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Frequency-dependent Streaming Potential of Reservoir Rocks

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Summary

The scientific literature is almost devoid of frequency-dependent electro-kinetic measurements on geological materials. We have designed, constructed and tested an apparatus that allows the measurement of the streaming potential coupling coefficient and zeta potential of unconsolidated reservoir materials. The apparatus uses an electro-magnetic drive and operates in the range 1 Hz to 1 kHz. The sample diameter is 25.4 mm and samples can be up to 150 mm long.

We have made streaming potential coupling coefficient measurements on samples of Ottawa sand as a function of frequency. The results have been analyzed using critically and variably damped second order vibrational mechanics models as well as the theoretical models of Packard (1953) for capillary tubes and Pride (1994) for porous media. Such modelling allows a transition frequency to be calculated, which can in turn be used to calculate the pore radius of the samples. The permeability of the samples can then be obtained using the work of Walker and Glover (2010). In all cases the transition frequencies were in good agreement with those expected from independent measurements of effective pore radius that were derived from laser diffraction and MICP measurements. This indicates that the transition frequency measurements can be used to calculate the effective pore radius of the reservoir material. Fluid permeability predicted from the transition frequency were also in good agreement with those measured on the sand samples.

Introduction

When an ionic fluid flows in a porous medium an electrical potential is created called the streaming potential (Glover and Jackson, 2009). The streaming potential increases linearly with the difference in fluid pressure that drives the fluid flow, providing that flow remains laminar. The steady state streaming potential coupling coefficient is defined as the ratio of the measured streaming potential to the driving fluid pressure difference. If the fluid flow is constant, the streaming potential coupling coefficient is described by the Helmholtz-Smoluchowski equation, which was originally derived for capillary tubes.

There are many uses of electro-kinetic measurements within the oil industry as reviewed by Glover and Jackson (2009). However, many applications of the streaming potential coupling coefficient in rocks involve time-dependent flow, such as seismo-electric exploration. There are a number of models that can be applied to frequency-dependent streaming potentials in rocks, including those which are valid for ideal vibrational systems, a model for capillary tubes (Packard, 1953) and one for generalised porous media (Pride, 1994). These models contain a parameter called the transition frequency which has been associated with the effective pore size of a rock or sand and can be used to predict the fluid permeability of the porous material (Walker and Glover, 2010). Unfortunately there are very few measurements of the frequency-dependent streaming potential available in the literature (only 5 sizes of capillary tube, 2 filters, 1 glass membrane and 1 rock). It is extremely clear that there is a great need for high quality frequency-dependent streaming potential coupling coefficient data on earth materials. Here we describe our apparatus for unconsolidated reservoir material. We also have an apparatus capable of measuring reservoir rocks.

Experimental approach

The frequency-dependent streaming potential measurements on disaggregated materials were made using the instrument shown in Fig. 1. The heart of the apparatus is a thick tube of polycarbonate ①, which is a good electrical insulator, resists corrosion well, is mechanically strong and transparent. The sample ② is held between two perforated polycarbonate disks ③ that are held in place by two stainless steel circlips. The sample is held in a compact form using a spring ④ on the upstream side of the sample to ensure that its dynamic properties have no effect on the frequency-dependent properties of the sample.

