Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

HRE28-01 Room:105 Time:May 25 09:00-09:30

Energy and Environmental Policy in Japan

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Japan's energy and environmental policy is presently at a historical turning point. Although the fundamental goals should be pursued as before to ensure stable energy supply, to sustain the Japanese economy by economical and efficient energy, to work on measures against global warming, and to achieve the three "E" s concurrently, debates are ongoing about the degree of future dependence on nuclear power and targeted measures against anti-global warming for 2020 and thereafter, in order to devise practical and concrete measures.

The author believes that to achieve the fundamental goals, it is important to maintain the widest possible range of Japan's energy and environmental policy options. It is necessary to retain the nuclear power option, further the energy-saving efforts, actively introduce renewable energy, and use fossil fuels cleanly and stably. Among them, as Japan's energy and environmental policy frontiers, it would be important to recognize the options for using CCS.

Keywords: Energy, Environmental, Policy, CCS

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HRE28-02 Room:105 Time:May 25 09:30-09:45

CO2 capture technology

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Carbon dioxide capture and storage (CCS) is widely recognized as one of promising technologies to mitigate CO2 emissions from fossil fuel usage to global warming. One of critical issues to implement CCS is a cost of CO2 capture which is estimated to be about 60% of CCS total costs. Therefore many research organizations and companies have been working on the improvement of the existing technologies and the development of more efficient capture technologies to reduce the cost. Current capture technologies will be introduced here.

Keywords: CCS, CCUS, Carbon dioxide, Capture

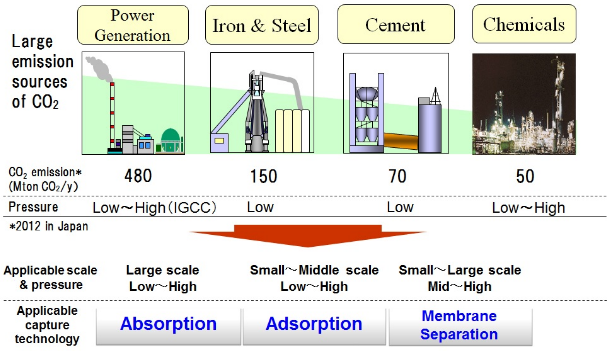

Figure 1, Large emission sources of carbon dioxide and capture technologies

Japan Geoscience Union Meeting 2015
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HRE28-03 Room:105 Time:May 25 09:45-10:00

CO2 Recovery Technology from Power Plants

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It is now widely agreed that capturing CO_2 from flue gases and the subsequent injection into geological formations can significantly contribute to reducing CO_2 emissions, the principal greenhouse gas. As well as having benefits in terms of reducing CO_2 emissions into the atmosphere, the deployment of Carbon Capture and Storage (CCS) can also allow nations around the world to continue using important domestic fossil fuels, such as coal, in an economic and environmentally sustainably way. Among the CCS technology, Enhanced Oil Recovery (EOR) utilizing anthropogenic CO_2 is believed to be an effective use of CO_2. For commercialization of CCS and EOR, scale-up of equipment and energy reduction for CO_2 capture and compression are essential considerations.

Mitsubishi Heavy Industries, Ltd. (MHI) has developed a high efficiency chemical solvent process to capture CO_2 from the flue gas, the KM CDR Process, in collaboration with Kansai Electric Power Co., Inc. Since 1990 MHI has continued R&D programs of CO_2 capture technologies using laboratory research and the CO2 recovery pilot plant at Nanko Power Station. As a result, the KM CDR process has been applied to eleven (11) commercial CO_2 capture plants for natural gas-fired boilers or heavy oil-fired boilers and all of these plants are now in commercial operations.

MHI has also focused on carbon capture technologies for coal fired power plants since 1999, performing numerous test programs for plant performance, optimization, and evaluation of flue gas impurities and their impact at the 1 tonne per day pilot test facility at MHI's R&D center in Hiroshima, Japan. MHI also completed several test programs capturing CO_2 utilizing the 10 tonnes per day slip stream test facility from the flue gas of a commercial 500MW coal fired power plant in Matsushima, Japan in 2006. Based on these R&D commercial experiences and scale-up studies, Southern Company Services, Inc. and MHI successfully started the world's first full chain anthropogenic carbon capture and sequestration (CCS) project applied to a coal-fired power plant. The plant, with a CO_2 capture capacity of 500 tonnes per day, began operation in June 2011 at Alabama Power Company's James M. Barry Electric Generating Plant, and 100,000 tonnes of CO_2 has been successfully injected into a geologic structure, the Citronelle Dome, as part of the Department of Energy (DOE) funded Southeast Regional Carbon Sequestration Partnership (SECARB) phase-III "Anthropogenic Test".

