

A study on the Variation of Streaming Potential Coefficient with Physical Parameters of Rocks

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Abstract: Streaming potential is induced by the relative motion between a fluid and a solid surface and is directly related to the existence of an electric double layer between the fluid and the solid grain surface. Streaming potential depend not only on the fluid and mineral composition of rocks but also on microstructure parameters of rocks. To investigate the variation of streaming potential with rock parameters including the effects of the variation of the zeta potential due to the difference in mineral compositions between samples, we perform streaming potential measurements on six samples of Berea sandstone saturated with four different NaCl solutions. The results show that the streaming potential coefficient strongly depends on permeability of rocks for low fluid electric conductivity. However, when the fluid conductivity is larger than a certain value, the streaming potential coefficient is completely independent of permeability. This observation is then explained by a theoretical model. Additionally, the results also show that there is no clear correlation between the streaming potential coefficient and porosity, grain density, tortuosity, formation factor, bulk modulus and or shear modulus of rocks.

Keywords: Streaming potential, microstructure parameters, porous media, rocks.

1. Introduction

Streaming potential plays an important role in geophysical applications. For example, the streaming potential is used to map subsurface flow and detect subsurface flow patterns in oil reservoirs [1]. Streaming potential is also used to monitor subsurface flow in geothermal areas and volcanoes [2, 3, 4]. Monitoring of streaming potential anomalies has been proposed as a means of predicting earthquakes [5, 6] and detecting of seepage through water retention structures such as dams, dikes, reservoir floors, and canals [7]. Permeability, porosity, grain density, tortuosity and formation factor are important physical parameters to describe reservoir rocks. A link between streaming potential coefficient (SPC) and some of those parameters has been studied by a number of authors for different types of rocks. For example, permeability dependence of the SPC was studied in publications (e.g., [8, 9]) for sandstone and limestone. Jouniaux et al. also stated that there is no specific correlation between

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the SPC with porosity or formation factor for volcanic rocks [10]. In the work [8 - 10], the authors presumed the zeta potential to be the same for the same family of samples (for example, Fontainebleau sandstone). However, the mineral compositions are somehow different from sample to sample even though they are taken from the same block as shown in [11] and therefore, the zeta potential that depends on the mineral compositions would vary. Additionally, the variation of the SPC with elastic moduli of rocks has not yet reported in literature to the best of our knowledge.

Therefore, we want to study the variation of the SPC with micro-structure parameters and elastic moduli of rocks when taking into account the effects of the difference in the zeta potential between samples for a set of Berea sandstone that has not yet studied. To do so, the ratio of the SPC and zeta potential is used rather than the SPC only. The results have shown that the SPC strongly depends on the permeability and the porosity of the samples for low fluid electrical conductivity. However, when the fluid conductivity is larger than a certain value that is determined by the mineral compositions of the sample, the SPC is completely independent of permeability. The results also show that there is no clear correlation between the SPC and porosity, grain density, tortuosity, formation factor, bulk modulus and or shear modulus of rocks.

This paper includes five sections. Section 2 describes the theoretical background of streaming potential. Section 3 presents the experimental measurement. Section 4 contains the experimental results and discussion. Conclusions are provided in the final section.

2. Theoretical background of streaming potential

The theoretical background of streaming potential in porous media has been already introduced [12]. Therefore, we just briefly introduce the theory of streaming potential in porous media. Streaming potential is induced by the relative motion between the fluid and the rock. Mineral grains forming the rock develop an electric double layer when in contact with an electrolyte. The electric double layer is made up of the Stern layer, where cations are adsorbed on the surface, and the diffuse layer, where the number of counterions exceeds the number of anions (for a detailed description, see [13]). The streaming potential is due to the motion of the diffuse layer induced by a fluid pressure difference along the interface. The zeta potential is defined at the slipping plane or shear plane (i.e., the potential within the double layer at the zero-velocity surface). In a porous medium the electric current density and the fluid flux are coupled, so that the streaming potentials are generated by fluids moving through porous media. The parameter that quantifies this coupling is the streaming potential coefficient (SPC) defined by

$$C_S = \frac{\Delta V}{\Delta P} = \frac{\varepsilon_r \varepsilon_o \zeta}{\eta \sigma_{eff}}, \quad (1)$$

