Geoelectric Monitoring at CO₂ Geological Storage

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The global warming is one of the most serious environmental problems of the day. CCS (Carbon dioxide Capture and Storage) technology, which is one of the most effective CO₂ discharge control technologies, is expected to suppress the CO₂ emission into the atmosphere. There are several options for the storage in CCS. Geological storage is one of the options but is the most feasible. Monitoring is essential and necessary not only for the accountability of the CO₂ storage but also the safety of the CO₂ injection. The operation from the critical damage should also be planned in the case of an abnormal monitoring data. The seismic reflection method is often used in the CO₂ storage sites because most of the sites are in the oil/gas fields and the seismic reflection is the most popular and fundamental survey method in the petroleum field. However, seismic velocity does not change at the proportion of the CO₂ saturation change in the laboratory test (Nakatsuka et al., 2009), indicating that the seismic velocity decreases rapidly during the CO₂ injection but the no remarkable decrease is detected after the CO₂ saturation up to about 30%. Moreover the seismic reflection method is expensive to carry out. To overcome these disadvantages of the seismic monitoring we have started a research work using the electromagnetic phenomena. Monitoring using geoelectric method was applied to an air injection and the increase of the geoelectric potential was observed. We have been monitoring earth-surface SP during gas injection tests at various sites in Japan. When air was injected into a 100-meter well within a geothermal field, a remarkable simultaneous increase in SP centered on the wellhead was observed. To explain the increase of the geoelectric potential, theoretical analysis was carried out.

1. INTRODUCTION

Self-potential (SP) is basically defined as the potential difference between two points on the surface or at the underground of the Earth. The Earth, in this meaning, is not a conductive body. SP changes its value due to several reasons, one caused by the external origin and other caused by the internal origin.

One of the sources of the SP change is telluric current. Telluric current, an electric current which moves underground or through the sea with low frequency and primarily induced by changes in the outer part of the magnetosphere of the Earth, creates SP difference according to the resistivity of the two points. There are other changes due to the inertial of the Earth.

Negative SP anomaly is found on surface over copper deposit. This technique has been widely used for a long time. SP distribution on the surface is used and positive and negative anomalies are mapped. Another approach to use SP distribution is to find out the discharge and recharge areas of the groundwater. Positive SP anomaly is found over the discharge of the groundwater and geothermal fluid. Especially the region where geothermal fluid wells up shows a large positive anomaly. Geothermal research work uses SP areal distribution and estimates the fluid movement at the underground.

![Figure 1 Result of the SP observation during air injection into a 100-meter well](image)

At this figure we have plotted the result of 6 electrodes. The nearest electrode to the well is N-01 and N-06 was located about 30m away from the well. Soon after the air injection started increases of SP were detected. The larger increase was detected at the closer electrode to the well.
geothermal fluid flow are theoretically explained using the electro-kinetic phenomena. Stable fluid flow is detected and mapped by the areal SP distribution and temporal SP change is associated with the underground flow changes.

2. SP MEASUREMENT AT THE INJECTION SITE

A field experiment of the SP change was carried out during the air injection in 2003. When air was injected into a 100-meter well within a geothermal field, a negative anomaly is expected at the area where the fluid diffuses based on the electro-kinetic theory. Air which is injected through an injection well pushes water at the aquifer. Therefore we expected the negative anomaly during the well was observed. The result was, however, quite different and the positive anomaly after the injection was observed (Fig. 1). This experiment was preliminary reported.

This experiment is explained qualitatively as follows (Fig.2):

At the normal condition, oxidation environment is expected near the surface and reduction environment is expected at the deeper layer. This means that electron is lacking at the surface and abundant in the deep layers. If conductive body like a casing pipe of a well is set in the normal condition, electron moves from the deeper layer to the shallow layer. Reducing species release the electron at the deep layer and oxidizing species get the electron. It implies that electron is relatively abundant around the conductive body on the surface and that a negative SP anomaly around the conductive body is observed. If air or CO$_2$, which has abundant oxygen, is injected at the bottom of the conductive body, they prevent reducing species from releasing the electron and cause the decrease of the electron flow through the conductive body. We expect the increase of SP on the surface caused by the decrease of the electron flow.

3. THEORETICAL APPROACH

The process around the casing pipe is similar to a battery. Casing pipe acts as a batter to create current at the surrounding layers. We have shown the process to calculate the potential on the surface created by the underground battery. Oxidation-reduction (redox) reaction happens. For example, ferro-iron and ferri-iron are in equilibrium.

$$\text{Fe}^{3+} + e^- = \text{Fe}^{2+}$$

Ferro-iron and ferri-iron is called a redox pair. Ferro-iron receives an electron and ferri-iron yield an electron. Electric potential (redox potential) is calculated from the Gibbs’s free energy. As a general, redox reaction is written as follows;

$$O + ne^- = R$$

where R and O are reductant and oxidant, respectively. And n means charge number. The standard redox potential ($E^\circ$) is obtained from the electrochemical table. The standard redox potential is defined at the temperature of 25°C (298K). At another temperature and another concentration are calculated after the Nernst Equation.

$$E^\circ(T) = E^\circ(298K) + \frac{dE^\circ}{dT}(T - 298) \quad (2a)$$

$$E_H = E^\circ(T) + \frac{RT}{nF} \ln(a_O / a_R) \quad (2b)$$

where R and F are gas constant and Faraday constant, respectively. $a_O$ and $a_R$ are activities of oxidant and reductant. Activity is defined as partial pressure at gas phase and molality at solute. When solution and solid, it set to unity. T denotes temperature.