In July 2014, MHI received an order for the world's largest post-combustion CO_2 capture plant (with a CO_2 capture capacity of 4,776 tonnes per day) from an enhanced oil recovery (EOR) project mainly promoted by NRG Energy Inc. and JX Nippon Oil & Gas Exploration Corporation. Captured CO2 will be utilized for EOR at mature oil fields in the Gulf Coast region in U.S.. The operation will be started in 4th quarter, 2016 and it is expected that oil production will be enhanced from 500 barrels/day to approx. 15,000 barrels/day. Furthermore, 1.4 million metric tons of greenhouse gas will be used annually or injection into geological formations.

This presentation will introduce MHI's CO_2 capture technologies and the current activities including the results of the CO_2 capture and storage demonstration test.

Keywords: CCUS, CO2, Capture, KS-1, KM CDR Process

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Japan Geoscience Union Meeting 2015
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HRE28-04 Room:105 Time:May 25 10:00-10:15

Bioelectrochemical Conversion of geologically sequestered Carbon Dioxide into Methane by using Indigenous Microorganisms

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[Introduction]

We are proposing a sustainable carbon cycle system which gives a solution not only to mitigate global warming but also to supply a carbon-neutral energy resource. Carbon dioxide Capture and Storage (CCS) technology, which is currently being developed around the world, could become a practical countermeasure to reduce emission of the greenhouse gas. As potential CO_2 geological storage site in CCS, utilization of depleted oil/gas reservoirs and aquifer has been proposed. The long-term aim of this research is to establish a biotechnological system to microbiologically convert geologically stored CO_2 into methane.

Our recent study revealed that methanogen (methane producing archaea) and exoelectrogen (electron emission bacteria) inhabiting subsurface reservoir are involved in the recently discovered bio-electrochemical reaction called electromethanogenesis ($CO_2 + 8\,H^+ + 8e^- \rightarrow CH_4 + 2H_2O$). In this reaction, methanogen receives a proton (H^+) from reservoir brine and electron from a solid electrode, as a result, reduces CO_2 into methane. Required electricity for the methane conversion can be obtained from renewable energy sources such as wind or photovoltaic power generations.

In this report, we introduce the latest result based on the experiment that used the microbes collected from actual oil field about the possibility of utilization of electrochemical hydrogen reduction power as a method to supply hydrogen to methanogen.

[Experiments]

Single-chambered electromethanogenic reactors were used for an evaluation.

The anode and cathode were made of a plain carbon cross of 4cm x10cm.

The reactors were inoculated with formation water anaerobically collected from Yabase oil field, located in Akita, Japan (oil formation depth: 1,293m - 1,436m, oil formation temperature: 40-82 degrees Celsius). Each reactor headspace was filled with mixed gases of N_2/CO_2 (80/20). The reactors were incubated at 55 ℃ with an applied voltage of 0.75 V.

In addition, methane production rate and conversion efficiency of electricity-to methane were observed changing the applied voltage level with 0.4, 0.5, 0.6, 0.7, 0.8 V.

[Results]

With an applied voltage of 0.75 V, the reactors produced methane at a rate of 386mmol/day m2. The current-methane conversion efficiency was almost 100%. On the other hand, no significant methane production was detected in the reactors without applied voltage. Furthermore, the methane production rate increased from 84 mmol/day m^2 to 1,103 mmol/day m^2, with increasing applied voltage from 0.4 V to 0.8 V. The current-methane conversion efficiency surpasses 90% in all reactors with applied voltages.

To investigate the mechanism of electromethanogenic reaction, the phylogenetic diversity of the microbes on the cathode was analyzed by constructing 16S rRNA gene clone library. As for archae, the result shows methanogene closely related to Methanothermobacter thermoautotrophicus dominated the consortium. On the other hand, as for bacteria, Therminecola ferriacetica, one of the exoelectrogen, was the dominant spices. Our research demonstrated for the first time that the possibility of bioelectrochemical methane conversion of carbon dioxide by utilizing microbes indigenous to oil field.