where ΔV is the streaming potential, ΔP is the fluid pressure difference, ε_r is the relative permittivity of the fluid, ε_o is the dielectric permittivity in vacuum, η is the dynamic viscosity of the fluid, σ_{eff} is the effective conductivity, and ζ is the zeta potential. The effective conductivity includes the fluid conductivity and the surface conductivity. The zeta potential is a function of many parameters including mineral composition of porous media, ionic species that are present in the fluid, the pH of fluid, fluid composition, fluid electrical conductivity and temperature etc. [14]. The SPC can also be written as [10]

$$C_S = \frac{\varepsilon_r \varepsilon_o \zeta}{\eta F \sigma_r}, \quad (2)$$

where σ_r is the electrical conductivity of the sample saturated by a fluid with a conductivity of σ_f and F is the formation factor. The electrical conductivity of the sample can possibly include surface conductivity. If the fluid conductivity is much higher than the surface conductivity, the effective conductivity is approximately equal to the fluid conductivity, $\sigma_{eff} = F\sigma_r = \sigma_f$ and the SPC becomes the well-known Helmholtz-Smoluchowski equation:

$$C_s = \frac{\varepsilon_r \varepsilon_o \zeta}{\eta \sigma_f}. \quad (3)$$

3. Experiment

3.1. Materials

Streaming potential measurements have been performed on a set of six Berea sandstone samples that were obtained from Berea Sandstone Petroleum Cores Company in the US. Mineral composition of the sample is silica, alumina, ferric Oxide, ferrous oxide (www.bereasandstonecores.com). Microstructure parameters (porosity, solid density, permeability and formation factor) and elastic moduli of the samples have been reported in the previous article of VNU Journal of Science [15] and re-shown in Table 1. NaCl solutions are used with 4 different concentrations (4.0×10^{-4} M, 2.5×10^{-3} M, 1.0×10^{-2} M, and 5.0×10^{-2} M). All measurements are carried out at room temperature ($22 \pm 1^\circ\text{C}$).

Table 1. Sample ID, parameters of the samples. Symbols k_o (in mD), ϕ (in %) , F (no units), α_o (no units), ρ_s (in kg/m^3), K_p (in GPa) and G_s (in GPa) stand for permeability, porosity, formation factor, tortuosity, solid density, bulk modulus and shear modulus of the rocks, respectively.

Sample ID	k_o	ϕ	F	α_o	ρ_s	K_p [GPa]	G_s [GPa]
1 BereaUS1	120	14.5	19.0	2.8	2602	9.67	6.86
2 BereaUS2	88	15.4	17.2	2.6	2576	11.15	6.46
3 BereaUS3	22	14.8	21.0	3.1	2711	10.09	7.00
4 BereaUS4	236	19.1	14.4	2.7	2617	9.65	4.69
5 BereaUS5	310	20.1	14.5	2.9	2514	10.14	4.67
6 BereaUS6	442	16.5	18.3	3.0	2541	13.75	5.85

3.2. Experimental setup

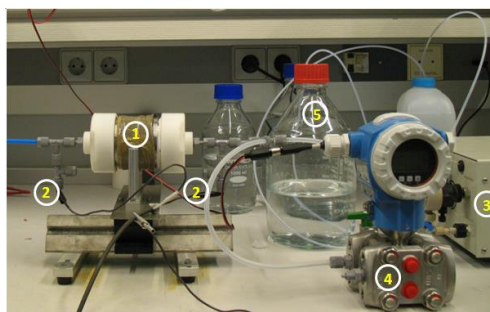


Figure 1. Experimental setup for streaming potential measurements. 1, Core holder; 2, Ag/AgCl electrodes; 3, Pump; 4, Pressure transducer; 5, NaCl solution container.

The experimental setup for the streaming potential measurement is the same as reported in [12] and re-shown in Fig. 1. The core holder contains a cylindrical sample of 55 mm in length and 25 mm in diameter. Each sample is surrounded by a 4 mm thick silicone sleeve inside a conical stainless steel cell and inserted into a stainless steel holder to prevent flow along the interface of the sample. The solution is circulated through the samples until the electrical conductivity and pH of the solution reach a stable value measured by a multimeter (Consort C861). The pH values of equilibrium solutions are in the range 6.0 to 7.5. Electrical potential differences across the samples are measured by a high input impedance multimeter (Keithley Model 2700). Pressure differences across a sample are measured by a high-precision differential pressure transducer (Endress and Hauser Deltabar S PMD75).

