Measuring the DC electrokinetic coupling coefficient of porous rock sample in the laboratory : a new apparatus.

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Abstract

Electro-kinetic properties of rocks allow the generation of an electric potential by the flow of an aqueous fluid through a porous media. The electrical potential is called the streaming potential, and the streaming potential coupling coefficient is the ratio of the generated electric potential to the pressure difference that causes the fluid flow. The streaming potential coupling coefficient for rocks is described in the steady-state regime by the well known Helmholtz-Smoluchowski equation, and is supported by a relatively small body of experimental data. However, the electrokinetic coupling coefficient measurement is important for the further development of different area of expertise such as reservoir prospection and monitoring, volcano and earthquake monitoring and the underground sequestration of carbon dioxide. We have designed, constructed and tested a new experimental cell that is capable of measuring the DC streaming potential of consolidated and unconsolidated porous media. The new cell is made from stainless steel, perspex and other engineering polymers. Cylindrical samples of 25.4 mm can be placed in a deformable rubber sleeve and subjected to a radial confining pressure of compressed nitrogen up to 4.5 MPa. Actively degassed aqueous fluids can be flowed by an Agilent 1200 series binary pump (2 to 10 mL/min). A maximum input fluid pressure of 2.5 MPa can be applied, with a maximum exit pressure of 1 MPa to ensure sample saturation is stable and to reduce gas bubbles. The pressures each side of the sample are measured by high stability pressure transducers (Omega PX302-300GV), previously calibrated by a high precision differential pressure transducer Endress and Hauser Deltabar S PMD75. The streaming potentials are measured with Harvard Apparatus LF-1 and LF-2 Ag/AgCl non-polarising miniature electrodes. An axial pressure is applied (1 to 6.5 MPa) to counteract the radial pressure and provide additional axial load with a hydraulic piston. It is our intention to complete the testing of the cell and to use it to measure the electrokinetic properties of porous rocks in the DC regime in order to provide sufficient data to improve the theories and models of DC streaming potentials.

I. Introduction

This poster describes the design, construction and testing of a new apparatus to measure the electro-kinetic streaming coupling coefficient in the DC regime (for a time-constant fluid flow) in a totally controlled environment for cylindrical porous rock samples. Such an apparatus allows us to measure the streaming potential coupling coefficient as a function of fluid flow rate, fluid saturation, fluid composition, temperature, type of rock, fluid pH and fluid conductivity in order to quantify the influence of each of those parameters on the electro-kinetic streaming potential coupling coefficient.

The apparatus is also capable of measuring the complex electrical properties (conductivity, resistivity or permittivity) of the sample as a function of frequency between 1 mHz and 20 MHz. The apparatus is supported by a set of fluid pumps, temperature, pH and pressure transducers linked to a logging computer and a system for keeping the measurement cell at a constant temperature during the measurement.

We have also designed and constructed a separate and significantly different apparatus for measuring the AC streaming potentials on cylindrical samples of disaggregated porous materials such as sand, which will be the subject of a separate poster.

