

MEASUREMENT OF STREAMING POTENTIAL COUPLING COEFFICIENT ON CARBONATE ROCKS FOR DOWNHOLE MONITORING IN SMART WELLS

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Abstract. Smart wells refer to wells containing downhole sensors and inflow control valves (ICV) mounted on the production tubing. These wells allow the operator to record fluid flow rates, temperature and pressure incessantly. Recently, streaming potential measurement in smart wells has been proposed to monitor water encroachment. However, there are still significant uncertainties associated with the interpretation of the measurements, particularly concerning the streaming potential coupling coefficient. This is a key petrophysical property that dictates the magnitude of the streaming potential for a given fluid potential. Streaming potential magnitude is basically related to the fluid flow rate, fluid properties (particularly salinity), and the rock matrix properties. The coupling coefficient has been measured experimentally in sandstone cores saturated with different brine salinities, but very little works have been published on carbonate rocks. The huge number of carbonate reservoirs around the world suggests that measurement of streaming potential in carbonate rocks is also important. In this study, we present value of streaming potential coupling coefficient in a carbonate rock saturated with various salinities of brine. As we expected, streaming potential in such core is small but measurable and higher salinity gives smaller streaming potential coupling coefficient. Consistent results are obtained using specially designed electrodes and paired pumping experiments to eliminate spurious electrical potentials. We noticed that streaming potential coupling coefficient in carbonate rock is lower compared to the one in sandstone cores saturated with the same salinity of brine. This observation could be explained by comparing the difference in point of zero charges (pzc) between those two types of rock. Qualitatively, the result suggests that measurements of streaming potential could be applied for monitoring water encroachment in carbonate reservoirs, in the same manner it is applied for sandstones reservoirs.

Keywords: Streaming potential; electrokinetics; downhole monitoring; intelligent wells; water encroachment; produced water control; carbonate rocks

Abstrak. Telaga pintar merujuk kepada telaga yang mengandungi pengesan dasar lubang dan injap kawalan aliran masuk (ICV) yang dipasang pada tiub pengeluaran. Telaga ini membenarkan pengendali untuk merekodkan kadar aliran bendalir, suhu dan tekanan yang berterusan semasa

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pengeluaran. Baru-baru ini, pengukuran keupayaan aliran dalam telaga pintar telah dicadangkan untuk memantau pencerobohan air. Walau bagaimanapun, masih terdapat ketidakpastian yang signifikan yang dikaitkan dengan tafsiran ukuran, terutamanya mengenai pekali gandingan keupayaan aliran. Ini adalah ciri petrofizik utama yang menentukan magnitud keupayaan aliran untuk potensi bendalir yang tertentu. Magnitud keupayaan aliran pada asasnya berkait dengan kadar aliran bendalir, sifat-sifat bendalir (khususnya kemasinan), dan sifat-sifat matriks batuan. Pekali gandingan telah diukur secara uji kaji dalam teras batu pasir yang tepu dengan kemasinan air garam yang berbeza, tetapi sangat sedikit hasil uji kaji telah diterbitkan bagi batuan karbonat. Bilangan reservoir karbonat yang besar di seluruh dunia menyorotkan bahawa pengukuran keupayaan aliran dalam batuan karbonat juga penting. Dalam kajian ini, kami kemukakan nilai pekali gandingan keupayaan aliran bagi batu karbonat yang tepu dengan berbagai kemasinan air garam. Seperti yang kami jangkakan, keupayaan aliran bagi teras itu adalah kecil tetapi masih boleh diukur, dan kemasinan yang lebih tinggi memberikan pekali gandingan keupayaan aliran yang lebih kecil. Keputusan yang diperolehi adalah konsisten hasil penggunaan elektrod yang direka khas dan uji kaji pam berpasangan untuk menghapuskan potensi elektrik palsu. Kami mendapati bahawa pekali gandingan keupayaan aliran di dalam batu karbonat adalah lebih rendah berbanding dengan yang ada di teras batu pasir yang ditepukan dengan kemasinan air garam yang sama. Pemerhatian ini boleh dijelaskan dengan membandingkan perbezaan titik caj sifar (pzc) di antara kedua-dua jenis batu. Secara kualitatif, hasil uji kaji menunjukkan bahawa pengukuran keupayaan aliran boleh digunakan untuk memantau pencerobohan air di dalam reservoir karbonat, sama seperti ia digunakan untuk reservoir batu pasir.

