Measurement of electrical impedance and P-wave velocity of a low permeable sandstone core during the displacement of saturated brine by CO2 injection

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Abstract

Evaluating and monitoring the CO2 behavior in the reservoir, understanding the mechanism of CO2 flow and distribution in the water-CO2 mixture state is essential. In this study, measurement of the complex electrical impedance (Z) and P-wave velocity (Vp) is conducted during the CO2 injection into the rock core under the reservoir condition. The core is low permeable sandstone and injection rate is ultra-low (in the low capillarity number (Ca) area) to high. In addition to measuring Z and Vp, differential pressure on the both sides of the specimen and CO2 saturation (SCO2) of the entire specimen are measured. The change of Z and Vp are observed according to the change of differential pressure and SCO2. After the injection test, SCO2 in cross-section of the specimen is estimated using Archie’s law and Gassmann’s equation (Patchy saturation model) to the experimental results.

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1. Introduction

As a CCS storage reservoir, largely existed deep saline aquifer about 1,000 m underground and consisted of porous sandstone is expected to have an enormous potential [1]. There are various techniques to estimate the CO2 migration and trapping mechanism. Among these techniques, measuring Z and p-wave velocity (Vp) is applied in the real reservoir scale. To get the precise understanding of the relationships between Z- SCO2 and Vp- SCO2 for the evaluation and prediction of the CO2 behavior, laboratory test under the reservoir condition is necessary. Simultaneous Z and Vp measurements have been implemented [2,3]. Archie’s law and Gassmann’s theory is often used to estimate SCO2 from Z and Vp [4,5].

To discuss the CO2 behavior in porous sandstone, capillarity number (Ca) is an effective parameter. Most of the research are targeting the high (Ca) area in the capillary fingering area of the drainage phase diagram [6,7]. In the real reservoir, various Ca area exists. For the purpose of compensating the data of low Ca area, we conduct the CO2 injection test to the low permeable sandstone in ultra-low flow rate.
In this study, measurements of $Z$ and $V_p$ are performed simultaneously during the CO$_2$ injection test into the brine-saturated sandstone. CO$_2$ injection test is conducted to the low permeable brine-saturated sandstone. Flow rate is set ultra-low rate to clear the CO$_2$ behaviour during the drainage in detail. In addition to measuring $Z$ and $V_p$, differential pressure on both sides of the specimen and $S_{CO_2}$ of the entire specimen are measured using the separator during the CO$_2$ injection test. Coupling these data, we report the CO$_2$ behavior and the relationship between the $Z$ and $V_p - S_{CO_2}$.

2. Experiment

2.1. Specimen

Rock core we use is sandstone (Ainoura sandstone, North-west Kyushu Is., Japan). This sandstone is classified Arkosic sandstone and mainly composed of quartz (88 %) and feldspar (3 %). Ainoura sandstone has a bi-module porosity distribution ($\phi$:11.9 %), and total porosity shows the 8.01 mL (1 PV). The permeability is measured to be 0.01 millidarcy (1.00x10^{-12} m$^2$) by using the constant flow water injection method. We cut this sandstone in column shape ($\phi$= 35 mm, $L$ = 70 mm). The core is attached Ag-AgCl electrodes for $Z$ and PZTs sensors for generation and monitoring $V_p$ on the surface of core sample (Fig. 1). Finally, its surface is coated with silicon for isolating the sample from oil for applied confining pressure. Six piezoelectrical transducers (lithium niobate PZTs, which has a 1 MHz resonant frequency) are set on the surface of the sample to monitor $V_p$ change.

2.2. Experimental system

The system consists of one pressure vessel, three syringe pumps and a separator (Fig.2). Supercritical CO$_2$ is injecting into the brine-saturated specimen (drainage process). Injected CO$_2$ replaces the brine in pore space. During the CO$_2$ injection test, we measured differential pressure (DP) between both ends of the specimen by the Pressure Gauge A and B.

For measuring $Z$, we used four electrodes method. We use Solartron 1260A as a $Z$ analyzer (0.1 to 10$^6$ Hz). A single sine voltage drive with a magnitude of 10 mV is applied to the two Ag (current) electrodes at both ends, and the potential between the two Ag electrodes attached in the central is measured simultaneously interval in three hours during the injection test. $V_p$ are generated by applying an electrical pulse (250 KHz tone burst excitation pulse) to the PZTs. The generated $V_p$ received at each receiver is fed to A/D converting equipment and is digitized with a dynamic range of 16 bits and sampling rate of 50MHz. The waves of all channels are stacked over 200 times to enhance the ratio of signal to noise). $V_p$ are measured in an hour interval during the injection test.