II. The electrokinetic phenomena in porous rock

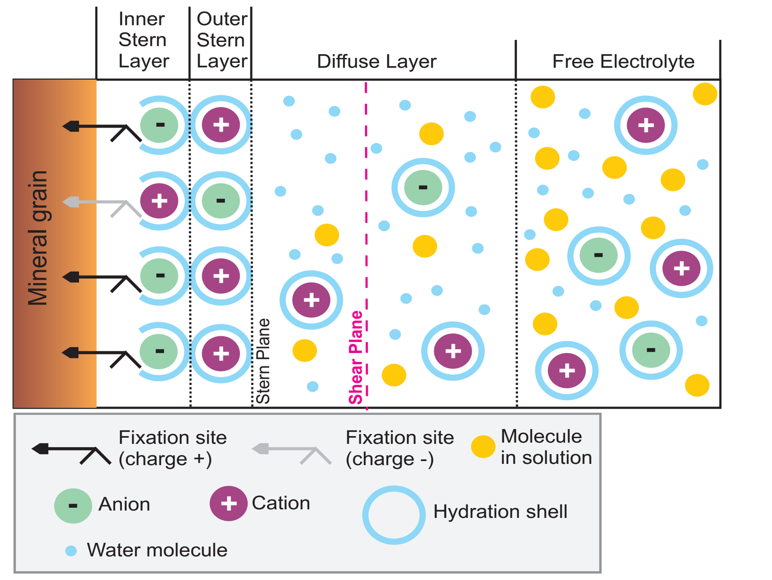


Figure I : Schematic representation of the Electrical Double Layer in a porous rock in which an electrolyte flows.

$$\Delta V = -\frac{\varepsilon\zeta}{\eta\left(\sigma_f + \frac{2\Sigma_s}{\Lambda}\right)}\Delta P \qquad \textbf{(EQ I)}$$

$$C_s = \frac{\Delta V}{\Delta P} \qquad \textbf{(EQ II)}$$

C_s: Coupling coefficient (V/Pa)
P: Fluid pressure (Pa)
V : Electrical potential (V)
σ_f : Fluid conductivity (S/m)
ε : Fluid dielectric constant
ζ : Zeta potential (V)
η : Fluid viscosity (Pa.s)
Σ_s : Specific surface conductance (S)
Λ : Caracteristic lenght (m)

In the case of electro-kinetic phenomena, a fluid flowing through a reservoir rock moves ions in such a way that an electrical potential difference called the streaming potential is created, and an electrical current called the streaming current flows to restore the balance, or vice versa. More precisely, the charge separation induce by a molecular dissymmetry at the rock-fluid interface takes place in what is it called the Electrical Double Layer (EDL) as shown in Figure I (**Revil *et al.* 1999**).

This theory is based on the fact that a fluid layer in contact with a mineral will be depleted in ions, to reach electroneutrality. The EDL is composed of different layers: (1) the solid mineral grain, which has adsorption sites in contact with the fluid, (2) the partially fixed part of the EDL, which is called the Stern layer and includes water molecules and ions. It can be divided into different layers. The inner Stern layer (where the ions are physically adsorbed to the solid surface) and the outer Stern layer, which is composed of hydrated ions that are weakly fixed to the now-hydrated solid surface. (3) the diffuse layer, beginning at a plane called the Stern plane, and which contains ions under the influence of both electrical and thermal forces. (4) The farthest layer from the solid is the free electrolyte where the solution is not influenced by the rock-fluid interface.

When fluid flows through the rock at a constant rate (DC regime), a shear plane develops. The fluid on the matrix side of the shear plane remains stationary, while that on the pore side flows. Because the shear plane generally falls inside the diffuse layer, the flow will tend to displace more anions or cations, depending on the fluid and the rock surface. The flow separates charge and creates a so-called streaming potential, which leads to a secondary streaming current. It should be noted that the electrical potential on the shear plane is called the zeta potential (in volts), and is an extremely important parameter in the characterisation of the electro-kinetic properties of porous media.

This electro-kinetic phenomenon is described by the Helmholtz-Smoluchowski (HS) equation (Equation I) which depends on both the electrical properties of the rock and its fluid properties. The HS equation is inferred from the Poisson law applied to electrical equilibrium at the fluid-surface interface of a capillary tube. It has not been validated for porous materials and rocks even though it is often used with them. From the HS equation, we obtain the expression of the electro-kinetic coupling coefficient (Equation II) which is the parameter we are going to measure in our experiments (**De Groot and Mazur, 1962** ; **Eccles *et al.*, 2005**).