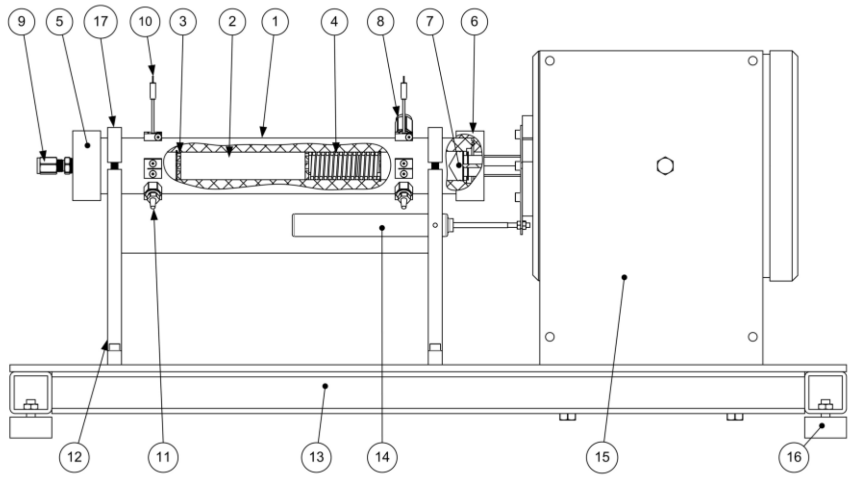

Figure 1: Diagram of the apparatus for making frequency-dependent streaming potential measurement on non-consolidated materials. ① sample tube, ②sand sample, ③ polycarbonate disk, ④ spring, ⑤ output end-cap, ⑥ piston end-cap, ⑦ piston, ⑧ one-way valve (fluid in), ⑨ fluid out, ⑩ Ag/AgCl electrodes, ⑪ dynamic pressure transducers, ⑫⑬⑯⑰ rigid frame and vibration-damped feet, ⑭ LVDT, ⑮ dynamic shaker.

There are four ports at each end of the sample tube, which are arranged radially. Of these, one houses one of two dynamic pressure transducers (⑪,DPX101-250, with a resonant frequency of 500 kHz, a low frequency limit of 0.08 Hz and a maximum frequency of 170 kHz), the second is fitted with a non-return valve ⑧, which allows fluid to enter the sample tube, the third holds one of two Ag/AgCl non-polarizing electrodes ⑩, and the fourth is currently unused. Each end of the tube is closed by an aluminium cap. The cap at the output end ⑤ contains a connector for water to leave the cell, while that at the piston end ⑥ contains a hole for the piston ⑦.

The piston is driven by a VTS100 electro-magnetic shaker ⑮ from Dynamic Solutions. This shaker is capable of a maximum force of 445 N and a peak-to-peak displacement of 2 cm and a frequency range from 2 Hz to 6.5 kHz. Power-line noise was attenuated by 46 dB using a Faraday cage, and custom designed pre-amplification, making it -17 dB with respect to the signal before cycle averaging.

Signal averaging was used to remove the small amounts of line noise that remained, resulting in a final noise level that is -51 dB with respect to the signal. The apparatus was also fitted with a LD610-15 linear variable differential transducer in order to measure the position of the piston to within 1.5 µm. Analysis of the streaming potential and the differential pressure measurement shows the absolute accuracy to be better than ±3% and ±2%, respectively.

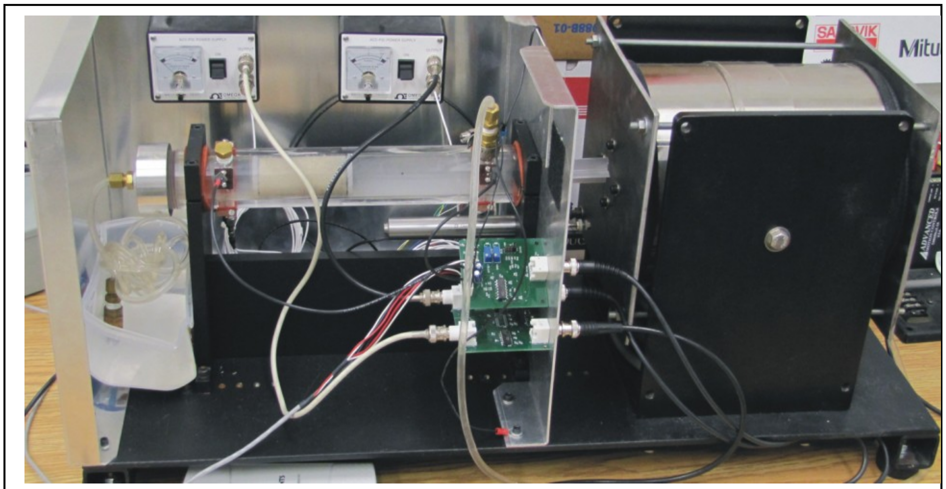

Figure 2: Theworking apparatus with faraday cage and signal processing boards.