Kata kunci: Keupayaan aliran; elektrokinetik; pemantauan bawah telaga; telaga pintar; air pencerobohan; kawalan pengeluaran air; batu karbonat

1.0 INTRODUCTION

One of the challenges in reservoir management is to reduce uncertainty in reservoir description. For this purpose, permanently installed downhole sensors are increasingly being deployed to provide reservoir data during production, and to facilitate the decision making [1]. Furthermore, if the well is equipped with inflow control valves, a feedback loop between measurement and control could be developed to optimize production [2]. Wells equipped with downhole sensors and control valves are often referred to as ‘intelligent’ or ‘smart’ [3]. In general, it has been recognized that those wells have the potential to significantly enhance production.

Streaming potentials occur in porous media when there is electrical double layer present at solid-fluid interfaces [4]. Charge distribution near the interface allows the solid surfaces to become electrically charged, in which case a diffuse layer in the adjacent fluid is formed which contains an excess of countercharge. In the case of more than one fluid phase present in the pore space, additional double

layers may form at fluid-fluid interfaces [4]. Flow of the fluid tangential to the interface will transport some of the excess charge within the diffuse layer, giving rise to a streaming current. Accumulation of charge associated with divergence of the streaming current density establishes an electrical potential, known as the streaming potential. Measurements of streaming potential, using electrodes permanently installed downhole, have recently been proposed as a promising new reservoir monitoring technology [5]. However, there are still significant uncertainties associated with the interpretation of the measurements, particularly concerning the magnitude and sign of the streaming potential coupling coefficient [6]. The coupling coefficient (C) is a key petrophysical property which relates the fluid (∇P) and electrical (∇V) potential gradients when the total current density is zero [7]

$$C = \left. \frac{\nabla V}{\nabla P} \right]_{j=0} \quad (1)$$

and which can be used to predict the magnitude of the streaming potential generated by a given fluid potential. The coupling coefficient is a function of a few parameters including; the electrical conductivity of the brine (σ_w) and brine-saturated rock (σ_m), the permittivity (ϵ_w) and viscosity (μ_w) of the brine, and the zeta potential (ζ), which is the microscopic electrical potential associated with the excess charge in the double layer. It can be expressed as [4]

$$C = \frac{\epsilon_w \zeta F}{\mu_w \sigma_w F_o} \quad (2)$$

where F is the formation factor ($=\sigma_w / \sigma_m$) and F_o is the intrinsic formation factor, measured when surface conductivity is negligible (typically with a very saline brine).

Values of the streaming potential coupling coefficient measured for sandstones have been presented in literatures, but until recently they were obtained only from samples saturated with relatively low salinity (less than seawater) NaCl or KCl brines [5]. Formation and injected brine in hydrocarbon reservoirs is typically more saline than this. Only Jaafar *et al.* [8] have measured the streaming potential coupling coefficient in sandstones saturated with brine of higher salinity (up to the NaCl saturation limit of c. 5.5 M at laboratory conditions). They investigated only

two samples of the same sandstone, saturated with simple NaCl brines. The coupling coefficient, however, may vary with rock texture or mineralogy.

The aim of this paper is to investigate the effect of brine salinity on the streaming potential coupling coefficient in carbonate rocks. We present the first measured values of the coupling coefficient in a carbonate sample saturated with a range of brine salinities relevant to oilfield conditions. Consistent results are obtained using specially designed electrodes and paired pumping experiments to eliminate spurious electrical potentials. Streaming potential measurements have been proposed as a method to characterize flow in fractures adjacent to a borehole, and the pressure response of a reservoir during transient production tests [9]. However, in this paper we focus on the use of streaming potential measurements to detect and characterize water encroaching on a well during production. Numerical studies [5] suggest that measured signals will be resolvable above background noise in most hydrocarbon reservoirs, and that water encroaching on a production well causes changes in the streaming potential at the well while the water is several 10's to 100's of meters away. This contrasts with most other downhole monitoring techniques, which sample only the region immediately adjacent to the wellbore. These findings raise the novel prospect of an oilfield in which the wells can detect the approach of water and respond appropriately. Such wells offer enormous potential economic and environmental benefits, particularly in fields which are difficult to access or dangerous to operate [5]. However, Jackson *et al.* [5] conducted their study using sandstones model. Whether the same approach could be applied to carbonate reservoirs will largely depend on the values of the streaming potential coupling coefficient for carbonates.