III. DC measurement apparatus

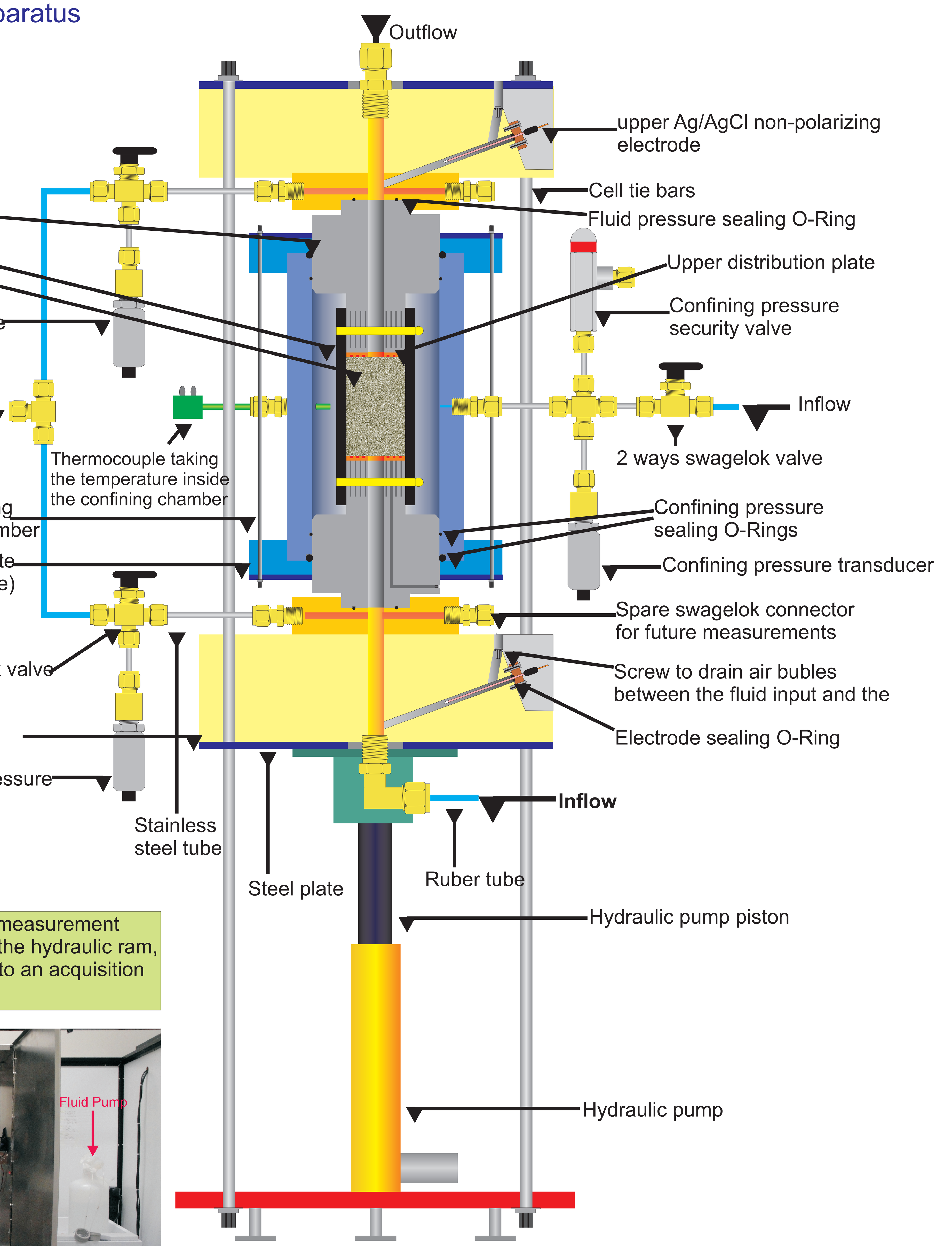
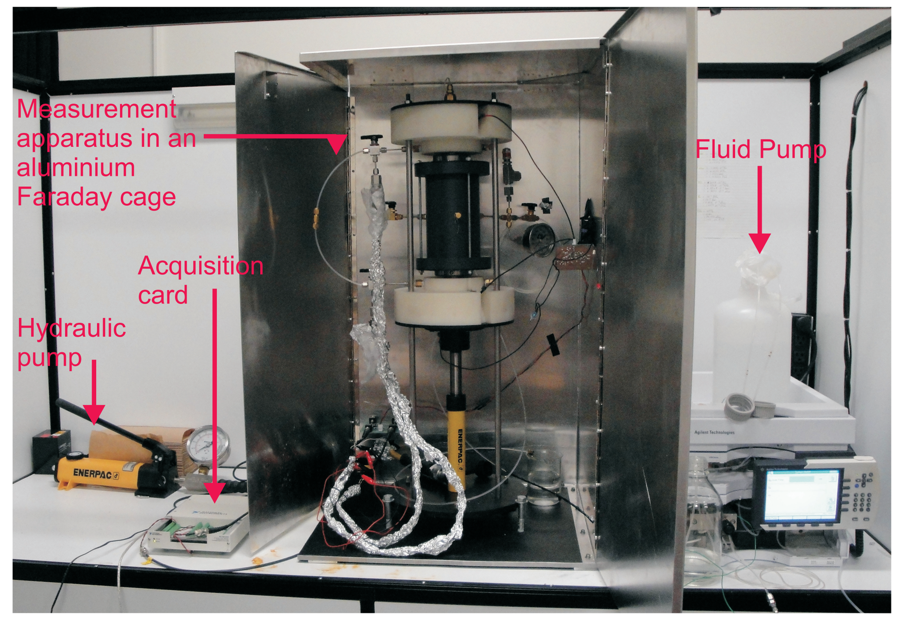