Keywords: Carbon dioxide Capture and Storage, electromethanogenesis, methanogen, exoelectrogen, carbon cycle

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Trend in the development of microbial technology in CCUS: a bottleneck in the realization of geo-bioreactors

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Carbon dioxide capture and storage (CCS) is the primary technological option to reduce CO_2 emission into the atmosphere. Furthermore, carbon capture, utilization, and storage (CCUS) has recently become widely recognized as a CO_2 reduction measure. CO_2-enhanced oil recovery (EOR) is profitable owing to oil production and is considered a major CCUS technology. It also provides economic incentives for CO_2 utilization. An ecologically sustainable energy production system using CO_2-EOR that yields additional economic incentives has been proposed. The proposed system uses the microbial conversion of injected CO_2 into methane in oil reservoirs[1)]. It is expected that oil reservoirs have applications as geo-bioreactors and can be used as microbial energy production systems in subsurface environments (Fig.1)[2,3)]. In this process, hydrogen that is required for methanogenesis supplies by degradation of hydrocarbons via thermophilic fermentative bacteria in oil reservoirs. However, *in situ* methanogenesis after injections of CO_2 has also been demonstrated[2,4)]; the thermodynamic process that results in anaerobic hydrogenesis from hydrocarbons such as hexadecane in oil reservoirs is unlikely to occur[5)]. There is a major problem associated with maintaining a stable supply of hydrogen for methanogenesis in oil reservoirs. A solution for this issue will be a breakthrough in geo-bioreactor technology.

To date, feasibility studies of the bioconversion of CO_2 to methane in domestic and foreign oil fields based on laboratory tests have been carried out. 16S rRNA survey of DNA extracted from production water confirmed the existence of thermophilic hydrogenotrophic methanogens such as *Methanothermobacter* spp., mesophilic hydrogenotrophic methanogens such as *Methanoculleus* spp. and *Methanofollis* sp., and thermophilic hydrogen-producing fermentative bacteria such as *Thermotoga* sp., *Thermoanaerobacter* spp. *Thermodesulfobacterium* spp., and *Desulfotomaculum* sp. in oil reservoirs. Laboratory gas production tests under high-temperature and high-pressure conditions were performed. Using *Methanothermobacter* sp., *Thermotoga* sp., or *Thermoanaerobacter* sp. as model microbes, methane and hydrogen production under reservoir conditions was observed.

These results demonstrated the potential for microbial conversion of injected CO_2 into methane in oil reservoirs, and highlighted some difficulties in the realization of geo-bioreactors. The number of microbes in oil reservoirs is low; generally, their density is less than 10^4 cells per ml of reservoir brine. In particular, hydrogen-producing fermentative bacteria were not highly represented in the oil reservoir microbial community. A stable supply of hydrogen would be difficult to achieve using these microbes. With respect to biomass, few microbes were available to activate microbial reactions. The shortage of microbes in subsurface environments is one of the bottlenecks in the realization of geo-bioreactors. To remove this bottleneck and establish geo-bioreactor technology, the development of effective microbial growth controls and environmental improvements suitable for microbial activity in subsurface environments is essential.

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Keywords: bioconversion of CO2 to methane, geo-bioreactor, oil reservoir

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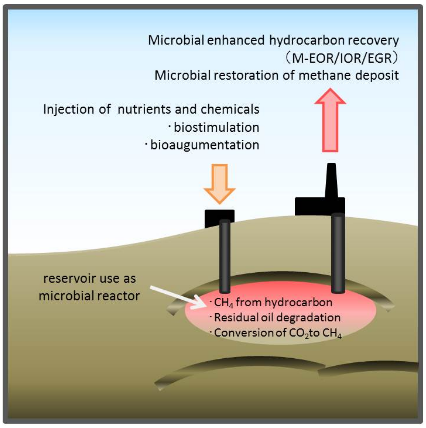

Fig. 1 Schematic representation of geo-bioreactor system [3)]

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HRE28-06 Room:105 Time:May 25 10:30-10:45

Influence of carbon capture and storage on the microbial ecosystem in a depleted oil reservoir