2.0 MATERIALS AND METHODS

Brine is pumped using a syringe pump and synthetic oil as a hydraulic fluid, at constant rate through the core samples, which are held within a pressure vessel with a confining pressure of 500 kPa (Fig. 1). The initial and outlet pore-fluid pressure is atmospheric. The syringe pump maintains constant rate to high accuracy, and flow can be directed in either direction through the samples. Using the synthetic oil as a hydraulic fluid allows air bubbles in the brine to be captured at the top of the oil layer in each reservoir, eliminates the flow of electrical current

through the brine along a path parallel to the core sample, and reduces corrosion of the pump. The pressure difference across the core sample is measured using a pair of pressure transducers, and the voltage across the sample is measured using two pairs of non-polarizing Ag/AgCl electrodes.

One pair of electrodes is positioned out of the flow path, to eliminate spurious potential drift and electrode flow effects [10]. These external electrodes are located in a brine reservoir which is in electrical contact with the flowing brine via a low permeability plug (Fig. 1b), and provide voltage measurements which are stable to 10's μV . The other pair of electrodes are located on each face of the core sample, inside the pressure vessel (Fig. 1c). These internal electrodes, which are in the path of the flow, are significantly less stable than the external electrodes, and record flow-rate dependent voltages at high salinity which are independent of pumping direction, and which can mask the streaming potential signal. However, they can be used to measure the conductivity of the saturated core. The set-up uses a stainless steel pressure vessel as the core holder and nitrogen as the confining fluid (Fig. 1a). The steel vessel is electrically isolated from the core sample by a rubber sleeve and plastic caps at both ends, and provides an earthed Faraday enclosure to eliminate spurious external currents.

The core sample used in the experiments is described in Table 1. It was obtained from a carbonate formation in Sarawak.

To measure the streaming potential, brine of the chosen composition is pumped through the core sample at a number of constant flow rates, until stabilized pressure and voltage differences are recorded across the sample (e.g. Fig. 2). Brine is pumped at the same rate in both directions through the sample to eliminate electrode polarization effects, which are apparent if the coupling coefficient interpreted from the measurements depends upon the flow direction [11]. The conductivity of the brine in each reservoir is measured at regular intervals to ensure it remains constant and equal; this is necessary to eliminate electrochemical potentials. The pH of the brine is measured before and after each experiment, and in the measurements reported here, varied between 6 and 8 pH units.

Table 3.1 Properties of the core sample

Length (cm)	Diameter (cm)	Grain Volume (cm ³)	Bulk Volume (cm ³)	Pore Volume (cm ³)	Porosity (%)	Permeability (mD)
3.80	3.79	36.57	42.94	6.37	14.83	66

