COMPARISON OF THE CHANGE OF CAP ROCK PERMEABILITY AND CAPILLARY ENTRY PRESSURE WITH VARYING EFFECTIVE STRESS

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ABSTRACT

The determination of a cap rock formation's capillary entry pressure is of major importance to determine the maximum non-wetting phase pressure that can safely be contained within a CO_2 sequestration reservoir before the non-wetting phase begins to pass through the seal formation and leak out of the reservoir. Traditional experiments rely on unrealistically long experiment time frames, lasting up to several months in length for a single measurement. Alternative approaches have been developed, and there has been a thorough comparison performed between each of the techniques[1]. The conclusion of this comparison work is that a dynamic method is the quickest and most accurate measurement technique considered, where the change in the production rate of the wetting phase from the downstream end of the core sample before and after capillary entry and breakthrough have occurred can be related to the capillary entry and breakthrough pressure.

This work focuses on the changes in permeability of a sample due to changes in the effective stress applied through the difference between confining fluid and pore fluid pressures. These changes in effective stress have been shown to have a significant impact on a sample's permeability with ductile rock samples. The change in sample permeability is then compared to the effect of varying sample effective stress on the capillary entry pressure of the sample. Several experiments were performed on low permeability, high capillary entry pressure samples from an anhydrite mine and a carbonate sample received from Qatar.

INTRODUCTION

In the face of growing concerns about climate changes caused by the continued and increasing output of carbon dioxide on the global scale, geological storage of carbon dioxide in underground aquifers or abandoned hydrocarbon reservoirs continues to gain international attention as a useful way of mitigating these immediate impacts as green technologies continue to develop [2]. The long-term safe and secure storage of carbon dioxide continues to be a driving force behind all policy considerations, and a proper analysis of reservoir cap rock is essential in the initial considerations of a geological

carbon storage project. Several criteria are considered important in understanding the potential sealing characteristics of a potential storage site such as a low permeability, high capillary entry pressure, analysis of pre-existing fractures and faults[3], and previously abandoned wells[4]. Here we will focus on the first two criteria.

Single Phase Permeability

The single phase permeability of a formation yields important information about the potential fluid flow rates in the event of any fluid movement that occurs during carbon storage. Permeability, an intrinsic property of a porous media, is well described by Darcy's law:

$$q = -\frac{Ak}{\mu}\frac{dP}{dx} \quad \textbf{[1]}$$

Where the flow rate of a phase through a rock sample (q) is determined by the fluid's viscosity (μ), the fluid flow cross-sectional area (A), the sample's permeability (k), and the pressure gradient driving flow (dP/dx). It is usually estimated with standard reservoir sample analysis equipment by measuring the fluid flow rate at a constant pressure drop.

Capillary Entry Pressure

The capillary entry pressure of a porous medium is related to the size of the largest unfilled pore throat connected to the injection face of a given core sample by a simplified form of the Young-Laplace Equation:

$$P_C^{entry} = \frac{2\sigma\cos\theta}{r} \quad \textbf{[2]}$$

Where σ is the interfacial tension of the fluids in the system, θ is the contact angle of the interface at the solid surface, and r is the radius of the pore throat.

Experiment Apparatus

The apparatus used to perform both permeability and capillary entry pressure measurements consists of a conventional core holder assembly manufactured in-house out of 316SS with an internal diameter of 19mm and 340mm in length. The system has a maximum working pressure of 400 bar at a temperature of 70°C. The system is only capable of delivering uniform confining pressure to cylindrical cap rock samples, with no physical compression systems commonly found in tri-axial systems. Confining pressure is managed via a HiP manual screw pump.

Small fluid reservoirs machined out of stock 5/8" hex bar with female 1/4" NPT taps are used for the single phase, pure water pressure decay permeability tests. These fluid reservoirs are designed to fit inside the core holder assembly to prevent any temperature fluctuations between the rock sample and the fluid reservoirs from interfering with experiment results. Pore fluid flow and pressure is controlled via a pair of Quizix 5000 series pumps capable of measuring flow rate values down to 18 nL/min. A PID diagram

of the apparatus can be seen in **Figure 1**.