3.3. Streaming potential measurement

The way used to collect the SPC is similar to that described in [12] where Ag/AgCl electrodes are used to avoid polarization. In our measurements, Ag/AgCl wire electrodes are bought from a manufacturer of A-M systems. Fig. 2 shows an example of streaming potential as a function of pressure difference at concentration of $5.0 \times 10^{-2} \text{ M}$. Therefore, the SPC is obtained as the slope of the straight line. Three measurements are performed for all samples with each solution to find the average value of the SPC.

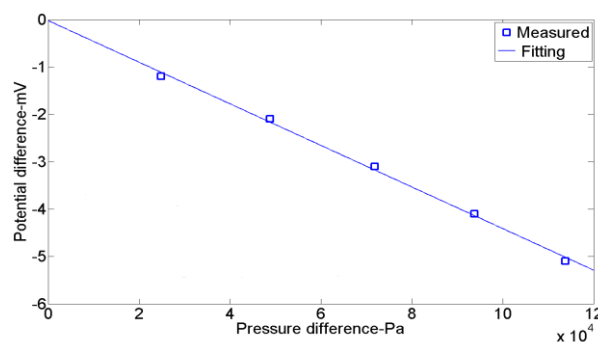


Figure 2. Streaming potential as a function of pressure difference for BereaUS5 at a concentration of $5.0 \times 10^{-2} \text{ M}$.

4. Results and discussion

The SPC for all samples at different electrolyte concentrations is shown in Table 2 (that has been reported in [16]). The electrical conductivity of the sample saturated by the solution is obtained from the resistance measured by an impedance analyzer (Hioki IM3570) with the knowledge of the geometry of the sample (the length, the diameter). Based on the measured SPC with the knowledge of electrical conductivity of the samples (σ_r), formation factor, viscosity and dielectric constant, the zeta potential is deduced from equation 2. The zeta potential at different electrolyte concentrations is also shown in Table 2. The result shows that for a given porous sample the zeta potential in magnitude increase with decreasing electrolyte concentration as expected [17].

Based on Table 1 and Table 2, the dependence of the SPC on permeability for a set of Berea samples at different concentrations is shown in Fig. 3. At first sight, it seems that no specific correlation between the SPC and permeability is observed, especially at low concentrations. This is because that the zeta potential is not the same for different samples.

Table 2. The streaming potential coefficient (in mV/bar) and the zeta potential for different electrolyte concentrations.

Sample ID	4.0×10^{-4} M		2.5×10^{-3} M		1.0×10^{-2} M		5.0×10^{-2} M	
	C_s	ζ	C_s	ζ	C_s	ζ	C_s	ζ
1 BereaUS1	-65.0	-27.7	-22.0	-20	-9.7	-17.7	-2.8	-15.6
2 BereaUS2	-72.0	-46.2	-32.5	-33.3	-12.0	-25.7	-3.3	-21.2
3 BereaUS3	-44.0	-33.3	-22.5	-30.4	-9.8	-25.1	-2.9	-20.8
4 BereaUS4	-130.0	-42.7	-45.0	-32.7	-14	-28.1	-4.1	-24.2
5 BereaUS5	-155.0	-43.2	-49.0	-35.5	-17	-30.7	-4.4	-27.5
6 BereaUS6	-75.0	-23.0	-25.0	-19.1	-6.4	-12.2	-2.0	-10.4

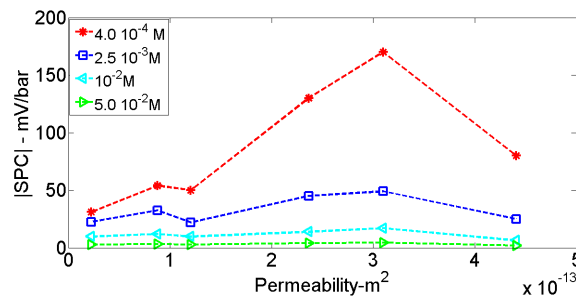


Figure 3. SPC versus permeability for Berea samples at different concentrations. The dash lines are the ones connecting the experimental points.