2.3. Experimental condition

The specimen saturated with synthetic brine (0.1wt%-KCl) is put in the tri-axel pressure vessel. The temperature, pore pressure, and confining pressure are set at 40 ℃, 10 MPa, and 20 MPa to reproduce the reservoir condition (supercritical CO$_2$ conditions, Critical point: 7.38 MPa, 31.3 ℃), respectively. CO$_2$ injection rate is 0.01, 0.05 and 0.1mL/min.

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Fig. 1. Specimen setup.  
Fig. 2 Illustration of the experimental system.
2.4. Experimental procedure

Checking the pressure and temperature stable, we open Valve A and B, and CO₂ injection test is started sending CO₂ by Syringe pump 1 (Syringe pump 2 is for keeping the pore fluid pressure 10 MPa) at FR: 0.01 mL/min. CO₂ injection continued until DP becomes stable. Once DP becomes stable on each FR, we close the Valve A and refill Syringe pump 1 with fresh CO₂ from the bottle. After confirming the pressure and temperature become stable, we re-open the valve and starting the CO₂ injection at the 0.05 or 0.1 mL/min. At FR: 0.05 mL/min to 0.1 mL/min, DP is keeping at the Final value at 0.05 mL/min.

3. Results

3.1. Differential pressure

Fig. 3 shows the results of DP change during the CO₂ injection. Starting the CO₂ injection at FR: 0.01 mL/min, DP is increasing and shows the step-by-step change. DP shows the peak at 70 hours. It can be indicated that CO₂ reached to the downstream side (breakthrough). After showing the peak, DP is decreasing and finally shows the stable value over 200 hours. From Fig. 3 (b), DP at FR: 0.05 mL/min also shows the peak at 28 hours. On the other hand, the peak is no remarkable than that of FR: 0.01 mL/min. DP shows the stable over 100 hours. These behaviours were not observed at FR: 0.1 mL/min.

3.2. CO₂ saturation

$S_{CO_2}$ are estimated by the mass-balance method to the results of the weight of separator. Separator could collect the discharged fluid (KCl-CO₂ mixture) and separate by the difference of their density. $S_{CO_2}$ at FR: 0.01mL/min shows 0.25 and that of at FR: 0.05 mL/min shows 0.39, and that of FR: 0.1 mL/min shows 0.55.

3.3. Electrical impedance

Fig. 4 shows the Bode plot of impedance during the CO₂ injection test at each FR. The magnitudes of Z ($|Z|$) become higher as FR increasing ($S_{CO_2}$ getting higher). Theta (phase angle) changes only in high frequency. Increasing FR, $|Z|$ could be confirmed the change of the value. Measuring electrical impedance is suitable for monitoring of high saturation area.

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**Fig. 3.** Change of DP (a) 0.01 mL/min, (b) 0.05 mL/min, (c) 0.1 mL/min.

**Fig. 4.** Bode plot of each FR.
3.4. P-wave velocity

The change of $V_p$ on each FR could be confirmed in Fig. 5. From the plot at FR: 0.01 mL/min, $V_p$ is reducing from the CO$_2$ injection side at 31, 37, 41 hours. It indicates that CO$_2$ reaches the each cross section at that timing. The velocity of CO$_2$ front became first reaching to the downstream side (Fig. 6). Table 1 shows the summary of reduction rate of $V_p$ change on each FR. The most reduced $V_p$ is Ch.1 (9.46 %). It is estimated that S$_{CO2}$ on the CO$_2$ injection side is higher than that of outlet side (capillary fingering).

Initial $V_p$ at FR: 0.05 mL/min and final value at FR: 0.01 mL/min are different. The reason for that happens is CO$_2$ migration while refilling CO$_2$ to the Syringe pump. During refilling, the valves on both ends of the specimen are closed and CO$_2$ in the specimen migrates entirely and evenly. Reduction of $V_p$ continued slightly until CO$_2$ injection stopped.

$V_p$ changes on each FR, however changed rate is too small.

![Fig. 5. Change of $V_p$ (a) 0.01 mL/min, (b) 0.05 mL/min, (c) 0.1 mL/min.](image)

![Fig. 6. CO$_2$ front in the rock core at FR: 0.01 mL/min.](image)

<table>
<thead>
<tr>
<th>FR</th>
<th>Ch.1</th>
<th>Ch.2</th>
<th>Ch.3</th>
<th>S$_{CO2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01mL/min</td>
<td>9.46 %</td>
<td>8.12 %</td>
<td>6.81 %</td>
<td>0.25</td>
</tr>
<tr>
<td>0.05mL/min</td>
<td>1.30 %</td>
<td>1.45 %</td>
<td>0.60 %</td>
<td>0.39</td>
</tr>
<tr>
<td>0.1mL/min</td>
<td>1.58 %</td>
<td>1.06 %</td>
<td>0.57 %</td>
<td>0.55</td>
</tr>
</tbody>
</table>
4. Discussion