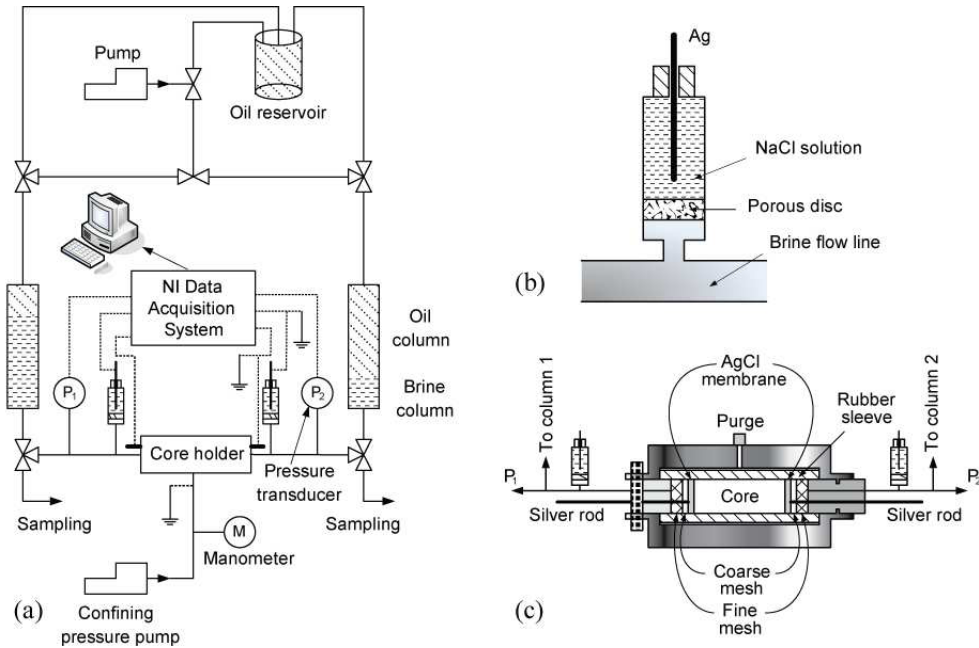


Figure 1 Experimental set-up for measuring the streaming potential coupling coefficient. (a) Brine is pumped through a pressurized core holder located between two brine reservoirs, driven by synthetic oil as a hydraulic fluid which allows gas bubbles to be isolated and prevents electrical current flow parallel to the core. Brine can be pumped in either direction through the core holder by adjusting the valves on the flowlines; (b) The external electrodes are located out of the flow path, in an NaCl solution which is more saline than the flowing brine. The electrodes are in electrical contact with the flowing brine via a low permeability porous disc; (c) Cross-section through the core holder. The internal electrodes are located on each face of the sample, and can be used to measure streaming potential or resistivity

Interpretation of the results follows from the observation that at steady-state, the streaming current induced by the flow is balanced by a conduction current to

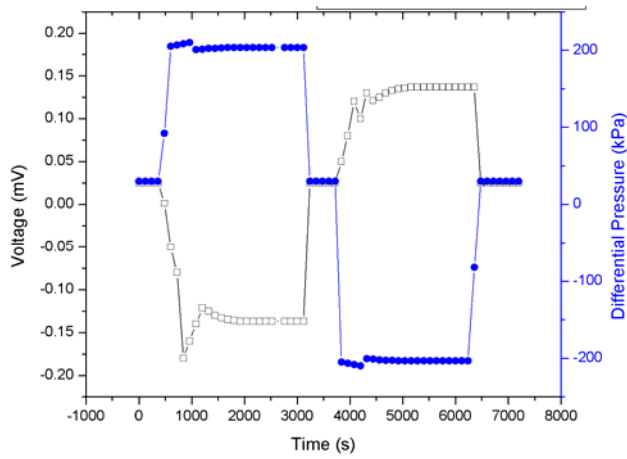
maintain overall electrical neutrality. Moreover, the currents follow approximately the same 1-D path along the core samples, so Equation (1) can be written

$$C = \frac{\Delta V}{\Delta P} \quad (3)$$

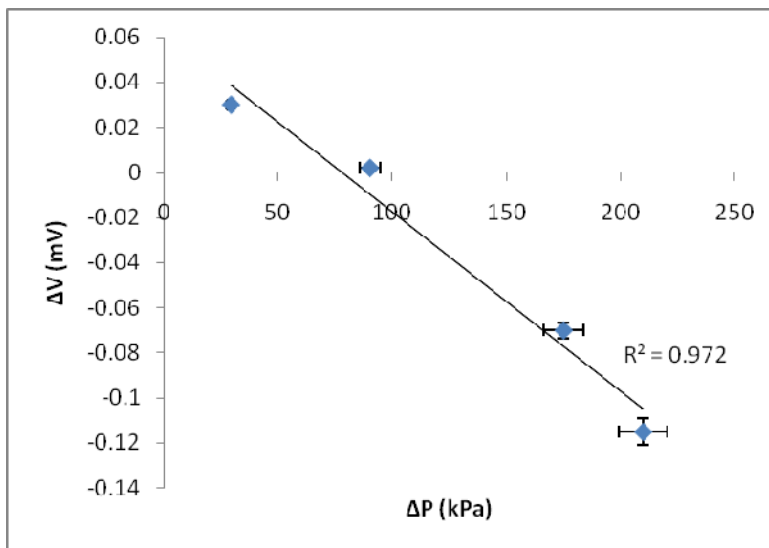
where ΔP is the pressure difference and ΔV the voltage across the core sample. A linear regression through the stabilized pressure and voltage differences yields the streaming potential coupling coefficient (e.g. Fig. 2b).

