CCS (Carbon dioxide Capture and Storage) demonstration project in Taiwan: Evaluation of hydro-geological structure by laboratory tests

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Abstract

This paper outlines a CCS demonstration project in Taiwan, and introduces the geological features of the test site and test results. A geological survey was conducted from 2012 to 2013 in western Taiwan for a CO_2 pilot injection test. A 3000m-deep well was drilled to characterize the hydro-geological features at the test site. With the use of rock cores that were obtained from this deep drilling, many laboratory tests were performed, including tests to evaluate the two-phase flow characteristics in a CO_2-water system. The permeabilities and basic physical properties of the rock cores recovered from the targeted layers were carefully examined. A decrease in the elastic wave velocity and an increase in resistivity due to CO_2 injection were observed in two-phase flow tests. The test results indicated that CO_2 migration would likely be detected by seismic or electrical survey techniques at the site. A maximum threshold pressure of 13.4 MPa was measured in threshold pressure tests and an inverse relationship was observed between the threshold pressure and permeability. Based on the tests results, we can expect that both the seal capacity and injectivity are at the same level as those in CO_2 injection sites in Japan (Nagaoka and Tomakomai), which are also located within an active seismic area, like the pilot injection site in Taiwan.

Keywords: CCS, laboratory test, demonstration project

1. Introduction

Many studies have sounded the alarm regarding global climate change. One promising technique for slowing the progression of global warming is to capture carbon dioxide and then store it deep underground (CCS). From the perspective of the volume of CO_2 that can be expected to be stored, CO_2 sequestration in a saline aquifer has been considered to be an effective option. Before CO_2 is injected underground, the physical properties of rocks in the candidate injection site have to be investigated to assess the injectivity, seal capacity and/or suitability of geophysical exploration. To predict the behavior of CO_2 that has been injected underground, we must also carefully evaluate the two-phase flow characteristics in a CO_2-water system.

Table 1 shows two-phase flow characteristics. The right-hand column shows how the respective test result can be used. An understanding of the geological structure is also needed to establish a hydro-geological model to simulate CO_2 storage.

This paper introduces a CCS demonstration project in Taiwan, and presents the geological features at the test site and the result of laboratory tests that were conducted by OYO Corporation (OYO). The feasibility of CO_2 sequestration is discussed based on the obtained geological and geophysical information.

Table 1 Two-phase flow characteristics

Two-phase flow characteristics	Purpose
Relative permeability	To predict the behavior of injected CO_2
Threshold pressure	To assess the seal capacity
Elastic wave velocity versus CO_2 saturation	To interpret geophysical exploration data
Resistivity versus CO_2 saturation	

2. Background and outline of the project in Taiwan

The Taiwanese government has set a goal of reducing carbon dioxide emissions to the 2000 level by 2025. CCS is considered to play an important role in achieving this goal. CO_2 emissions from the energy sector account for 66% of the total CO_2 emissions in Taiwan (Tso, 2012). Measures to reduce CO_2 emissions from thermal power plants, which account for approximately 80% of all generated electric power (Bureau of Energy, 2013), have become an important issue in greenhouse gas reduction policy in Taiwan. Taiwan Power Company started a littoral and geological survey in 2008 to screen sites for CCS, and the saline aquifer in the southern part of the Tai-hsi basin was selected as a candidate site for the CO_2 pilot injection test (Fig. 1).