To see how the permeability itself affects the SPC without influence of the zeta potential, the ratio of the SPC and the zeta potential is plotted against permeability at different electrolyte concentrations (Fig. 4). It is shown that the ratio of the SPC and zeta potential drastically increases with increasing permeability at low concentration solutions and does not depend on permeability at high concentration solutions starting from a concentration of 5.0×10^{-2} M. This permeability dependence may be a consequence of a change of the effective conductivity σ_{eff} with permeability [8, 9, 10] at low fluid electric conductivity σ_f . The behavior observed in Fig. 4 (symbols) can be theoretically explained by the effect of surface conductivity. Effective conductivity σ_{eff} is given by

$$\sigma_{\text{eff}} = \sigma_f + \frac{2\Sigma_s}{\Lambda}, \quad (4)$$

where Σ_s is the surface conductance and Λ is a characteristic length scale that describes the size of the pore network [18].

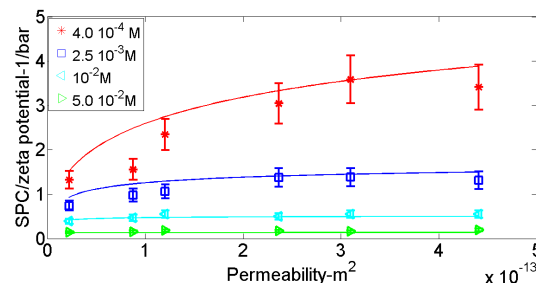


Figure 4. The ratio of SPC and zeta potential versus permeability for Berea samples at different electrolyte concentrations. The solid lines are from the theoretical model. The points are experimental data.

According to [19], the permeability of the porous medium k_0 is related to the characteristic length scale by

$$k_0 = \frac{\Lambda^2}{aF}, \quad (5)$$

where a is a parameter thought to be constant and equal to 8/3 for a wide range of porous media, including reservoir rock.

Equation (4) can be rewritten as

$$\sigma_{eff} = \sigma_f + \frac{2\Sigma_s}{\sqrt{aFk_0}}, \quad (6)$$

And equation (1) can be rewritten as

$$\frac{C_s}{\zeta} = \frac{\varepsilon_r \varepsilon_o \zeta}{\eta \left\{ \sigma_f + \frac{2\Sigma_s}{\sqrt{aFk_0}} \right\}}, \quad (7)$$

At salinity higher than 10^{-3} M, the specific surface conductance almost does not vary with salinity [20]. Therefore, the surface conductance is assumed to be constant over the studied range of electrolyte concentration. As reported in [16], the surface conductance is found to be 40×10^{-9} S for Berea sandstone.

From equations (6) and (7), it is seen that both permeability (k_0) and formation factor (F) of rocks simultaneously influence the SPC via the product Fk_0 . For the Berea sandstone rocks, the formation factor varies from 14.4 to 21 (about 45%) but the permeability varies from 22 mD to 442 mD (about 2000%). Therefore, the formation factor can be approximately considered to be constant in the range of the permeability and taken as a constant averaged over all the samples (approximately 17.4).

The value of ε_r is normally taken to be 80 for an aqueous solution at 25°C. In this work, the variation of the relative electric permittivity as a function of fluid electrolyte concentration and temperature is taken into account by using an empirical equation [21]:

$$\varepsilon_r(T, C_f) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + c_1 C_f + c_2 C_f^2 + c_3 C_f^3, \quad (8)$$

where $a_0 = 295.68$, $a_1 = -1.2283 \text{ K}^{-1}$, $a_2 = 2.0941 \times 10^{-3} \text{ K}^{-2}$, $a_3 = -1.41 \times 10^{-6} \text{ K}^{-3}$, $c_1 = -13 \text{ Lmol}^{-1}$, $c_2 = 1.065 \text{ (Lmol}^{-1})^2$, $c_3 = -0.03006 \text{ (Lmol}^{-1})^3$, T is in Kelvin, the equation is valid in the range from 273 K to 373 K, and C_f is the electrolyte concentration in mol/L.