Results and Permeability Prediction

Data captured as a function of time (at any frequency) show sinusoidal curves for the piston position and quasi-sinusoidal curves for the pressure difference and the streaming potential. The latter to are in antiphase, which makes the streaming potential coupling coefficient negative as required by theory (because the zeta potential is negative). The measured pressure and potential curves are not perfectly sinusoidal because fluid is pushed through the sample on the forward stroke of the piston but does not flow back during the return stroke due to new fluid flowing into the tube through the one-way valve. However, the ratio of the two, which gives the required streaming potential coupling coefficient is stable and provides high quality data when stacked over a large number of cycles.

Figure 3 shows the streaming potential coupling coefficient of samples of Ottawa sandstone in the range 1 Hz to 1 kHz. The streaming potential coupling coefficient in the low frequency limit C_{so}, which is represented in our data by the point at 5 Hz is C_{so}=0.518 V/MPa, which is consistent with physical modelling using the Glover and Déry (2010) approach and with the database of silica-based earth materials made by Jaafar (2009).

All five frequency-dependent models fit the data very well ($0.967 < R^2 < 0.993$). The vibrational mechanics models give transition frequencies of ω_t=230 Hz and 273 Hz, while the Pride and Walker and Glover models both give 256.58 Hz. These transition frequencies can be used to derive the effective pore size of the sand using the theory in Walker and Glover (2010). The results are given in Figure 4 in the form of a graph where the derived transition frequencies are plotted as a function of the reciprocal effective pore radius squared, with errors, and compared with the dashed lines which represent the theoretical model. The red symbols are our new determinations, while the black symbols represent all the previous data (5 capillary tubes, 2 filters, 1 glass membrane and 1 rock). It is clear that our measurements conform very well to the

