Influence of Saturant on Seismoelectric Coupling Response of Porous Media

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Abstract. The seismoelectric coupling phenomenon in porous medium saturated with gas and water was studied numerically. The numerical model was formulated based on Pride’s theoretically developed seismoelectric coupling coefficient that describes conversion of seismic energy into electromagnetic radiation. The conversion is complex function of physical, electrical and poroelastic properties of the porous medium and the saturant. In this study, a porous medium that is partially saturated with water is considered. Pore spaces that are not saturated with water are considered to be filled with gas. The gas phase is methane. The water saturation was varied from 0.2 to 0.9. The physical and electrical properties of both phases are determined at a temperature of 325 °K. The porosity and permeability of the porous medium is 0.2 and 500 mD, respectively. The porous medium in this study is isotropic. Zeta potential was estimated using an empirically derived correlation. At 0.001 mol/lit salinity, zeta potential is 66.7 mv. The numerical study result shows that at a fixed seismic wave frequency, lower water saturation results in higher seismoelectric coupling coefficient. When water saturation increases, the seismoelectric coupling coefficient decreases. However, the rate of decline is lower at higher seismic frequency. The rate of decline at 10 kHz is 1.38 nV/Pa compared to 4.35 nV/Pa at 100 kHz. Higher frequencies result in stronger nonlinearities, which causes higher mechanical energy dissipation. As such, the result obtained in this study is consistent with what is normally expected when mechanical wave propagates through a porous media.

1. Introduction

When a porous rock is saturated with an electrolyte, an electric double layer is formed on the interface between the solid and the fluid (Zhu et al., 2013). When a seismic wave passes through a saturated porous rock, it creates charge separation in the electrical boundary layer. Subsequently, the charge separation leads to formation of an electric dipole. These dipoles in turn emit an electromagnetic wave, which can be measured to infer the properties of the fluid, flow and the porous rock. Zhu et al. (2000) experimentally investigated seismoelectric conversion in fluid-saturated porous media. They concluded that the mechanism of the seismoelectric conversion is completely different from the piezoelectric effect of quartz grains. They also determined the seismoelectric sensitivity with respect to salinity of the saturant. It was shown that the amplitude of seismoelectric signals increases as the saturant conductivity decreases. They demonstrated that seismoelectric measurements could be an effective means of obtaining transport coefficients such as hydraulic permeability and other porous...
rock properties. Theoretically, the seismoelectric is related to the fluid conductivity, rock porosity, pore size, etc. (Pride et al., 1996).

The objective of this paper is to investigate the possibility of applying seismoelectric conversion phenomenon to monitor saturation changes and fluid propagation pattern in a reservoir. Seismic waves and electromagnetic waves are applied to investigate the subsurface. Seismic waves have fair resolution as well as good penetration depth, however, impedance contrast between reservoir fluids are small. As such, they are insensitive to change in fluid content of a reservoir. On the other hand, electromagnetic waves have good electrical conductivity determination, but due to large wave length, they have poor resolution. In the present paper, electromagnetic wave generated due to seismic wave excitation, a phenomenon called seismoelectric conversion, will be examined to monitor changes in saturation in gas-water system. Successful implementation of the method should exploit the merit of using seismic and electromagnetic methods individually. Accordingly, the main goal of this paper is to provide some insight into how change in water saturation affects the seismoelectric response in gas-water system so that the seismoelectric phenomenon can be used to monitor and map the desaturation pattern of the porous media.