Image of the entire set up: The measurement cell, the quaternary fluid pump, the hydraulic ram, and the acquisition card, linked to an acquisition computer.



Schematic diagram of the apparatus to measure the DC electrokinetic coupling coefficient in the Rock Physics Laboratory, Université Laval. The cylindrical rock sample has a 1 inch diameter.

IV. Developpement, design and construction of the apparatus

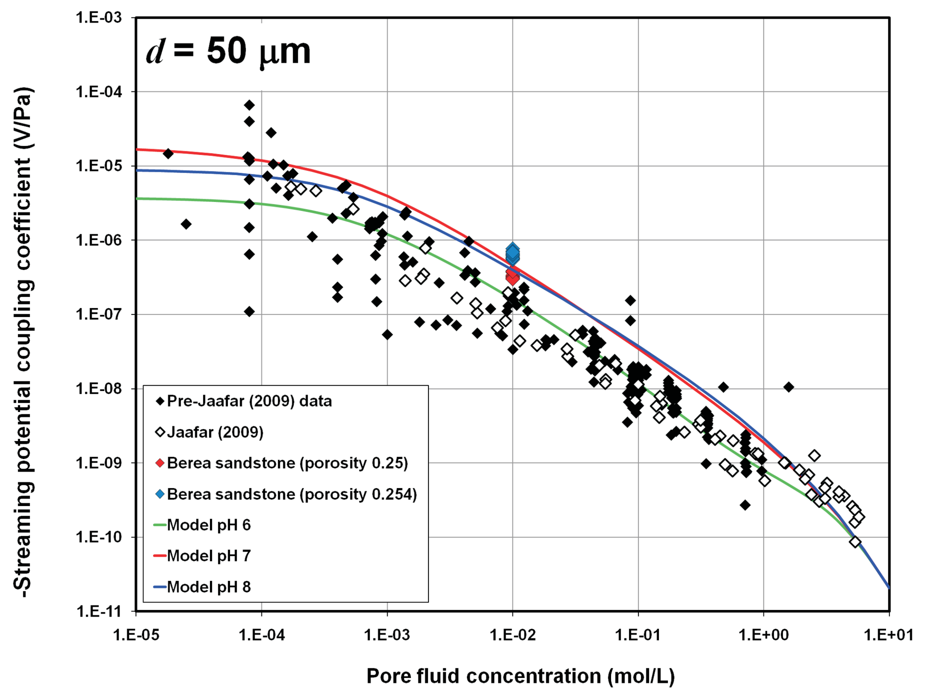
The development phase of our apparatus is constrained by rigorous characteristics. Our apparatus must allows quasi-simultaneous measurements of different parameters (such as fluid pressure difference, electrical potential, pH and fluid conductivity).