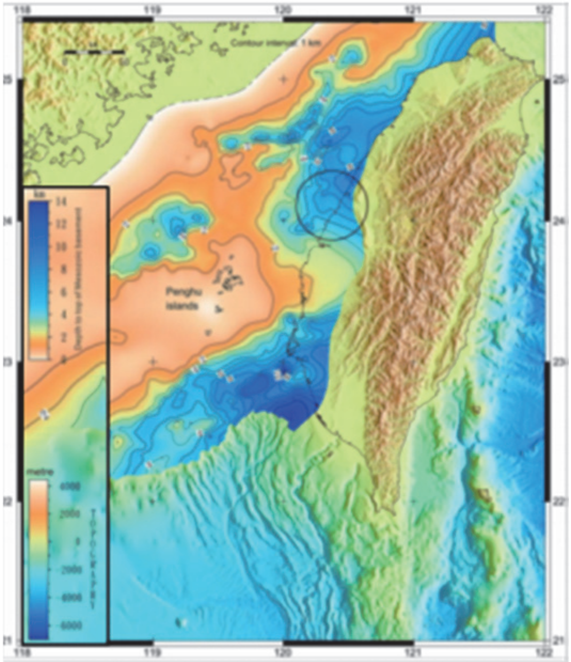

Fig. 1 Location of the pilot injection test site and an isopach map of the Tai-hsi basin (based on Yu et al., 2013)

A seismic survey was conducted in 2010 to obtain further geological information (Ko et al., 2013). Based on an analysis of seismic survey data in 2010 and a pre-existing 2-D seismic image, a thick sandstone layer (Kueichulin formation) at a depth of around 2400 m was considered to have high CO_2 storage potential (up to 4.5 Gt-CO_2) to be the most promising reservoir (Yu et al., 2013). The pilot injection test program was launched in 2011. In the first stage of the program, a 3000 m vertical well was drilled for site characterization. Non-core boring was conducted until 1500 m, and an effort was made to sample all rock cores from 1500 m to 3000 m. Sampled cores were used in various tests to obtain a better understanding of both the geological structure and geophysical information.

3. Geological feature

The island of Taiwan is located at the boundary between the Philippine Sea Plate and the Eurasian Plate, and is thought to have been formed by the collision between these two tectonic plates. This long time-scale tectonic activity has produced an imbricated structure that mainly consists of sedimentary rocks after the late Paleozoic and runs north-northeast/south-southwest. The structure is divided into six or seven geological groups and a younger geological layer is located toward the west (Fig. 2).

The Tai-hsi basin, the candidate site for CO_2 pilot injection, is a Cenozoic sedimentary basin in which settlement and sedimentation have continued to date. The geological characteristics of the basin regarding CO_2 sequestration are as follows:

(1) Neogene or Quaternary geological layers that are more than 3000 m thick constitute a gently sloping homocline structure. Each of these layers stretches continuously to the north-northeast. We expect that large amounts of CO_2 can be stored here.

(2) Mud-stone layers that are expected to act as cap-rock and sandstone layers that are potential CO_2 reservoirs are found at a depth of 800 m or more. Thus, several CO_2 storage scenarios can be constructed.

(3) The candidate site is far from active faults and micro-earthquakes rarely occur in this area.

Therefore, with regard to geological characteristics, the Tai-hsi basin is a feasible site not only for CO_2 pilot injection but also for commercial-scale CO_2 sequestration in Taiwan.

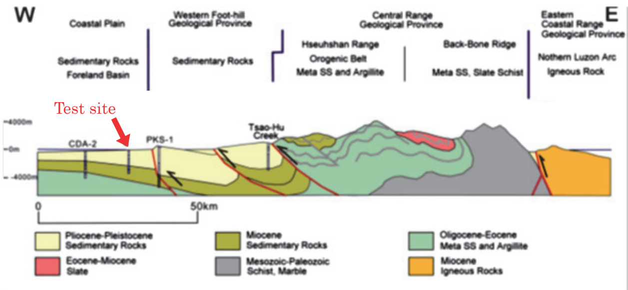

Fig.2 Geological profile along the southern flank of the Tai-hsi Foreland Basin and location of the test site (based on Yu et al., 2014)

4. Laboratory tests

4.1. Test items

The laboratory tests that were conducted by OYO are shown in Table 2. Additional information about the entire program has been reported previously (Yu et al., 2013; 2014). In addition to standard laboratory tests to determine the basic physical properties, two-phase flow experiments using CO_2 in a supercritical state (Photo 1) were extensively conducted on rock cores obtained at various depths. The test results were used not only to evaluate the injectivity of preferred reservoirs and the seal capacity of candidate cap-rock, but also as reference data for determining the controlling parameters in a numerical flow simulation.