2. The Seismoelectric Phenomenon

Ivanov (1939) and Frenkel (1944) are the pioneers of the seismoelectric method, as they were the first ones to record seismoelectrically induced signals and to develop the electrokinetic theory of the seismoelectric phenomenon. Ivanov (1939) measured an electric field generated due to seismic wave passing through the earth without the application of external voltage. Frenkel (1944) developed set of equations to explain the phenomenon using the concept of electric double layer. Their works were extended and widely implemented in Soviet Union, whereby a great number of theoretical and field works were conducted using seismoelectric method for mineral exploration and to determine the weathered zone thickness to assist in interpretation of seismic data (Revil et al., 2015). Years later, Thompson et al. (1993) and Thompson et al. (2007) conducted a study, they adopted seismoelectric method to use for exploration of hydrocarbon reservoirs. As Thompson and Gist concluded, the signals induced due to the seismoelectric effects were detected at the depth of 300 meters, however, they proposed that this method could be successfully applied to much greater depths (several kilometers). A great deal of theoretical and field works done aspire us to attempt to study the seismoelectric method for monitoring saturation changes in gas-water system. The seismoelectric method has been studied for several decades. However, a comprehensive theory of the phenomenon was developed by Pride in the early ‘90s (Pride, 1994). His work has led to numerous breakthroughs and the phenomenon is being studied for various applications. In this paper, we adopted Pride’s model to investigate the effect of water saturation in partially saturated porous media.

3. Methodology

3.1. Pride’s Model for Partially-Saturated Medium

Pride (1994) developed a complete set of equations that characterizes the coupling between seismic and electromagnetic wave propagation by combining Biot’s poroelasticity theory and Maxwell’s equations via frequency-dependent seismoelectric coupling shown in Eq. 1 (Jouniaux et al., 2012). The coupling equation is considered to be quite complex, since it takes into account multiple variables that affect both seismic and electromagnetic fields.

\[
L(\omega) = L_0 \left[ 1 - i \frac{\omega}{\omega_c} \frac{m}{4} \left( 1 - 2 \frac{\tilde{d}}{\Lambda} \right)^2 \left( 1 - i^{3/2} \frac{\tilde{d}}{\eta_f} \right)^{2\gamma-1/2} \right]
\]  \hspace{1cm} (1)

where \( L_0 \) is the low-frequency electrokinetic coupling, \( m \) is a dimensionless number, \( \tilde{d} \) is the Debye length, \( \Lambda \) is a geometry term of the porous material, \( \omega_c \) is the transition angular frequency, and \( \omega \) is
the angular frequency. Additionally, $\rho_f$ and $\eta_f$ denote the density and dynamic viscosity of the fluid mixture, respectively.

Due to complexity of Pride’s coupling coefficient, Walker and Glover (2010) proposed a simplified version of the equation assuming that the Debye length can be neglected when compared to the characteristic pore size. Moreover, they modified the following parameters:

$$m = 8 \left( \frac{\Lambda}{r_{\text{eff}}} \right)^2$$

(2)

where $r_{\text{eff}}$ is effective pore radius. The transition angular frequency is given by equation 3.

$$\omega_t = \frac{8\eta_f}{\rho_f r_{\text{eff}}^2}$$

(3)

And thus, the simplified Pride’s electrokinetic equation for fully-saturated porous medium becomes

$$L(\omega) = L_0 \left[ 1 - 2i \frac{\omega}{\omega_t} \left( \frac{\Lambda}{r_{\text{eff}}} \right)^2 \right]^{-1/2}$$

(4)

where

$$L_0 = -\frac{1}{F} \frac{\varepsilon_f \varepsilon_{\text{os}} \zeta}{\eta_f}$$

(5)

Early theoretical developments accounted for seismoelectric effects that occur only in fully-saturated conditions (Ivanov, 1939; Frenkel, 1944). However, the practical potential of using the seismoelectric method is realized when it takes into account both fully- and partially-saturated conditions in porous media. Therefore, in the numerical study presented in this paper, we adopted the simplified version of Pride’s seismoelectric coupling coefficient modified by Walker and Glover (2010) and extended it for partially saturated conditions with water and gas saturating the porous medium.

