Simultaneous Measurement of Permeability and Effective Porosity in Rock Formations using Flowing Laser Polarized Xenon

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1. Introduction

Effective Porosity is the fractional volume of pore space that permits fluid flow in a rock sample. It is lower than the absolute porosity, which is the fractional volume of pore space in a porous medium, regardless of whether the pores are connected or dead-ended. Effective porosity can also be determined using the ratio of the average fluid velocity (Darcy velocity), to the mean velocity of a tracer flowing through the pore space. Effective porosity is the more important parameter when describing fluid flow under pressure.

Permeability represents the ability of a porous material to transmit fluid. For laminar flow in the low Reynolds number regime (Re < 1), permeability (k) is the constant of proportionality relating the volume rate of fluid flow (Q) to the driving pressure gradient (∇P), through Darcy’s Law (A is the sample’s cross-sectional area and μ is the fluid viscosity):

\[ Q = k \frac{\Delta P}{\mu} \]

Tortuosity describes the ease of fluid flow through a porous medium. It can be thought of as the ratio of the actual distance traveled by a tracer between two points to the direct straight-line distance. Hence, tortuosity is always greater than 1. Tortuosity has been notoriously difficult to measure accurately, and the relation between permeability and tortuosity is a subject of debate in the geophysics community.

We have earlier demonstrated the tortuosity can be determined in reservoir rock samples using thermally-polarized xenon restricted diffusion experiments.

2. Introduction

Direct measurement of effective porosity

It is difficult to determine effective porosity since it depends on the volume of mobile fluid inside a rock, which is not easily measurable. In the literature, absolute porosity is typically used to approximate effective porosity.

Simultaneous measurement of eff. porosity and permeability

Permeability values of rock cores are usually measured with a steady-state gas flow permeameter, governed by Darcy’s Law, while total porosity is approximately determined using a gas pycnometer. Our new method enables simultaneous determination of effective porosity and permeability with gas-phase MRI.

Comparison of measured permeability and tortuosity

Permeability and tortuosity can be measured from samples from the same rock formation.

3. What’s new

The Xe diffusivity in Fontainebleau Sandstone

Xenon time-dependent diffusion coefficient (D(t)) normalized to free diffusion coefficient (D0) in Austin chalk, plotted against diffusion length (L). The asymptotic limit of D(t)/D0 at long lengths scales is equal to the inverse of the tortuosity. From such a plot, the homogeneous length scale (length at which the pore structure becomes homogeneous) can also be read off. For Austin Chalk, the tortuosity is 5.6, and the homogeneous length scale ~ 1 mm.

The procedure for determining the penetration depth is:

- Saturate the spin polarization in the sample
- Wait a delay time \( t \)
- Measure one-dimensional, \(^{129}\text{Xe}\) spin profile along flow direction

Penetration depth measurement

Penetration depth \( z \) (mm) - Sample length \( L \) (m) - Gas velocity \( V \) (m/s) - Absolute porosity \( \phi \) - Pore velocity \( V_p \) - Pore diameter \( D_p \) - Penetration depth \( \xi \)

\[ z = \frac{4 \mu V_p}{\xi \left( V - V_p \right) L} \]

The NMR signal amplitude is proportional to the volume of inter-connected void space, which forms the flow path for the Xe gas. Effective porosity is determined from comparison of signal amplitudes from Xe spins in the rock and that in the diffuser plate (with known void space). One must also calibrate for different \( T_2^* \)’s in rock and the diffuser.

4. Experimental Setup

The apparatus provides an apparatus for simultaneously measuring effective porosity and permeability. Effective porosity is the more important parameter when describing fluid flow under pressure. Effective porosity can also be determined using the ratio of the average fluid velocity (Darcy velocity), to the mean velocity of a tracer flowing through the pore space. Effective porosity is the more important parameter when describing fluid flow under pressure.

5. Pulse Sequences

Penetration depth measurement

PGSTE-bp

6. Method for Effective Porosity Measurement

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7. Xe Profile in Fontainebleau Sandstone

Xe profiles in Fontainebleau Sandstone, acquired using the penetration depth pulse sequence. From each profile, the polarized xenon xenon penetration depth was calculated for the corresponding delay time: 6.46 mm for \( t = 1.0 \text{ s} \), 10.7 mm for \( t = 1.5 \text{ s} \), and 16.5 mm for \( t = 2.0 \text{ s} \). The gas pressure difference across the rock was 0.020 bar.

Correction for polarization loss (dashed lines) was minimal for this sample, but significant for lower permeability rocks.

8. Xe Profile in Austin Chalk

Steady state Xe flow profiles in samples with very low permeability show dramatic reductions in profile amplitude due to Xe depolarization as it travels along the rock. Effective porosity was estimated from the Xe signal amplitude in the rock, after correction for polarization losses in the rock core (black points, above). This correction is based on the Xe \( T_2^* \) pressure dependence throughout the core.

9. Method for Permeability Measurement

Permeability is determined from the gas pressure drop across the rock sample and the resulting gas flow rate. We measure the time-dependence of the penetration depth \( \xi \) of polarized Xe gas in the sample, and derive permeability from an expression assuming viscous laminar flow:

\[ \xi = \frac{4 \mu V_p}{\xi \left( V - V_p \right) L} \]

10. Penetration Depths in Fontainebleau Sandstone

Menard’s method for effective porosity evaluation:

\[ \phi_{\text{eff}} = \frac{Q_{\text{gas}}}{Q_{\text{Xe}}} \]

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11. Tortuosity Measurements

Tortuosity is measured in seated, static samples containing the rock, and a known pressure of Xe and \( O_2 \).

References