Table 2 List of tests conducted by OYO

Test items	Amount of test
Porosity measurement	20
Air permeability test	20
Water permeability test	20
Capillary pressure measurement by mercury intrusion porosimetry	27
Thermal conductivity measurement	20
Threshold pressure measurement with CO_2	7
Threshold pressure measurement with N_2	12
Relative permeability test	11
Resistivity measurement during CO_2 injection	10
P-wave velocity measurement during CO_2 injection	6
In-situ stress measurement by core deformation method	16

Photo 1 Test apparatus for two-phase flow experiments using supercritical CO_2

4.2. Permeability

The absolute and relative permeabilities are important information for characterization of the reservoir. The absolute permeabilities are shown in Fig. 3. Depending on the rock type, the absolute permeability of the rocks ranged from 10^4 to 10^{-5} millidarcy. The absolute permeabilities of sand stones, which are expected to be a potential CO_2 reservoir, ranged from tens to thousands of millidarcy. On the other hand, the absolute permeabilities of silt stones, which could be a candidate cap-rock, were lower than 10^{-2} millidarcy.

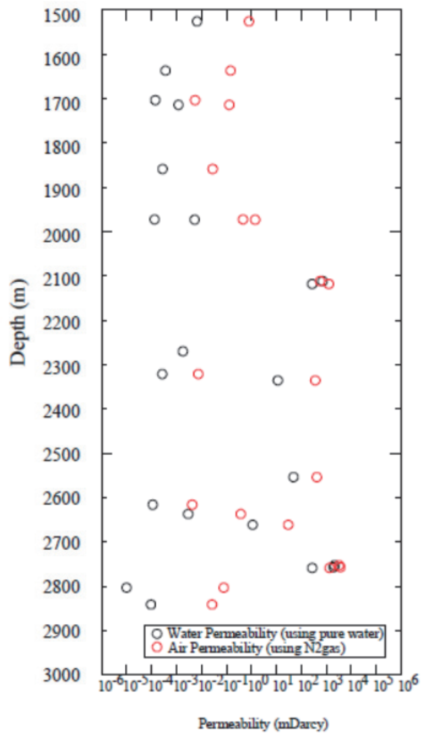

Fig.3 Absolute permeability data

Relative permeability is needed for use in a numerical flow simulation to predict the behavior of injected CO_2. Relative permeability is the ratio of the effective permeability, the permeability of fluids in a multiphase flow condition, to the absolute permeability, which can be measured by a permeability test in a single-phase flow condition. The relative permeability ranges from zero to one if the physical properties of a porous medium are the same in multi- and single-phase flow. The shapes of relative permeability curves have to be evaluated precisely to ensure the accuracy of the numerical flow simulation.

Typical relative permeability curves in a drainage process that were obtained in this work are shown in Fig. 4 and Fig. 5. A core flood test with CO_2 in unsteady state was used. The relative permeability curves for both CO_2 and water were calculated by using a history matching technique and a Corey exponent model was applied to the test data for curve-fitting. Capillary pressure that should act at the interface of CO_2 and water and the electrochemical force that acts around the clay mineral are different in sandstone and siltstone due to the difference in the diameter of the pore throat and the size of the rock minerals. Differences in capillary pressure and electrochemical forces affect the shape of the relative permeability curves. The irreducible water saturation, which is the water saturation ratio at the endpoint of the curves, in sandstone (approximately 0.45) is smaller than that in siltstone (0.65).