**Table 1.** Parameters used in the numerical study.

| Notation            | Value  | Unit     |
|---------------------|--------|----------|
| Water density       | $\rho_w$ | 988   | kg/m$^3$  |
| Gas density         | $\rho_g$ | 1.1829 | kg/m$^3$  |
| Water dynamic viscosity | $\eta_w$ | 0.000894 | Pa·s |
| Gas dynamic viscosity | $\eta_o$ | 0.0000181 | Pa·s |
| Porosity            | $\Phi$ | 20      | %          |
| Tortuosity          | $\alpha_{\infty}$ | 4 | m$^2$ |
| Zeta-potential      | $\zeta$ | 66.7    | mV         |
| Formation factor    | $F$    | 18.28   | –          |
| Effective pore radius | $r_{\text{eff}}$ | 80 | $\mu$m   |
| Pore geometry length | $\Lambda$ | 8E-6  | m          |

Seismoelectric coupling is directly dependent on reservoir rock and fluid properties and the electric double layer (Jouiaux et al., 2012). The zeta-potential, which is an electric potential on the slipping plane within the double layer, is a key element in the seismoelectric phenomenon (Vinogradov et al., 2010). It is directly dependent on brine concentration, and this in turn, has a substantial effect upon the magnitude of the seismoelectric amplitudes (Zhu et al., 2016). Additionally, recent studies revealed that seismoelectric effects are also greatly affected by changing fluid saturations in a porous medium (Revil et al., 2015). In this study, the zeta-potential was estimated using an empirically derived correlation (Vinogradov et al., 2010), which links zeta-potential to the saturant salinity. At 0.001 mol/lit salinity, zeta potential is 66.7 mV. Water is assumed to be the wetting phase in the porous
medium, and thus varying water saturation does not affect both the electric double layer and the zeta-potential. The frequency in the present study is varied between 10 kHz to 150 kHz. Brine concentration was varied from 0.001 mol/l to 0.1 mol/l. Water saturation was varied from 0.2 to 0.9. The remaining parameters used in our calculations are listed in Table 1 that is shown below.

4. Results and Discussion
As discussed in the introduction section, the zeta-potential strongly affects the seismoelectric coupling coefficient \( L \). The charge density and fluid properties in the electric double layer in turn affects the zeta-potential. As such, the zeta-potential varies with salinity. Fig. 1 shows variation of the seismoelectric coupling coefficient with salinity at various water saturations and constant frequency of 10 kHz. In semi-log plot, the coupling coefficient varies with salinity linearly. The model we used in this study is valid for salinity values as high as 0.4 mol/l. In Fig. 1 salinity is varied from 0.001 mol/l to 0.1 mol/l. When water saturation is fixed at 0.2 and salinity increases from 0.001 mol/l to 0.1 mol/l, the seismoelectric coupling coefficient decreased from 5.47 nV/Pa to 2.35 nV/Pa, which is about 57 % drop. Under the same change in salinity, but at water saturation 0.9, the seismoelectric coupling coefficient decreased by about the same percentage from 2.56 nV/Pa to 1.10 nV/Pa. Even though the general trend shows that the coupling coefficient declines with salinity, fitting the semi-log plot to a straight line correlation shows that the rate of decline is larger at lower water saturation. At saturation 0.2, the decline rate is 0.678 compared to 0.317 at saturation 0.9. Hence, at fixed water saturation, the change in seismoelectric coupling coefficient as salinity changes is significant when water saturation is lower. In hydrocarbon reservoirs, salinity changes with depth and we may not expect sudden jumps in concentration gradient. The observation shown here can be useful during water injection where higher water saturation zones near the injector well prevails. When the porous medium is at higher water saturation, the seismoelectric coupling coefficient seems to be less sensitive to variation in salinity. As such, the contrast between zones with different water saturation can be observed. In general, the seismoelectric coupling coefficient contrast is significant at lower salinities.

Figure 2 shows variation of the seismoelectric coupling coefficient with frequency on a linear plot. The salinity of the water is fixed at 0.001 mol/l and frequency is varied from 10 kHz to 150 kHz at various water saturations. At a given frequency, the seismoelectric coupling coefficient is higher at lower water saturation. However, at constant water saturation the seismoelectric coupling coefficient is higher at lower frequency. When frequency increases, the seismoelectric coupling coefficient decreases and beyond some frequency values it starts to level off. Higher frequencies are associated with larger dissipation due to nonlinearities. Hence, the conversion of mechanical energy from the seismic source to the electromagnetic radiation becomes less efficient. Such characteristics is manifested by the trend shown in Fig. 2. The important observation from Fig. 2 is that at fixed frequency, the seismoelectric coupling coefficient is sensitive to the fluid content of the porous medium. The frequency range indicated here is much larger than those normally used in seismic surveys. However, since lower frequencies give off higher electromagnetic radiation, the magnitude of the signals should be much larger than what is shown in Fig.2. Therefore, the fluid content and the saturation of a porous medium may be recognized by

\[ L \text{(nV/Pa)} \]

\[ C_f \text{(mol/l)} \]

\[ S_w \]

\[ f = 10 \text{ kHz} \]