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Deep subsurface petroleum reservoirs are candidate sites for carbon capture and storage (CCS). The feasibility of CCS has been mainly studied from a geological perspective. However, little is known about the effects of CO2 storage on microbes inhabiting the reservoirs. In this study, we investigated the effects of the elevated CO2 concentration on the methanogenic microbial community and function in a high-temperature petroleum reservoir by high-pressure incubation experiments mimicking the in situ reservoir (55 ℃, 5 MPa) or CO2 storage conditions. The microcosms were constructed using the production water and crude oil, pressurized with either N2 or N2+CO2 (90:10) at 5 MPa and then incubated at 55 ℃. Methane production was observed with the decrease of acetate included in the production water under both high and low CO2 conditions. However, the stable isotope tracer experiments and molecular biological analyses for both microcosms showed that the major methanogenic pathway under the in situ reservoir condition was acetate oxidation coupled with hydrogenotrophic methanogenesis, whereas acetoclastic methanogenesis occurred under the CO2 storage condition. Based on thermodynamic calculations, the change to acetoclastic methanogenesis by the increase in CO2 partial pressure was energetically more favorable than acetate oxidation. These results clearly indicated that CO2 storage into a high-temperature petroleum reservoir would cause a drastic change in the methanogenic pathways. Importantly, the elevated CO2 concentration invokes the faster and more favorable methanogenic pathway (acetoclastic methanogenesis) for crude oil biodegradation. Our study presents a possibility of CCS for enhanced microbial production of natural gas in high-temperature petroleum reservoirs.

Keywords: Carbon capture and storage, Depleted oil reservoir, Microbial ecosystems, Methane production

HRE28-07 Room:105 Time:May 25 11:00-11:15

An attempt of geostatistical modeling for spatial mud content: a case study of the Nagaoka pilot site, Japan

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The geological storage of carbon dioxide is considered one of the technologies for mitigation of greenhouse gas emissions. The storage of CO_2 in saline aquifers is the most favorable option. The reservoir characterization such as lithology, petrophysical properties and geological modeling is important for assessing laterally and vertically reservoir heterogeneity, which affects on CO_2 behavior inside the reservoir rock. It is known that reservoir heterogeneity of lithology has effects on CO_2 behavior. Therefore, detailed reservoir characterization is essential to estimate the CO_2 behavior for a long-time scale and storage capacity. Here we present 1) depositional environments, and 2) lithologic model in terms of mud content using geostatical modeling technique under the sequence stratigraphic framework as a case study of the Nagaoka pilot site.

The CO_2 reservoir is interpreted as deltaic or coastal plain deposits characterized by upward-shallowing successions from shelf to shoreface environments. It is known that sedimentary facies agrees with mud content in shallow depositional environments (e.g., Ishihara et al., 2013). At the Nagaoka pilot site, the sediment core analysis indicates that mud content is available for the classification of the depositional environments; mud content in outer shelf is 62.0 % in average, that in inner shelf is 33.7 % in average, and that in shoreface is 20.4 %, respectively. This fact implies that spatial mud content distribution can be regarded as a lihtologic model. The lithologic model estimated by geostatistical modeling technique indicates the heterogeneity of mud content distribution. This lithologic model is reasonable for explaining the geophysical monitoring results showing the heterogeneity of CO_2 distribution inside the reservoir rock. This result indicates that the lithologic model in terms of mud content is a useful for prediction and estimation of the injected CO_2 distribution.

Keywords: CO2 geological storage, Mud content, Geostatistics, Sedimentology, Nagaoka

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HRE28-08 Room:105 Time:May 25 11:15-11:30

Effects of heterogeneity on the distribution of CO_2: Numerical simulation in a CO_2 storage reservoir at Nagaoka

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[1]Research Institute of Innovative Technology for the Earth, [2]Department of Earth Resource Science, Akita University

This paper discusses heterogeneity of petrophysical properties in the reservoir for geological carbon dioxide (CO_2) storage at Nagaoka pilot site in Japan. Detailed site characterization is critical for successful geological storage of CO_2. Not only the traditional site characterization techniques, but also the injection and monitoring data can be used for the geological modeling with heterogeneity. In this study, we carried out numerical simulations using reservoir models with heterogeneity, and compared the results to investigate effects of heterogeneity in the reservoir.

Nagaoka pilot-scale CO_2 injection site was used in this study. Nagaoka project was undertaken in order to verify an ability of CO_2 injection into Japanese formation. CO_2 was injected into a thin permeable zone at a depth of 1100m, and the total amount of injected CO_2 was 10.4 k-tons. Bottom-hole pressure, time-lapse well loggings and cross-well seismic tomography were conducted as the monitoring of injected CO_2.