3.0 RESULTS AND DISCUSSION

Fig. 2 shows a typical example of data recorded from the experiments. Fig. 2a shows a plot of voltage (ΔV) and pressure difference (ΔP) against time when flowing the formation brine at $7.1 \times 10^{-2} \text{ mL.s}^{-1}$. As soon as pumping starts at $t = 360\text{s}$, the pressure difference increases and stabilizes after approximately 400 s. The voltage also changes, stabilizing at the same time as the pressure. When pumping stops at $t = 3300 \text{ s}$, the pressure difference and voltage relax to their initial values. Pumping then starts in the opposite direction, but at the same flowrate, at $t = 3900\text{s}$, causing the pressure and voltage to respond in the opposite sense to the previous flow, but with the same magnitude, which gives us confidence that electrode effects are small. When pumping stops at $t = 6600 \text{ s}$, both pressure and voltage relax to their initial values. Fig. 2b shows a plot of stabilized voltage (ΔV) against pressure difference (ΔP). A linear regression through these data yields a value of the streaming potential coupling coefficient $C = -7.97 \times 10^{-10} \text{ VPa}^{-1}$, with $R^2 = 0.972$.



(a)



(b)

Figure 2 Typical experimental results. (a) Measured voltage and pressure difference against time for the carbonate core, saturated with formation brine of electrical conductivity that corresponds to 10^3 mol/L NaCl solution flowing at 7.1×10^{-2} mL.s $^{-1}$; (b) Stabilized voltage against pressure difference plotted for different flowrates. The regression gives a value of $C = -7.97 \times 10^{-10}$ VPa $^{-1}$ with $R^2 = 0.972$

Fig. 3 shows the measured value of coupling coefficient as a function of brine salinity along with sandstones data from previous studies. Also shown is an empirical relation between the coupling coefficient and brine salinity obtained directly from a regression through the available data for sandstones [8]

$$C = -1.36C_f^{-0.9123} \quad (4)$$

where the coupling coefficient is expressed in mVMPa^{-1} and the brine salinity is expressed in M . This regression matches the sandstone data with $R^2 = 0.93245$. However, the coupling coefficients for carbonates appear to be much lower. This observation could be explained by comparing the difference in point of zero charges (pzc) between those two types of rock. Since pzc for carbonate is at pH 8-9, which is closer to the brine pH, the surface charge on carbonates might be smaller compared to the one in sandstones. Therefore, there will be less countercharge in the diffuse layer, which results in a lower streaming current. Pzc for sandstones, on the other hand, is around 2-3.