**Figure 1.** Effect of salinity on the seismoelectric coupling coefficient at \( f = 10 \text{ kHz} \).
measuring the amplitude of the seismoelectric response. However, it should be mentioned that the signal to noise ratio during the measurement of this electrokinetic effect is low. With the development of sensitive instrumentation, reliable measurement and post-processing, interpretation may become routine and its sensitivity to fluid saturation, porosity, permeability and other rock and fluid properties can be exploited for practical application.

Figure 2. Effect of frequency on the seismoelectric coupling coefficient at $C_f=0.001$ mol/l.

Effect of water saturation on the seismoelectric coupling coefficient at 0.001 mol/l salinity and various frequencies is presented in Fig. 3. When frequency is fixed at 10 kHz and water saturation is increased from 0.2 to 0.9, the seismoelectric coupling coefficient decreased by about 2.91 nV/Pa from 5.47 nV/Pa to 2.56 nV/Pa. Similarly, for the same change in saturation but at salinity frequency 100 kHz, the seismoelectric coupling coefficient decreased by about 0.91 nV/Pa from 1.64 nV/Pa to 0.73 nV/Pa. Although the seismoelectric coupling coefficient declines when water saturation increases at a given frequency, the rate of decline is lower at higher frequency. Table 2 summarizes the rate of decline at various frequencies.

As can be seen from Fig.3, the dependence of the coupling coefficient on saturation can be exploited to map saturation changes in a reservoir during hydrocarbon production. The contrast is significant at lower frequencies. But the challenge is the inherent difficulty in measuring the seismoelectric signals. With the advent of proper measurement techniques, the phenomenon should be capable of monitoring the saturation profile of a reservoir during hydrocarbon production. As such, various fluid injection and production processes can be monitored and optimized for better performance.

Table 2. Rate of decline of the seismoelectric coefficient at various frequencies

| Frequency (kHz) | Rate of Decline (nV/Pa) |
|-----------------|------------------------|
| 10              | 4.35                   |
| 50              | 1.93                   |
| 90              | 1.45                   |
| 100             | 1.38                   |

5. Conclusion

In this paper, we have numerically studied effect of change in saturation in gas-water saturated porous medium by extending Pride’s seismoelectric coupling model. The result of the numerical study shows that the seismoelectric coupling coefficient is sensitive to changes in water saturation. However, the response is salinity and frequency dependent. The effect of salinity is stronger at lower water saturations. At higher water saturation, the response is less sensitive to salinity. At the given frequency, lower water saturation results in higher seismoelectric coupling coefficient. However, when
water saturation remains constant and frequency is increased, the seismoelectric coupling coefficient decreases faster until certain values of frequency beyond which the response seems to level off. The characteristics described here is based on the range of frequency studied in this paper, i.e. 10 kHz to 150 kHz. The study also shows that the seismoelectric coupling coefficient is sensitive to the change in saturation characteristics of the porous media in gas-water system. In general, when water saturation increases at constant salinity, the seismoelectric coupling coefficient decreases. However, the rate of decline is frequency dependent. The rate of decline is higher at lower frequencies. Regardless of frequency, the change in saturation results in change in the seismoelectric coupling coefficient. Apparently, the dependence of the coupling coefficient on saturation can be exploited to map saturation changes in a reservoir during hydrocarbon production. However, from practical point of view measuring seismoelectric response is inherently difficult due to small signal-to-noise ratio. Nevertheless, with the advent of improved measurement techniques and processing algorithms, the method should be capable of monitor change in saturation characteristics of a reservoir. Such possibility allows reservoir engineers to understand details of fluid propagation behavior in a reservoir. Such understanding is very helpful in maximizing sweep efficiency.

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