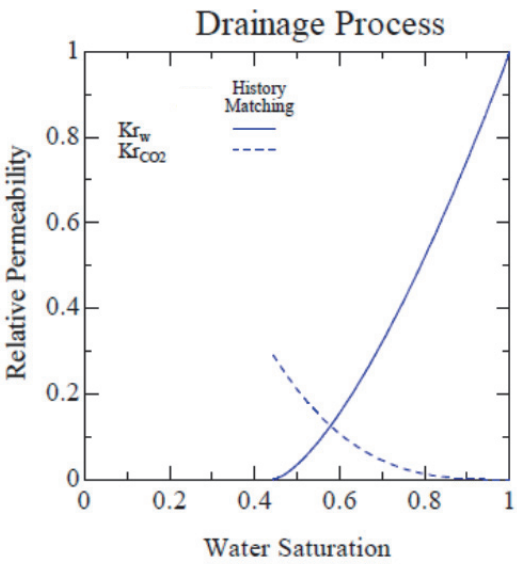

Fig.4 Relative permeability curves of sandstone (Absolute permeability is 95 millidarcy)

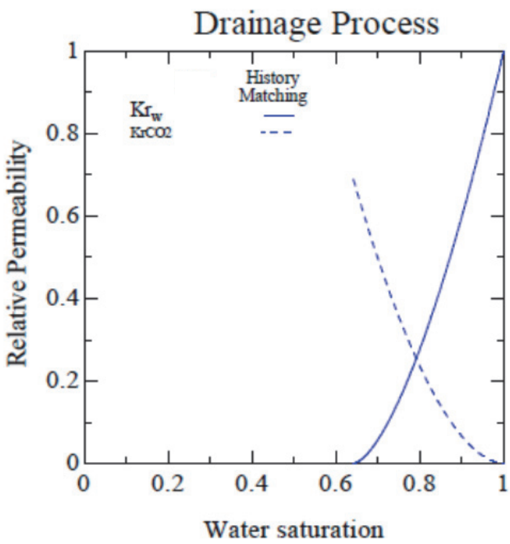

Fig.5 Relative permeability curves of siltstone (Absolute permeability is 0.003 millidarcy)

4.3. Seal capacity

Threshold pressure is at which the injection pressure of CO_2 overcomes the capillary pressure and CO_2 starts to percolate into rock. If we consider CO_2 sequestration at a depth of roughly 1000 m since CO_2 is less dense than water so that the buoyancy force acts upward in CO_2, a CO_2 plume moves toward the surface. When this upward force (buoyancy force × CO_2 column height) exceeds the capillary pressure in the cap-rock, CO_2 percolates into the cap-rock and, in an extreme case, can finally reach the surface. For safety assurance, an evaluation of the threshold pressure is necessary, especially when CO_2 is injected into a saline aquifer, since little geological data is available for a CO_2 sequestration project in a saline aquifer, compared with CO_2 injection into a depleted oil reservoir or EOR (Enhanced Oil Recovery). The results of the threshold pressure test are shown in Fig. 6. The test results from previous studies are also shown for reference (Li et al., 2005; Hildenbrand et al., 2004). In this work, threshold pressure tests were conducted by the staged pressurization method (Li et al., 2005) on low-permeable silt stones that could be candidates for cap-rock. CO_2 in a supercritical state and gaseous N_2 were used as the injection fluids.

The yellow squares in Fig. 6 represent the threshold pressure determined with gaseous N_2. These values were converted to those for a CO_2-water system by considering the interfacial tension ratio between CO_2 and N_2. The green triangles show the test results obtained with CO_2. An inverse correlation was observed between absolute permeability and threshold pressure. If we excluded the results obtained with abnormal cores that showed cracks or veins of sand, the maximum and minimum threshold pressures were 13.4 MPa and 0.71 MPa, respectively, in the test using supercritical CO_2.