The apparatus is set to allow electro-kinetic measurements of a cylindrical sample (1.5 inch diameter, 2.5 inch long). The sample is put into the cell in a rubber jacket and held in place by an axial pressure applied at each end by an hydraulic pump (maximum applied pressure: 1000 psi). The sealing of the fluid path is made by various rubber "O"-rings and a confining pressure applied to the rubber jacket around the sample (100 - 600 psi). The fluid flow is applied through the sample thanks to either an Agilent 1200 series Quaternary Pump or a Pharmacia P100 pump. The fluid flow rate can be varied between 0.02 and 10 mL/min. The Agilent pump is provided with a fluid degasser which degases the fluid in real time. The Agilent pump can mix up to four fluids, pumped at the same time, or can create a gradient to change fluid during an experiment. The Pharmacia pump requires previously degassed fluids but produces a lower level of electrical noise and can be used at lower flow rates than the Agilent.

The electro-kinetic measurements involved quasi-simultaneous measurements of the fluid pressure and the electric potential at each end of the sample (corresponding to the input and the output of the saturating fluid). The pressure variation is measured with two pressure transducers (Omega PX302-300GV) and the electrical potential is measured by two leak-free Ag/AgCl electrodes (Harvard LF1 LeakFree Reference Electrode Ag/AgCl). We have also added a pressure transducer to measure the confining pressure (Omega PX302-1kGV) and a temperature sensor to monitor the temperature variation during the experiment.

We have used a National Instruments *Ni USB-6229* data acquisition card which is linked to a computer and driven by Labview.
Control of the signal to noise ratio is extremely important in this type of measurement. A number of strategies have been used to reduce the noise and increase the quality of the data, including: (i) Ensuring that there are no earth loops. (ii) Ensuring that the fluid reservoir do not act as an antennae. (iii) Designing and constructing buffer amplifiers for the pressure transducers that filter out signals associated with the power supply and above. (iv) Designing and constructing a differential buffer amplifier to measure the streaming potential across the sample while filtering out high frequency noise. (v) Placing the entire instrument within a Faraday cage.

V. Preliminary results



This diagram shows a collection of streaming potential data for sandstones and glass beads together with preliminary data from our apparatus (shown in red and blue points). The two samples were Berea sandstone with a diameter 1.5 inches, length 2.5 inches, porosities of 0.25 and 0.254, permeabilities of about 200 mD and a mean grain size of 50 µm. The fluid was an aqueous solution of 0.01 mol/L NaCl.
The diagram also shows a theoretical model of streaming potential (for three different pH) from **Glover *et al.* (2010)** that includes micro-structural parameters.

VI. Conclusion and developpements

The design, construction and testing of this apparatus has required significant resources and skill. So why construct a brand new apparatus to measure the electro-kinetic properties of rocks? As there are few papers dealing with experimental data of DC streaming potential measurements and the theory explaining it is not sufficiently understood to fully interpret them, we wanted to be able to totally control our experimental environment and parameters. The apparatus we built allows us to change only one parameter at the time (fluid flow rate, fluid saturation, fluid composition, temperature, type of rock, fluid pH, fluid conductivity) and to know exactly by how much it changes. Therefore, we can quantify the influence of each of those parameters on the electro-kinetic properties of the rock we want to study.

Bibliography

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