The variation of the viscosity of the fluid against electrolyte concentration and temperature was mentioned in [22]

$$\eta(T, C_f) = e_1 + e_2 \exp(\alpha_1 T) + e_3 \exp(\alpha_2 C_f) + e_4 \exp(\alpha_3 T + \alpha_4 C_f), \quad (9)$$

where $e_1 = 4.95166 \times 10^{-5} \text{ Pa.s}$, $e_2 = 6.034658 \times 10^{-4} \text{ Pa.s}$, $e_3 = 9.703832 \times 10^{-4} \text{ Pa.s}$, $e_4 = 1.025107 \times 10^{-4} \text{ Pa.s}$, $\alpha_1 = -0.06653081/^\circ\text{C}$, $\alpha_2 = -0.1447269/\text{molar}$, $\alpha_3 = -0.02062455/^\circ\text{C}$, $\alpha_4 = -0.1301095/\text{molar}$, T is in $^\circ\text{C}$.

By putting the surface conductance Σ_s , the corresponding fluid electric conductivities, the viscosity, and the relative electric permittivity at different electrolyte concentrations (at room temperature-22°C) into equation (7), the ratio of the SPC and the zeta potential versus permeability for a set of Berea sandstone is theoretically plotted in Fig. 4 at different electrolyte concentrations (solid lines). It is shown that the SPC strongly depends on permeability of rocks for low fluid electric

conductivity. When the fluid electric conductivity is larger than 0.50 S/m, the SPC is completely independent of permeability.

The value of electrical conductivity of 0.50 S/m above which the SPC becomes independent of permeability is generally not applicable thresholds for all rock types and brine composition. It is determined from the condition for which the surface conductivity that partially depends on the permeability is much smaller than the fluid electric conductivity.

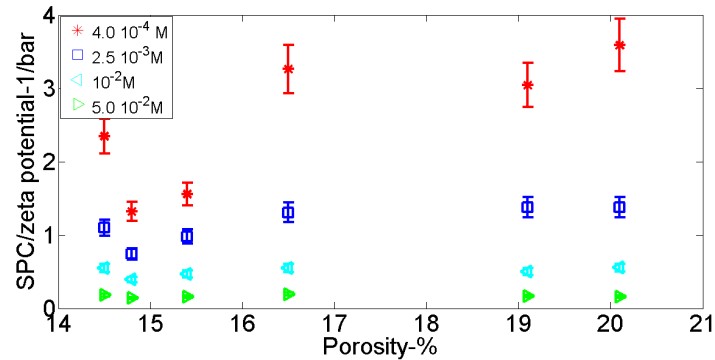


Figure 5. The ratio of SPC and zeta potential versus porosity at different electrolyte concentrations.

Based on Table 1 and Table 2, the variation of the SPC with porosity, grain density, tortuosity, formation factor, bulk modulus and shear modulus is shown in Figs. 5, 6, 7, 8, 9 and 10, respectively. The results in Fig. 5 and Fig. 6 show that there is no specific correlation between the SPC and porosity or formation factor. The observations are the same as what is stated for volcanic rocks [10]. It is also shown that no clear dependence of the SPC on grain density, tortuosity, bulk modulus or shear modulus is observed. The reason is that the SPC only depends on (1) the zeta potential that is determined by mineral composition of rocks, ionic species in the fluid, the fluid pH, fluid electrical conductivity and temperature; (2) the relative permittivity of the fluid, (3) the viscosity of the fluid and (4) the effective conductivity that is partially determined by permeability. Therefore, the parameters of porosity, grain density, tortuosity, formation factor, bulk modulus and shear modulus may influence the mass, the length of the capillaries (due to tortuosity), the speed of acoustic waves propagating in rocks, etc. but they do not influence the SPC.

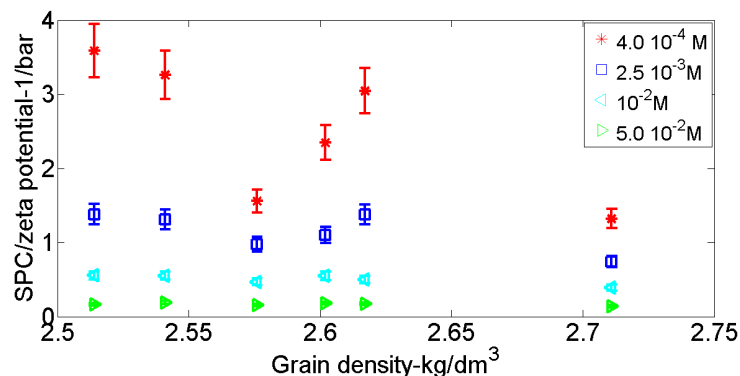


Figure 6. The ratio of SPC and zeta potential versus grain density at different electrolyte concentrations.