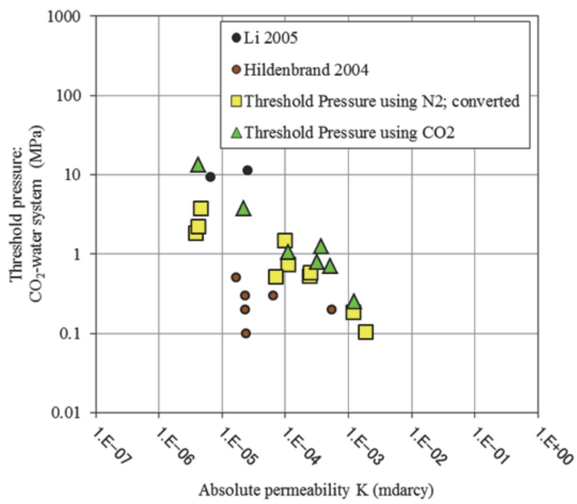

Fig.6 Correlation between threshold pressure versus absolute permeability

4.4. Changes in the elastic wave velocity and resistivity due to CO_2 injection

After CO_2 is injected underground, CO_2 monitoring with a geophysical exploration technique will be needed not only to ensure that CO_2 is sequestrated in the reservoir, but to check the accuracy of the numerical flow simulation. Seismic methods such as seismic reflection, velocity logging and elastic wave tomography are effective tools for CO_2 monitoring. Electrical methods such as resistivity logging, resistivity tomography and electromagnetic survey are also potential techniques for capturing CO_2 migration underground. These techniques are based on the fact that elastic wave velocity and electrical resistivity change depending on changes in the fluid within the pore space of rock.

To confirm that geophysical exploration techniques are suitable for CO_2 monitoring, P wave and electrical resistivity measurements were performed in the laboratory during CO_2 injection into a rock core. Sandy and high-permeable rocks were used. The change in P wave velocity during CO_2 injection is shown in Fig. 7. Although the percentage of the decrease in the P wave velocity differed depending on the rock core, in all cases a distinct decrease in P wave velocity was observed with an increase in CO_2 saturation.

The change in electrical resistivity during CO_2 injection was also measured. Rock cores were saturated with a sodium chloride solution that was adjusted to have approximately the same electrical characteristics as sea water because the electrical characteristics of rock are strongly influenced by the pore fluid. Three electrodes were placed on the upper, middle and bottom parts of the cores to measure the changes in electrical resistance. The electrical resistivities that were measured during CO_2 injection are shown in Fig. 8 (normalized by initial resistivity). The Parameters n in Fig. 8 are the saturation exponent in Archie's formula. In contrast to the results in the P wave measurement, electrical resistivity increased in all of the tests.

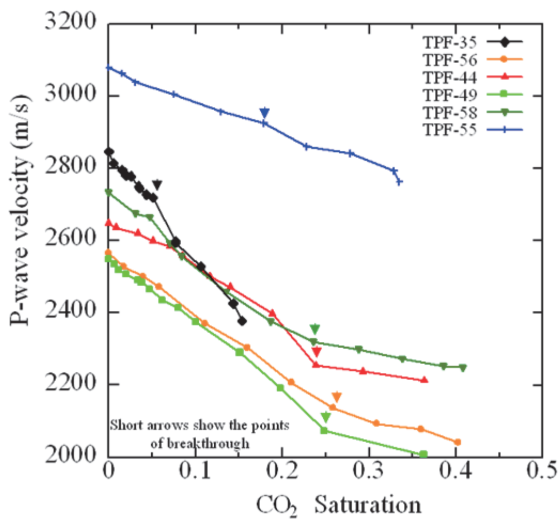

Fig.7 Correlation between P wave velocity versus CO_2 saturation

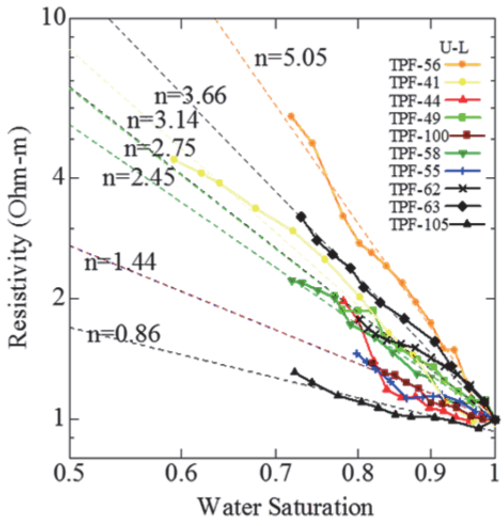

Fig.8 Correlation between normalized electrical resistivity versus water saturation