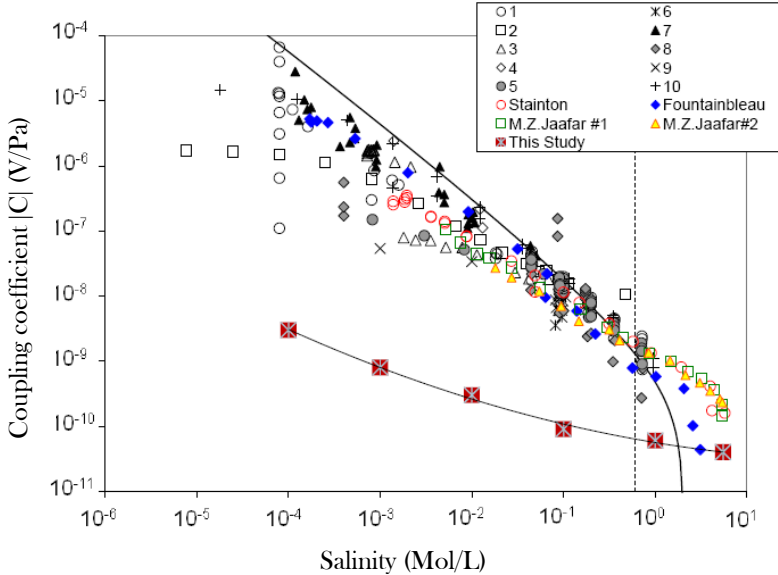


Figure 3 Coupling coefficient measured as a function of brine salinity, compared with values from previous studies [8]. All values are negative; only the magnitude of the coupling coefficient is shown. The curve is the predicted coupling coefficient using Equation (4). Brine pH varies between 6 and 8 in all cases

The magnitude of the measured coupling coefficient decreases with increasing salinity as observed in previous experimental studies and as predicted by models of the electrical double layer. At high salinity, the coupling coefficient does not fall to zero as predicted by models of the electrical double layer [4, 12]. Rather, the magnitude of the coupling coefficient remains greater than zero until the NaCl saturation limit is approached. The coupling coefficient is negative across the entire salinity range.

These results suggest that the magnitude of the streaming potential coupling coefficient remains greater than zero up to the NaCl saturation limit. The salinity dependence of the coupling coefficient for carbonates cannot be described using Equation (4). Further studies are needed to collect more data and suggest a new equation which relates the coupling coefficient to salinity for carbonate rocks.

Our laboratory measurements have demonstrated that the streaming potential coupling coefficient is nonzero in carbonates saturated with brine at salinities far above seawater, and up to the saturated NaCl salinity. This suggests that streaming potential measurements may be used to monitor flow in a wider range of subsurface environments than previously thought. The presence of multivalent ions in high enough concentration can lead to charge inversion, which occurs when the accumulation of multivalent ions on the mineral surface causes the apparent surface electrical charge to change sign [4].

Simulation results show that streaming potentials during multiphase flow arise at fluid fronts, where fluid saturation changes and the divergence of the streaming potential coupling term is nonzero [6]. The streaming potential is a maximum at these locations and decays toward zero (relative to a distant reference electrode) with distance from the maximum. As a moving fluid front approaches a production well, the streaming potential associated with the front encompasses the well while the front is still some distance away, so the streaming potential measured at the well starts to change significantly. Consequently, streaming-potential measurements are ideal for locating and characterizing moving fluid fronts, as long as there is a strong contrast in the streaming potential coupling coefficient of the rock-fluid system on each side of the front [6].

If the reservoir is water-wet and there is no electrical double layer associated with the oil-water interface, then the streaming potential coupling coefficient is zero ahead of the water-oil displacement front and a maximum behind it, yielding a strong contrast in coupling across the front. In this case, numerical studies [6] suggest that the water front might be detected at the well when it is several tens to

hundreds of metres away. However, significant uncertainties remain in characterizing streaming potential measurements for oilfield monitoring, particularly relating to the nature of the streaming potential coupling coefficient during multiphase flow. Additional experimental data are required to reduce these uncertainties. For example, understanding the nature of the streaming potential in oil-wet and mixed-wet reservoirs requires knowledge of the nature of the electrical double layer at oil-mineral interfaces and at the oil-water interface. As yet, both of these are poorly understood. Moreover, ambient reservoir temperature is higher than the room temperature experiments used to measure streaming potentials to date. In such conditions, the relationships between salinity, conductivity, zeta potential, and coupling coefficient might be different.

4.0 CONCLUSIONS

Based on this research work, several conclusions could be drawn:

- (1) The streaming potential for carbonates is lower compared to the one in sandstones for the same brine salinity.
- (2) The streaming potential coupling coefficient measured in the carbonate sample saturated with NaCl brine is nonzero at high salinity (up to the NaCl saturation limit at room temperature).
- (3) This finding suggests that streaming potential measurements may be used to monitor flow in a wider range of subsurface environments than previously thought.
- (4) However, there are still significant uncertainties to be resolved before the measurements can be interpreted with confidence, most of which relate to the coupling between electrical and fluid potential during multi-phase flow and in non-water wet reservoirs.