4.1. Estimation of the CO₂ saturation by Archie’s law

To estimate the $S_{CO₂}$, Archie’s equation is basically used. $S_{CO₂}$ is determined by following equation (1) and (2) [8].

\[ RI = \frac{R}{R₀} = (S_w)^n \]  
\[ S_{CO₂} = 1 - S_w = 1 - \left( \frac{1}{RI} \right)^\frac{1}{n} \]  

where $S_w$: the water saturation, $R$: resistivity of the rock partially saturated with brine, $R₀$: the resistivity of fully saturated rock with brine, and $n$: the saturation exponent. Using equation (1) and (2), we estimate $S_{CO₂}$ on each FR. Fig. 7 shows the results comparing the measured value from the experiment. We can confirm the increasing $S_{CO₂}$, however the value from the Archie’s law is nearly two times less than that of experiment. This difference is caused by the low permeability and clay content in Ainoura sandstone we used.

4.2. Estimation of the CO₂ saturation by Gassmann’s equation

We try to estimate the relationship between $V_p$-$S_{CO₂}$ by the CO₂-brine mixture models: Gassmann and Wood [9] model and Gassmann and Hill [10] model. These two models have dominated the CO₂ cluster size in the pore space [11]. The CO₂-brine mixture model gives the maximum (Gassmann-Hill) and minimum (Gassmann-Wood) CO₂ patchy size.

$V_p$ in homogeneous isotropic materials can be described by the following equation (3). $K_{eff}$ is the bulk modulus of saturated rock. Gassmann model employed as the following equation. (4).

\[ V_p = \sqrt{\frac{K_{eff} + \frac{4}{3}G}{\rho_{eff}}} \]  
\[ K_{eff} = K_{dry} + \frac{1}{\phi} \frac{K_{min}}{K_{dry}} \left[ 1 - \frac{\phi}{K_{min}} + \frac{1 - \phi}{K_{dry}} \right] \]  

where $G$: the shear modulus of the saturated rock, $K_{dry}$: dry bulk modulus, $K_{min}$: bulk modulus of rock forming minerals $V_s$ in homogeneous isotropic materials can be described by the following equation (5). we measured $V_s$ under the room temperature and 0 MPa (atmospheric pressure).

\[ V_s = \sqrt{\frac{G}{\rho_{eff}}} \]  

The density $\rho_{eff}$ of the CO₂ saturated rock and $S_{CO₂}$ are given by

\[ \rho_{eff} = \rho_{eff} + \phi \left[ (1 - S_w) \rho_{CO₂} + S_w \rho_w \right] \]  
\[ S_{CO₂} = 1 - S_w \]  

Fig. 8 shows the relationships between $V_p$-$S_{CO₂}$ from the experiment and CO₂-brine mixture models at the central cross section of the core. Measured $V_p$ exist between Gassmann-Wood model and Gassmann-Hill model. It is assumed that CO₂ patchy size is approaching from Gassmann-Wood model to Gassmann-Hill model as increasing $S_{CO₂}$. In addition, plot of $|Z|$ on each frequency are shown in the Fig. 8. Increasing $S_{CO₂}$, $|Z|$ on each frequency getting higher and shows more change than $V_p$.
5. Conclusion

We succeeded in measuring fluid mechanical properties; DP, \( S_{CO_2} \), and rock physical properties; \( V_p \) and \( Z \). During the supercritical \( CO_2 \) injection to the brine saturated low permeable sandstone, DP shows 0.8 MPa at the \( CO_2 \) breaking through the specimen, and finally shows stable. Increasing the FR, both DP and \( S_{CO_2} \) become higher and \( S_{CO_2} \) shows the 0.55. Measuring both \( V_p \) and \( Z \), monitoring the \( CO_2 \) front and \( CO_2 \) behavior before the breaking through the specimen. From the \( V_p \) reduction on each cross section of the specimen, it is clear that \( S_{CO_2} \) is higher as close to \( CO_2 \) injection side. Furthermore, applying the basic Archie’s law to estimate the \( S_{CO_2} \), there is a large difference between estimated values and measured one. In high \( S_{CO_2} \) area, \( Z \) is more sensitive than \( V_p \). We need to improve the Archie’s law in considering the effect of clay content and low permeability. The relationship between \( V_p \) and \( S_{CO_2} \) shows in the theoretical area of the \( CO_2 \) cluster size in the pore space.

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