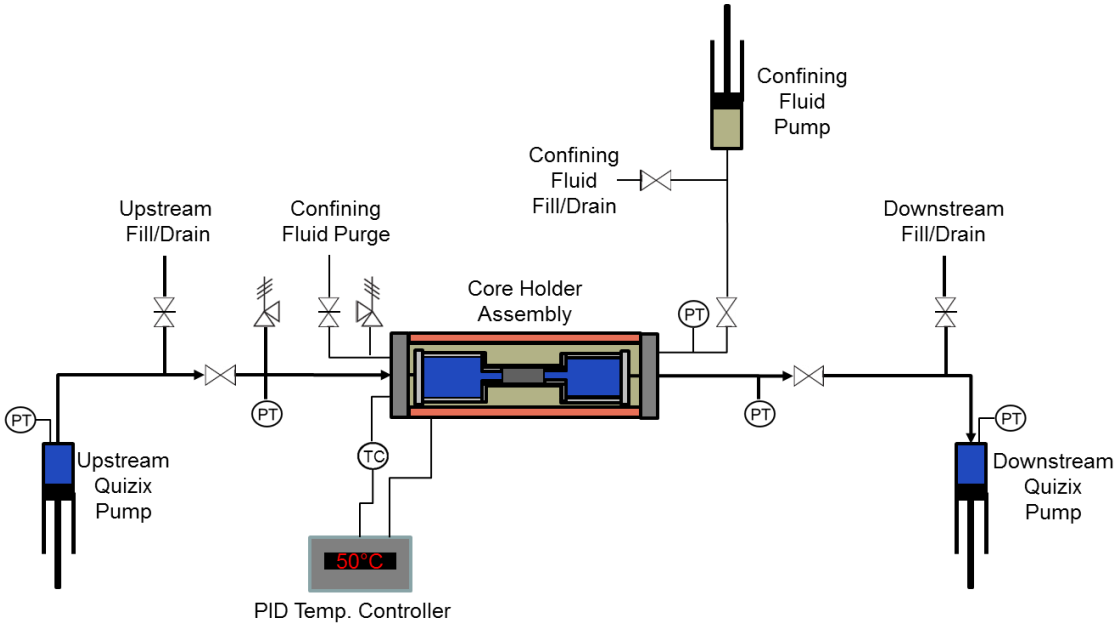

Figure 1: Experiment apparatus process flow diagram

Sample Preparation

Samples were prepared by initially drilling 6mm plugs out of the larger sample provided, using tap water as a drilling fluid. After drilling, samples were dried in an air oven at 65°C for storage in individual sample tubes before fluid flow experiments. Before being loaded into the core holder, samples were vacuum saturated with deionized (DI) water overnight. Samples were then inserted into a 6 mm inner diameter length of Viton tubing and connected to the fluid reservoirs inside the core holder. Confining pressure was initially increased to 7 bar to verify a leak free system.

Single Phase Permeability Procedure

Single phase permeability measurements were performed using the transient pressure decay technique, developed by Brace, et al. [5]. Permeability tests were performed using DI water with an initial upstream pressure of 25 bar and a downstream pressure of 20 bar. The confining pressure was first established at 30 bar, then sequentially increased for each measurement in increasing effective pressure. The effective pressure of the system being given as:

$$P_{eff} = P_{conf} - P_{pore} \quad \textbf{[3]}$$

With the pore pressure being the pressure of the internal fluid of the rock sample, controlled via the Quizix pump. The sample was allowed to equilibrate at the desired effective pressure for several hours, during which fluid continuously flows through the rock sample under the applied pressure gradient. The two fluid reservoirs are then isolated from external pressure control, and the pressure response of the system is

recorded via pressure transducers connected externally via flow lines. The pressure response of the system followed an exponential decay form, slightly modified from a form presented by Brace, et al. [5], and subsequently by Kwon, et al. [6] as:

$$P_{up} - P_{dn} = \Delta P_i e^{-\alpha t} \quad \textbf{[4]}$$

Where,

$$\alpha = \frac{kA}{\mu\beta L}\left(\frac{1}{V_1} + \frac{1}{V_2}\right) \quad \textbf{[5]}$$

The natural logarithm of the pressure difference of the upstream and downstream reservoirs often used to linearize this pressure response and determine the value of α. Following this development of an experimental apparatus capable of accurately measuring low permeability rapidly, the full response of the effect of changes in effective pressure on sample permeability could be determined. These changes of permeability are thought to be the result of the compaction of grains as well as changes in tortuosity. The pressure-permeability response has been demonstrated numerous times on different rock materials [6-10], and was also seen in our experiments on a mine anhydrite sample, **Figure 2.** However, a tight carbonate did not change significantly over the range of effective stress applied as also seen in **Figure 2** (right panel).