For the modeling of the reservoir at this site, the method presented by Ito et al. (2015) was used; constructed a profile of the reservoir using seismic results, and generated horizontal distribution of petropysical properties by applying Random function Gaussian Simulation. It is worth to note that the feature along N-S direction had reported at this site (Chiyonobu et al., 2013). The derived models showed that the high porosity and permeability area located in the eastern part of the reservoir.

For the reservoir simulation, hydrological properties for the multiphase flow are also important. We measured capillary pressure function using mercury injection tests. The measurements indicated that the functions in sandy and shaly rocks were different. For the relative permeability function, we referred the results reported by Ohtake (2013), and approximated to van Genchten function. We did not assume hysteretic functions in this study.

We made simulation using the reconstructed models and TOUGH2 simulator. For the history matching, bottom-hole pressure and CO_2 saturation data were used. Several absolute permeability models were tested manually in order to find the best match between the monitoring data and the reservoir simulation. We could find a geological model reasonably matched to the monitoring data. The result of CO_2 distribution was also consistent with the observed velocity anomalies by the cross-well tomography. The numerical results revealed the migration of CO_2 plume to up-dip direction. This explained the behavior of CO_2 distribution observed by the wire-line logging very well.

During the history matching, sensitivity analysis of the model was conducted. The results suggested that anisotropy of the permeability was essential to explain the monitored CO_2 behaviors. This anisotropy could be created during the depositional process of the reservoir. It should be noted that not only the permeability distribution, but the properties depending on facies were also important to the matching.

This work was supported by Ministry of Economy, Trade and Industry of Japan under the research contract ”Development of Safety Assessment Technology for Carbon Dioxide Capture and Storage”.

Keywords: CO2 geological storage, Nagaoka site, multiphase flow, heterogeneity

HRE28-09 Room:105 Time:May 25 11:30-11:45

Sensitivity Analysis of internal structure and rock properties on Long-term Behavior of CO2 Injected into Multi Layers

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Multi-layer formations composed of alternating sandy, high-permeable layer and muddy, low-permeable layer are expected to trap CO_2 due to dissolution and residual gas mechanism. In general, anisotropic permeability is allocated to sedimentary formations, however, this anisotropy is possibly due to finer alternating structure and/or intrusion of sandstone channels into mudstone in actual. Such difference of internal structure can affect on the long-term behavior of injected CO_2. In this study, we will present the results of the sensitivity analysis of internal structure and rock properties on the long-term behavior of CO_2 injected into multi-layer formations.

We constructed a two-dimensional radial model with 20 km width and 1.4 km depth for the simulation. Submarine conditions of 10 ℃ and 2.0 MPa are assumed for the top boundary. The topmost 300-meter region is composed of the unconsolidated sediment, and the alternating layers of 120-meter sandy formation and muddy formation underlie it. The lowermost 100-meter region is assumed to be the basement. Each sandy formation has vertical/horizontal permeability of 10/100 mD. We investigated two cases of permeability of muddy formation, that is, 1/10 mD and 0.1/1 mD. We represented these 120-meter-thick formations by i) homogeneous porous model as a base case, ”finer multi-layer model” composed of alternating sandstone layers and mudstone layers which have isotropic permeabilities and thickness of ii) 30-meter and iii) 10-meter, and iv) 120-meter ”MINC” double-porosity model with impermeable matrix and sandstone channels. For ”finer multi-layer model”, we defined permeabilities of sandstone layers and mudstone layers in such a way that their harmonic and arithmetic averages were equivalent to vertical and horizontal permeabilities of sandy/muddy formation, respectively.

Capillary pressure was represented by van Genuchten type, and the threshold pressure (P_{th}) was given as a function of vertical permeability (k_z) obtained from experiments using either sintered compacts or rocks. We also assumed two cases for the presence of hysteresis of relative permeability for sandstone. Except for hysteresis, models of relative permeability for water and CO_2 were assumed to be common to all formations. They are represented by functions of van Genuchten type and Corey type, respectively. CO_2 is injected into a sandy formation at a depth from 940 m to 1,060 m at a rate of 1 Mt/year. The injection interval is 50 years.