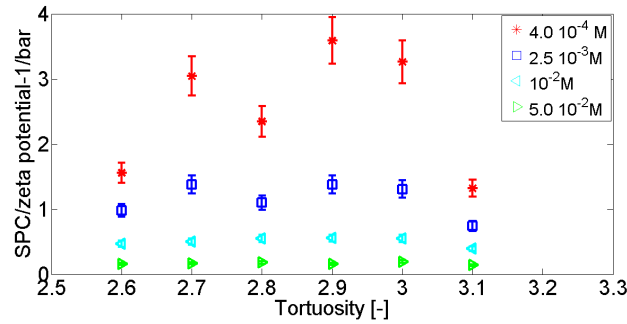


Figure 7. The ratio of SPC and zeta potential versus tortuosity at different electrolyte concentrations.

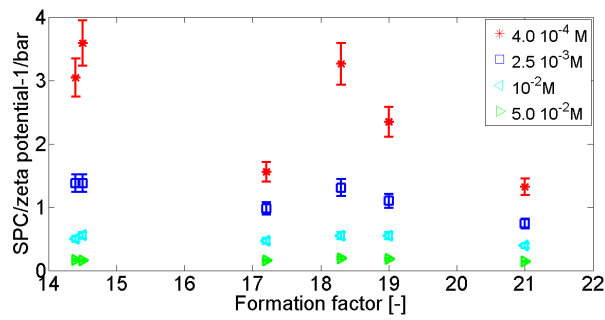


Figure 8. The ratio of SPC and zeta potential versus formation factor at different electrolyte concentrations.

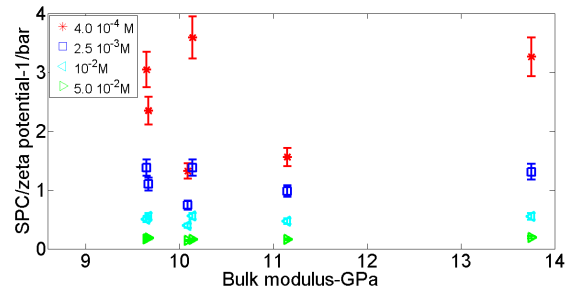


Figure 9. The ratio of SPC and zeta potential versus bulk modulus at different electrolyte concentrations.

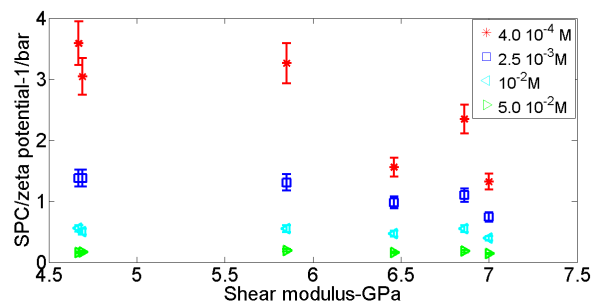


Figure 10. The ratio of SPC and zeta potential versus shear modulus at different electrolyte concentrations.

5. Conclusions

Measurements of the SPC on a set of Berea sandstone of different permeability have clearly shown that the SPC strongly depends on permeability of porous media for low fluid electric conductivity only if the variation of zeta potential between the samples is taken into account. We use a theoretical model to explain the relationship between the SPC and permeability. In the model, we take into account the variation of zeta potential from sample to sample. Consequently, the modeled results are in good agreement with the experimental data. Additionally, the results show that there is no clear correlation between the SPC and porosity, grain density, tortuosity, formation factor, bulk modulus and or modulus of rocks. The reason is that those parameters do not influence the properties of the solid-liquid interface of rocks as well as the surface conductivity of rocks. Therefore, they do not affect the streaming potential coefficient.

Acknowledgments

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