5. Discussion

The CCS demonstration project in Nagaoka, Japan in 2003 is one of the few CCS projects that has been conducted in a seismically active area. Another demonstration project is now on-going in Tomakomai, Japan. These two projects can be used as a reference. In the Nagaoka project, the lower part of the Haizume layer (early Pleistocene), which had an absolute permeability of several millidarcy, was selected as the reservoir. The upper part of the Haizume layer, which had an absolute permeability on the order of 10^{-2} millidarcy, was expected to act as a cap-rock (Research Institute of Innovative Technology for the Earth, 2002). A total of one M-ton CO_2 was injected successfully, and the geophysical exploration data have indicated that the CO_2 has remained sequestrated in the reservoir to date. In the Tomakomai project, 10 M-ton/year CO_2 has been scheduled for injection into two different reservoirs (Ministry of Economy, Trade and Industry, 2011). Based on an investigation that included laboratory tests, physical properties have been determined to establish the hydro-geological structure and a series of numerical flow simulations have been conducted.

The permeability tests in this work revealed that sandy stones, which could be a candidate reservoir, have high permeability that was almost the same or even higher than that at the Nagaoka site. This suggests that the sufficient injectivity could be expected in the preferred reservoir at the demonstration site in Taiwan.

A maximum threshold pressure of 13.4 MPa and a minimum threshold pressure of 0.71 MPa were obtained by the threshold pressure test using supercritical CO_2. The minimum value is almost the same as the minimum threshold pressure of mudstones that was obtained from a characterization well (Tomakomai CCS-2 well) in Tomakomai.

Test data for both P-wave and electrical resistivity during CO_2 injection showed clear changes in these physical parameters. In the CCS demonstration project in Nagaoka, Japan, a decrease in the P wave velocity of up to 13.4 % was observed by acoustic logging analysis (Xue and Matsuoka, 2008). Although there are some significant differences between a laboratory-scale test and a field survey such as the wavelength of the P wave, the characteristics of the measuring device and the measuring environment, it is highly likely that we could determine the area of CO_2 by acoustic logging if the decrease in P wave velocity measured in the field is comparable to that in a laboratory-scale test.

The change in electrical resistivity during CO_2 injection also suggests that the electrical geophysical exploration technique could be a useful for supplementing a seismic survey.

6. Conclusion

The conclusions that can be drawn from the geological features and the test results can be summarized as follows:

(1) Based on the geological features of the test site, such as the presence of thick and continuous geological layers, the availability of potential cap-rocks and potential storage layers and the distance from an active fault, the Tai-hsi basin is a feasible site for CO_2 pilot injection.

(2) The absolute permeabilities of sandy stones obtained in this work were almost the same or even greater than those in the reservoir at the Nagaoka site. This result supports the feasibility of a CO_2 pilot injection test at the test site.

(3) The minimum threshold pressure obtained with the use of supercritical CO_2 was 0.71 MPa. This value is comparable to the minimum threshold pressure of mudstones that was determined from a characterization well (Tomakomai CCS-2 well) in Tomakomai.

(4) Changes in both the P-wave velocity and electrical resistivity were measured in a CO_2 flooding test. This result suggests that CO_2 migration would likely be detected by a geophysical exploration technique in situ.

This study attempted to evaluate the validity of a pilot test of CO_2 injection that has been planned in Taiwan by considering only limited information regarding the geology and laboratory test data. The geological study and laboratory data indicate that there is a high possibility of successful CO_2 storage at the preferred site in Taiwan. However, further studies will be needed for a precise evaluation of the feasibility of the project. For example, the continuity of preferred storage and seal layers has to be investigated. Heterogeneities in each layer are an important consideration in the numerical flow simulation.

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