Using this model, we conducted 32 cases of numerical simulations on the long-term behavior of CO_2 for the injection period and 1000 years of shut-in. Simulations are carried out using the ”STAR” reservoir simulation code with the ”SQSCO2” equation of state.

Simulated results of the cases where kz of muddy formation was 1 mD and P_{th} was defined by experimental results of rocks showed that i) CO_2 migrated upward to a depth of 640 m by 1000 years after shut-in with the 120-meter porous model, however, ii) its upward migration was restricted with the ”finer multi-layer model” due to enhancement of multi-layer trapping. On the other hand, iii) presence of sandstone channels with high permeability and low capillary pressure allowed buoyant migration of during shut-in period. However, presence of liquified phase between depths from 360 m to 700 m slowed down CO_2 upward migration to a depth of 120 m by 1000 years after. These results indicate that internal structures significantly affect long-term behavior of CO_2, even if their 120-meter-average permeabilities are equivalent.

Additionally, upward migration of CO_2 significantly restricted with P_{th} defined by experimental results of sintered compacts, and effects of relative permeability hysteresis are relatively limited in this study, especially for ”finer multi-layer model”.

This research is funded and supported by Ministry of Economy, Trade and Industry (METI).

Keywords: geological CO2 storage, saline aquifer, multi layers, anisotropy, numerical simulations

HRE28-10 Room:105 Time:May 25 11:45-12:00

Prediction of the fingering CO2 flow in homogeneous and porous sandstone

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CO_2 flow mechanisms in porous geological materials are essential to understanding CO_2 behavior in CCS reservoirs. Recently, computer simulations based on Lattice Boltzmann method (LBM) illustrated characteristic fingering-flow patterns associated with invading CO_2 displacing the resident brine in porous materials. These studies also indicated that these fingering flow patterns are strongly controlled by transport properties (e.g., capillary number, C_a,; and viscosity ratio, M). On the other hand, injected CO_2 behavior in the reservoir is monitored by geophysical and geo-mechanical parameters. In particular, seismic survey is the most useful for CO_2 monitoring. Unfortunately, we have only a little knowledge about the relationships between mechanisms of two-phase flow in the porous rock and measurable physical properties. In this study, we conducted the V_p and strain measurements to elucidate the relationship between transport properties and geophysical properties by using Mt. Simon sandstone (porosity: ϕ=26.4). The Mt. Simon sandstone has a high absolute permeability (105 mD) and a unimodal pore-size distribution (peak size: 23 μm). We set three V_p-measurement lines and two strain gages (vertical and horizontal) at the center of core. We observed changes in flow rate, volumetric strain and the differential pressure between the two pumps during the drainage and imbibition processes. In the drainage stage, CO_2 is injected at a constant rate into the sample upto 2.17 PV (1PV=95.1 ml) for 429 min. During this stage, differential pore pressure increased slowly from 0.1 MPa to 0.12 MPa. The upward flow rate is constant at 0.5 ml/min during drainage, which corresponds to the flow velocity 1.6x10^{-5} m/s. All the V_p-measurement lines indicate simultaneous small velocity reductions ($<$2%), after 2.17PV CO_2 injection, lower than the values reported in previous studies. Some previous studies reported over 10 % V_p-reduction in drainage. In contrast, the strain data indicate expansions of over 2000$\mu\epsilon$ and 1400$\mu\epsilon$, at the up- and down-stream side of the flow, respectively. The amounts of the strain are consistent with previous studies. Since the changes in V_p should be directly related to the changes in CO_2-saturation around the P-wave propagation paths. These results suggest a possibility that there are no large saturation of CO_2 However, strain data indicate the existence of injected CO_2 in pore-space. Thus, we presume that the CO_2 makes a channel out of the Fresnel zones of all V_p-measurements lines. We also estimate the Ca based on flow rate data and viscosity ratio of CO_2 and water. Our estimated C_a is low (2 x10^{-8}). From these transport properties, it is clear that the flow within the porous rock resides in the capillary fingering domain. This estimation based on fluid mechanical analysis is supported by direct flow monitoring experiments with X-ray CT scanner. These studies illustrated the change of flow pattern of the non-wetting phase (CO_2). In the case of low flow rate, CO_2 makes a few thin paths through the porous rock. Together, these results suggest the potential for petro-physical properties to infer the characteristics of the heterogeneous two-phase flow in porous rock.