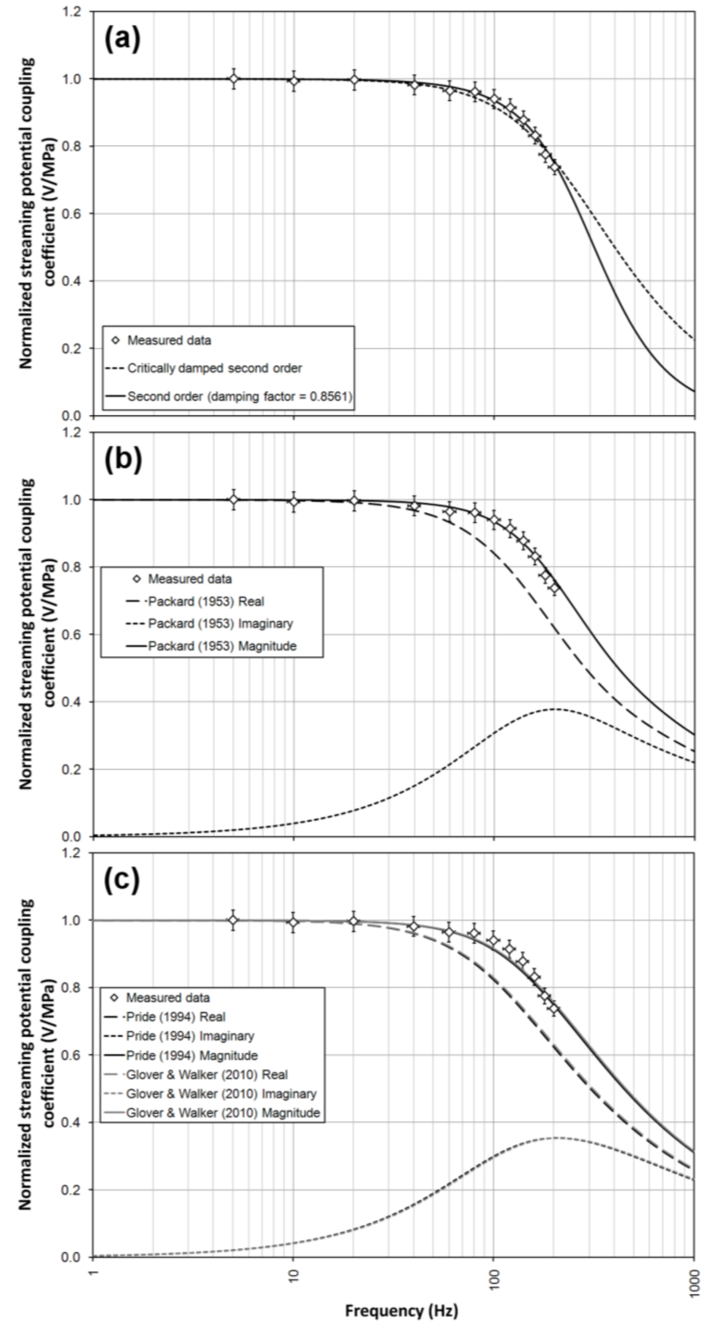

Figure 3. Normalized streaming potential coupling coefficient of Ottawa sand with 0.001 mol/L NaCl, T=24±0.8°C as a function of frequency for (a) critically (ω_t = 230 Hz) and variably (273 Hz) damped vibrational models (Thomson and Dahleh, 1998), (b) the model of Packard (1953), and (c) the model of Pride (1994) and the approximation of that model by Walker and Glover (2010).

theory, predicting an effective pore radius of 67.5 μm compared with 67.6±16.2 μm from independent laser diffraction and MICP measurements.

These transition frequencies and effective pore radii can be used to predict the DC permeability of the sand using the method of Walker and Glover (2010) giving $\kappa_{DC}=[1.156\pm0.021]\times10^{-10}$ m^2 (117.13±2.12 D). Here we have used the mean and range from transition frequencies obtained using the vibrational mechanics models and the Pride model. The predicted permeability agrees extremely well with the measured value of $\kappa_{DC}=[1.19\pm0.06]\times10^{-10}$ m^2 (120.58±6.1 D). We also note that the Pride model provides the best transition frequency for use in permeability prediction (1.135×10^{-10} m^2, 115.01 D).

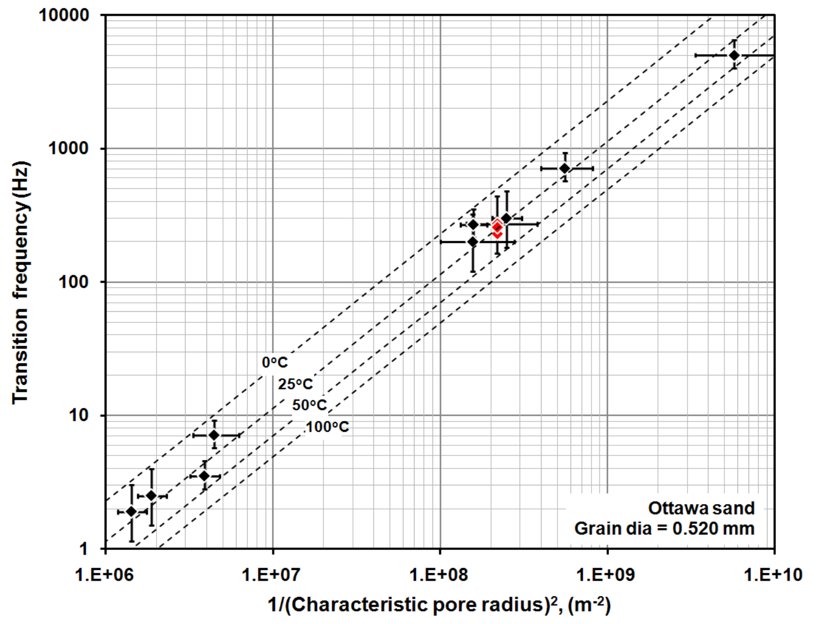

Figure 4: The transition frequency as a function of the inverse square effective pore size for Ottawa sand (red symbols) at T=24±0.8°C. The dashed lines represent the theoretical result (Walker and Glover, 2010) at 4 different temperatures. The black symbols show all previously existing experimental data for capillary tubes, filters frits and rocks (Figure 6 of Walker and Glover (2010)).

Conclusions

Apparatuses for measuring the frequency dependence of the streaming potential coupling coefficient of reservoir rocks have been designed, constructed, tested and used successfully in the laboratory. Samples of Ottawa sand have been measured. The data is consistent with theoretical dynamic models and provides a transition frequency which can be used to reliably predict the effective pore radius and fluid permeability of a reservoir rock. We conclude that streaming potential coupling coefficient measurements as a function of frequency represent an interesting new addition to our armoury for characterising reservoir rocks.

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