NOMENCLATURE

C = electrokinetic coupling coefficient (VPa^{-1})

C_f = brine concentration (salinity) (M)

F = electrical formation factor (dimensionless)

F_0 = intrinsic formation factor (dimensionless)

\mathbf{j} = flow of charge (Cs^{-1})

P = fluid potential (Pa)

V = electrical potential (V)

ϵ_n = brine permittivity ($\text{CV}^{-1}\text{m}^{-1}$)

μ_n = water viscosity (Pas)

σ_m = conductivity of the brine saturated rock (Sm^{-1})

σ_n = conductivity of the brine (Sm^{-1})

ζ = zeta potential (V)

REFERENCES

- [1] Laurence, O. S. and Brown, G. A. 2000. *Using Real Time Fibre Optic Distributed Temperature Data for Optimising Reservoir Performance*. Paper SPE/CIM 65478 Presented at the 2000 SPE/CIM International Conference on Horizontal Well Technology, Calgary, Alberta, Canada, 6-8 November. DOI: 10.2118/65478-MS.
- [2] Addiego-Guevara, E. A., Jackson, M. D. and Giddins, M. A. 2008. *Insurance Value of Intelligent Well Technology Against Reservoir Uncertainty*. Paper SPE 113918 Presented at the SPE/DOE Symposium on Improved Oil Recovery, Tulsa, Oklahoma, 20-23 April. DOI: 10.2118/113918-MS.
- [3] Robison, C. E. 1997. *Overcoming the Challenges Associated With the Life Cycle Management of Multilateral Wells: Assessing Moves Towards the "Intelligent Completion."* Paper SPE 38497 Presented at the 1997 Offshore Europe Conference, Aberdeen, Scotland, 9-12 September. DOI: 10.2118/38497-MS.
- [4] Hunter, R. J. 1981. *Zeta Potential in Colloid Science*. New York: Academic Press.
- [5] Jackson, M. D., Saunders, J. H. and Addiego-Guevara, E. A. 2005. *Development and Application of New Downhole Technology to Detect Water Encroachment Toward Intelligent Wells*. Paper SPE 97063 Presented at the 2005 SPE Annual Technical Conference and Exhibition, Dallas, Texas, 9-12 October. DOI: 10.2118/97063-MS.
- [6] Saunders, J. H., Jackson, M. D. and Pain, C. C. 2008. Fluid Flow Monitoring in Oil Fields Using Downhole Measurements of Electrokinetic Potential. *Geophysics*. 73(5). DOI: 10.1190/1.2959139.
- [7] Sill, W. R. 1983. Self-Potential Modelling From Primary Flows. *Geophysics*. 48(1): 76-86.
- [8] Jaafar, M. Z., Vinogradov, J. and Jackson, M.D. 2009. Measurement of Streaming Potential Coupling Coefficient in Sandstones Saturated with High Salinity NaCl Brine. *Geophys. Res. Lett.* 36 (L21306). DOI: 10.1029/2009GL040549.
- [9] Chen, M. Y., Raghuraman, B. and Bryant, I. D. 2006. *Streaming Potential Applications in Oil fields*. Paper SPE 102106 Presented at the 2006 SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 24-27 September. DOI: 10.2118/102106-MS.
- [10] Korpi, G. K., and deBruyn, P.L. 1972. Measurement of Streaming Potentials. *J. Colloid Interface Sci.* 40(2): 263-266.
- [11] Ball, B., and Ferstenau, D. W. 1973. A Review of the Measurement of Streaming Potentials. *Miner. Sci. Engng.* 5: 267-277.

- [12] Revil, A., Pezard, P. A. and Glover, P. W. J. 1999. Streaming Potential in Porous Media 1: Theory of the Zeta Potential. *J. Geophys. Res.* 104(B9): 20,021-20,231.