Keywords: two-phase flow, porous sandstone, Capillary number, fingering flow, P wave velocity, Carbon Capture and Storage

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HRE28-11 Room:105 Time:May 25 12:00-12:15

Effective confining stress-dependence of hydraulic properties of mudstones under conditions of geological storage of CO2

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For implementation of the carbon dioxide (CO_2) capture and storage, during CO_2 injection process, overpressure within targeted reservoirs might occur because of changes in stress related to the CO_2 pressure, which could lead to deformation of the surrounding rocks, including caprocks which are geological formations with low permeability overlying a CO_2 storage reservoir. The understanding for impact of effective pressure (i.e., the difference between confining pressure and pore pressure) on hydraulic parameters (i.e., threshold pressure and permeability) of such caprocks has a critical role in the safe implementation of CO_2 geological sequestration. The purpose of this study was to examine the hydraulic properties of mudstones, which were taken from Otadai (OTD), Ohara (OHR), and Namihana (NMH) formations of Kazusa group, depending on effective pressure at 40 ^{0} C and effective pressures of the range from 1-20 MPa. Change in porosity as a function of effective pressure was also investigated in order to infer the critical pressure, which provided an insight into the relationship between threshold pressure and permeability. Our results demonstrated that with increasing effective pressure, OHR mudstone exhibited a steeply decreasing trend in permeability at around 5 MPa, whereas OTD and NMH mudstones exhibited a monotonous decrease. All data of threshold pressure as a function of effective pressure exhibited linear correlation with permeability data on a log-log scale, except for the OTD and OHR mudstones at below the inferred critical pressure. It was suggested that the relationship between threshold pressure and permeability depends strongly on changes in pore structures as a function of effective pressure for each mudstone tested.

The present results pointed out that the presence of microfractures could be critical in characterizing the hydraulic parameters of mudstones, and mudstones with crack-like pores and/or microfractures such as the OTD and OHR mudstones might be significantly more susceptible to decreasing threshold pressure compared with fracture-less structures under below the critical pressure condition. However, considering CO_2 injection process which means that CO_2 is injected into the targeted reservoirs within normal stress states, all the obtained data above the critical pressure could be explained fully by the linear correlation between threshold pressure and permeability, even if the mudstones incorporated micofractures.

Keywords: threshold pressure, permeability, mudstone, effective pressure, CO2 geological storage

HRE28-12 Room:105 Time:May 25 12:15-12:30

Quantitative interpretation of experimentally-observed poroelastic behavior of Berea sandstone in two-phase fluid system

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Deformation behavior of rocks associated with geological sequestration of carbon dioxide has been studied based on coupled processes of two-phase fluid flow and deformation of porous media (e.g., Rutqvist et al., 2010). However, it is not easy to interpret the deformation behavior because of its complexity, such as heterogeneity of rock masses. Laboratory experiment can be helpful in understanding the physical processes, and it will be useful for the interpretation of deformation behavior of rock masses in situ. Recently, Goto et al. (2014) observed the poroelastic behavior of Berea sandstone under two-phase fluid flow condition through laboratory experiments, and reproduced the experimental results by numerical simulation. In this presentation, we will interpret the experimental results obtained by Goto et al. (2014) through numerical simulations, and future subjects which are necessary for further understanding of the studied behavior will be clarified.

References

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Keywords: Geological sequestration of carbon dioxide, Poroelastic behavior, Two-phase fluid flow, Laboratory experiment

HRE28-13 Room:105 Time:May 25 12:30-12:45

Influence of reservoir conditions on CO2-brine behavior in natural sandstone: Insight from lattice Boltzmann method