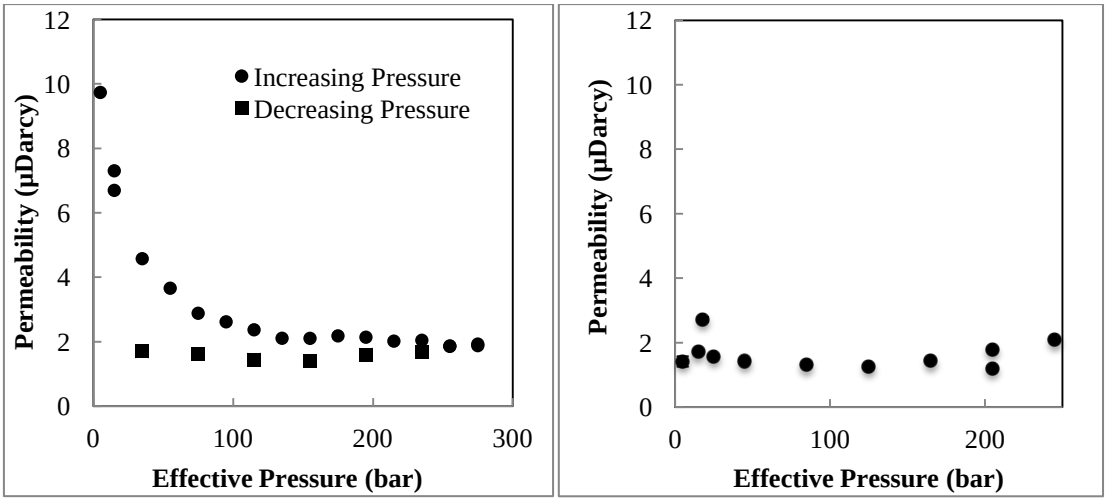

Figure 2: The effect of effective pressure on sample permeability for an anhydrite (left) and a tight carbonate (right). Error bars are included on right plot for standard deviation of multiple experiment tests, but are below resolvable levels at this scale.

Capillary Entry Pressure

The capillary entry/breakthrough pressure was measured experimentally using a fast method outlined by Egermann, et al. [11]. This method is based around a continuous flow system in which a sample, fully saturated with the wetting phase, has a pressure step applied at one face using the non-wetting phase. As the non-wetting phase contacts the saturated rock sample, a distinct change in wetting phase production will occur in the downstream flow of the system. This change in flow rate can then be related to the capillary pressure via:

$$P_c^{entry} = \Delta P_t - \frac{\mu_w L}{kA} q_w^{effective} \quad \textbf{[6]}$$

Experiments were performed on a standardized ceramic sample selected for its uniform pore structure and homogeneity. The wetting and non-wetting fluids used during the capillary entry pressure experiment were DI water and $N_2(g)$. The inlet and outlet pore fluid lines as well as the core sample were kept at 50°C for both fluid saturation and capillary entry pressure measurements. This change in wetting phase production can be seen in **Figure 3** and can then be used to estimate a capillary entry pressure of 30.88±0.47 bar from three experiments.

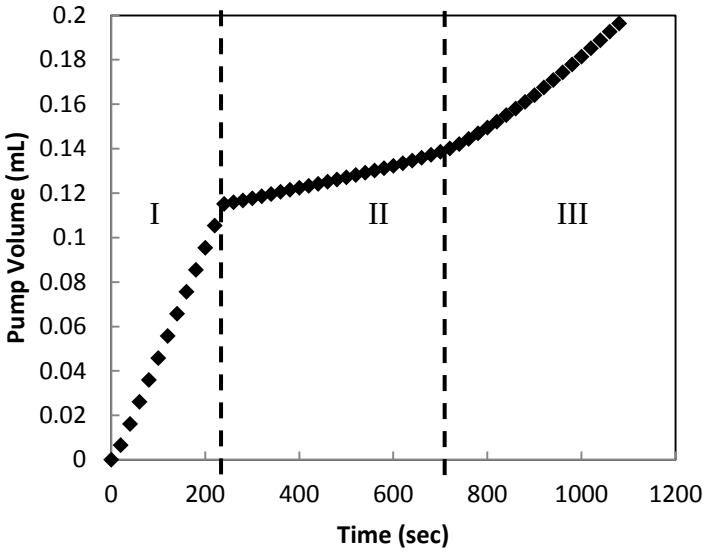

Figure 3: Recorded downstream pump volume showing the wetting phase (water) production rate change upon contact with non-wetting phase (N_2). Region (I) is the wetting, single-phase flow, region (II) is the initial change in wetting phase production during capillary entry/breakthrough, and region (III) is the multiphase mixed wetting/non-wetting phase production.

CONCLUSIONS

An apparatus for the analysis of cap rock permeability and capillary entry pressure has been assembled and successful experiments performed for both measurements. High repeatability was observed for both experiment procedures, and development of

the recently published capillary entry technique showed drastic decreases in experiment times. Future work will be focused on investigating a potential relationship between changes in permeability and capillary entry pressures as a function of system effective stress.

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