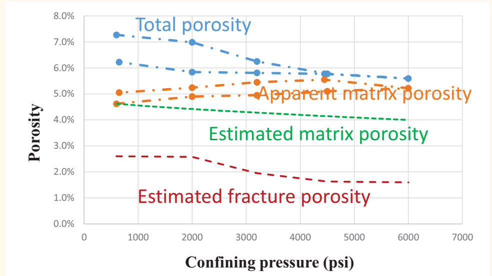
Permeability: 1-inch vs. 1.5-inch plugs



- Matrix permeability from 1- and 1.5-in plugs of the same sample
  - The 1.5-in plug has an open crack
  - Close values of permeability are obtained
  - Further verification: matrix permeability (not fracture permeability) is measured

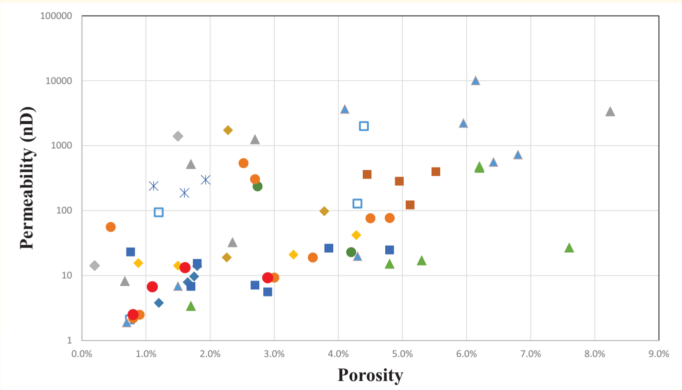
The change of matrix and fracture porosity





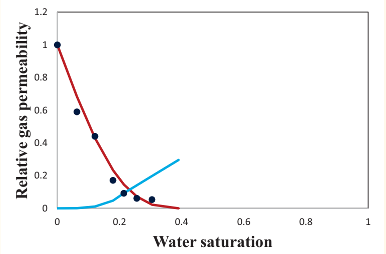
- Matrix porosity: estimated based compressibility
- Fracture porosity: non-negligible

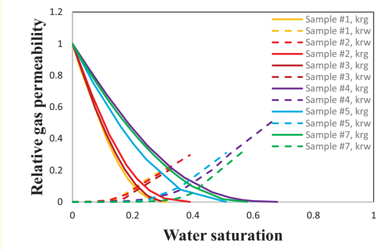
Porosity-permeability relationship and lithofacies



- ~60 samples from different wells and formations: Austin chalk & Wolfberry
- Relative trend for some lithofacies:
  - Calcareous mudrock (■): general low perm
  - Siliceous mudrock (▲): lower porosity-permeability relationship
  - Wackestone/packstone (●): low por, low perm
- No clear trend for most other lithofacies

Relative permeability measurement using the MGE method





- Gas permeability measured at different saturation
- Modified Brooks-Corey equation for water relative permeability
- Residual gas saturation (where k_{rg} = ~0) is a key parameter in determining the shape of the curves, and
- It is a function of wettability, pore shape, and connectivity
- Fast decline of k_{rg} and relatively slower increase of k_{rw} Can explain the fast decline of gas production while the increase of water saturation is not significant
  - Can also explain the low gas production when water-cut is low
- Combining effect from layers with different relative perm
  - Can lead to decent gas/oil production but with high water-cut

Conclusions: the MGE method is reliable, faster, and makes direct gas relative permeability measurement possible.

Acknowledgements: STARR program and MSRL member companies; Bo Ren and Mianmo Meng.

References: 1. Peng and Loucks, 2016, Marine and Petroleum Geology 73, 299-310;
2. Peng et al., 2019, SPE-195570-PA