The equation (2b) is obtained at the equilibrium (balanced) condition. When the potential is shifted from the balanced position, the current is created calculated by the Butler-Volmer equation.

$$i = nFk_o \exp(-G*/RT) \cdot \left[a_R \exp(nF \eta / 2RT) - a_O \exp(-nF \eta / 2RT)\right]$$

where $G*$ and $k_0$ are activation energy and electric constant between electrode and dilution,
respectively.

\[ \eta(= E - E^0) \] is potential difference between a new potential level (E) caused by the exchange current and the standard redox potential.

We can calculate anode current density \( i_A \) and cathode current density \( i_K \) separately using the Equation (3). The principle of conservation of charge leads the following equation;

\[ i_A + i_K = 0 \quad (4) \]

Using Equation (4) and linearization of Equation (3) under the assumption that anode potential \( E_A \) and cathode potential \( E_K \) are close to the redox potential \( E_H \), we can get the redox potential as follows;

\[ E_H = \frac{1}{n_K i_0^K \sqrt{a_{KR}/a_{KO}} + n_K i_0^K \sqrt{a_{KR}/a_{KO}} E_K + n_A i_0^A \sqrt{a_{AO}/a_{AR}} E_A} \quad (5) \]

where \( i_0^K \sqrt{a_{KR}/a_{KO}} \) and \( i_0^A \sqrt{a_{AO}/a_{AR}} \) are exchange current densities at cathode and anode, respectively.

At each depth there is deferent redox potential depended by the chemical condition like oxygen partial pressure. Once the conductive body is intruded into the layers, the potential should be shifted from the balanced point and the current happens followed by the Butler-Volmer equation. The new redox potential is calculated by Equation (5).

To calculate SP variations, we examine a simple case of the radial horizontal flow. The current flows through the circuit in the layers At this moment, we assume a simple current circuit. The current flows horizontally through the geological layers and runs to an infinite direction. On the other word, we assume radial current flow from the well. The radial flow is calculated theoretically shown in Equation (6).

\[ V_c - V_0 = \frac{\ln(r_0/r_c)}{2\pi H\sigma} I \quad (6) \]

where \( r_c \) and \( r_0 \) are radius of the conductive body and the distance from the origin. \( V_c \) and \( V_0 \) are the potential at the conductive body of the geological layer and the potential at \( r=r_0 \). \( \sigma \) denotes conductivity. \( I \) is the radial current density.

If we can assume that the potential \( V_0 \) becomes zero at 100m (=r_c), \( V_c \) is simply written

\[ V_c = \frac{\ln(100/r_c)}{2\pi H\sigma} I \quad (7) \]

The current density \( I \) denotes as following equation

\[ I = \frac{2\pi Hr_c F}{RT} I_0 (V_m - V_c - E_H) \quad (8) \]

where \( V_m \) is the potential at the conductive body and \( I_0 \) is the exchange current density. \( V_m \) is different from \( V_c \) because of the existence of the surface double electric layer.

If the conductive body (casing pipe) penetrates several geological layers, we can compute the current \( I \) at each layer using Equations (7) and (8). Then the law of conservation charge is applied and potential of the conductive body is constant at all layer is assumed. Using Equation (5), we can get \( V_c \) at each layer and \( V_m \).

### 4. CASE STUDY

In this study we took two electrochemical reactions into account. First reaction is associated with water at the Cathode. Oxygen and Hydrogen makes water.

\[ O_2 + 4H^+ + 4e^- = 2H_2O \quad (9) \]

Activity of the oxygen is defined as the partial pressure. The oxygen partial pressure at the surface is about 0.2bar and we assumed the partial oxygen pressure at the depth \( z \) km by following Equation (10).

\[ P_{O_2} = 0.2 \cdot \exp(-0.5z) \quad (10) \]

The surface temperature is assumed as 25 centigrade and thermal gradient is set to 30(degree/km). Temperature at the depth of \( z \) km is simply assumed

\[ T(z) = 298 - 30 \cdot z \quad (11) \]

The standard redox potential at the cathode \( (E^0_K) \) varies according to oxygen partial pressure, pH, and temperature.

Another reaction we assumed is oxidation and reduction of iron happened at anode.

\[ Fe^{3+} + e^- = Fe^{2+} \quad (12) \]
Redox potential at the anode ($E^\circ_A$) is changed only by temperature.

Another assumption is about the geological layers. We adopted a 5 layers model and a radial current flow (Fig. 3). At 100m away from the well, potential is set to be zero. That means the current is also zero at 100m away from the well. Based on these assumption we tried to explain the field result of SP measurements.

Fig. 4 shows the results of the observation and the theoretical analysis. The observed SP are scattered because of the noises partly caused by the terruric current. However the theoretical SPs are close to the observed SPs basically.

5. CONCLUSIVE REMARKS

1. Self-Potential survey was carried out around the air injection well.
2. Apparent SP increase was observed during the injection.
3. The SP increase was analysed by the redox potential change due to the connected conductive casing.
4. Horizontal current flow (Radial flow) was assumed at the formation layers.
5. The calculated SP changes are basically condordant to the observed changes.
6. To more excise analysis, combination with the geochemical simulation should be necessary.

REFERENCES


Figure 3 (a) A simplified draft of the injection well
(b) a model with five layers and a radial current flow at each layer.

Figure 4 Results of the observed and calculated SP changes.
Horizontal axis is distance from well in meter and vertical axis is Self Potential in mV.