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In CO2 geological storage, the behavior of CO2 inside a reservoir can be characterized as two-phase flow in a porous media system. Microscopic two-phase fluid behavior in porous media is influenced by temperature, interfacial tension, pore structure, and porous medium characteristics (e.g., wettability), which vary significantly from one reservoir to the next. Pore-scale interfacial instabilities, such as snap-off and fingering phenomena, influence the stability, injectivity, mobility, and saturation of CO2 within the reservoir. Therefore, understanding microscopic CO2 flow in porous media is crucial to estimating CO2 critical reservoir-scale characteristics, including storage capacity, leakage risk, and storage efficiency. Here we calculated fluid displacements within 3D pore spaces of Berea sandstone using two-phase lattice Boltzmann (LB) simulation, in order to characterize the influence of reservoir conditions upon multiphase flow. We classified the two-phase flow behavior that occurred under various conditions into three typical fluid displacement patterns on the diagram of capillary number (Ca) and viscosity ratio of the two fluids (M). We then characterized dynamic pore-filling events (i.e., Haines jumps) from the fluid pressure variation. The results revealed the onset of capillary fingering in natural rock at a higher Ca than previously reported for homogeneous porous media, with the crossover region between typical displacement patterns much broader than in a homogeneous granular model. These differences between two-phase flow in natural rock and in a homogeneous porous structure could be the result of the heterogeneity of the natural rock. Capillary fingering at higher Ca indicates that the dominant fluid displacement mechanism in most parts of the reservoir is likely capillary fingering. The simulation results reveal the influence of reservoir conditions on saturation of the CO2. Therefore, we have clarified suitable conditions for CO2 storage.

Keywords: Multiphase flow, 3D digital rock, Lattice Boltzmann simulation, Displacement patterns, Heterogeneity

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HRE28-14 Room:105 Time:May 25 14:15-14:45

Moving toward Commercialization of CO2 Storage in Japan

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The IPCC published a special report on Carbon dioxide Capture and Storage(CCS) in 2005, stating that CCS is one of the promising options for mitigating carbon dioxide emissions into the atmosphere. Among several CO2 storage options, storing CO2 in saline aquifers is the most promising because of the large storage potential, estimated at from about 2,000 Gt CO2 to more than 10,000 Gt CO2. Some CCS technologies are already in practical use in several countries and are economically viable. Close attention has been paid recently to deep saline aquifer storage, which is expected to have a large storage potential of about 2,000 Gt CO2 throughout the world. First of all this presentation describes current global trends of CCS technology development and national policies. Then this presentation focuses on the mechanisms of deep saline aquifer CO2 storage. In deep saline aquifer storage, chemical reactions in the water-rock-CO2 system play important roles for trapping CO2 in the aquifer formation, as well as physical trapping by overburden impermeable cap rocks and residual gas trapping mechanisms. The presentation will also stress the importance of the long-term monitoring of the storage aquifer because CO2 would be trapped stably in the formation for a long time. It is thus important to develop effective monitoring techniques for the behavior of CO2 in the aquifer. Physical as well as chemical monitoring techniques should be used for storage aquifer monitoring. Finally the presentation conclude with discussions about storage potential in Japan and some important issues related to deep saline aquifers. Deep saline formations are distributed widely in Japan, and have the potential for the geological storage of 146 Gt of CO2. It is therefore economically feasible to use deep saline formations near large emission sources such as coal-fired power plants and integrated steel works. To realize CCS in Japan, it is important to make further advances in studies on the basic physical and chemical trapping mechanisms of water-rock-CO2 system, and in studies on the geological characteristics of aquifer formations.

Keywords: CO2, CCS, monitoring, trapping mechanisms, storage potential, commercialization

HRE28-15 Room:105 Time:May 25 14:45-15:00

Geomechanical modelling for CO2 geological storage: insights from natural analogue research

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When CO2 gas is pressure-injected into an underground reservoir for geological storage, the pore pressure underground increases, and the stress distribution underground may change. Stress redistribution within and surrounding the reservoir and caprock system my lead to geophysical changes, microseismicity, fault reactivation, and may even trigger large earthquakes. For example, at a gas field in In Salah, Algeria, where CO2 is pressure-injected to enhance natural gas production, synthetic-aperture radar observations from a satellite have indicated a ground uplift rate of about 1 cm/year around the CO2 pressure injection wells, along with a similar amount of subsidence around the gas production wells. In some gas fields in the Sichuan Basin, China, following injection of unwanted water into depleted gas reservoirs, a number of seismic sequences have been observed with sizable earthquakes ranging up to M5.

Indeed, geophysical changes and microseismicity are useful in the monitoring and management required during and after a large-scale injection project. However, the risks related to fluid leakage and earthquakes that can be felt may give rise to strong social impacts. The issue of noticeable or damage-causing earthquakes induced by artificial operations is controversial, and has been the cause of delays and threatened cancellation of some projections such as the EGS (Enhance Geothermal System) project at Basel. To carry out geological CO2 storage safely and for this technology to be accepted not only by the inhabitants around the storage sites, but also by the society as a whole, technological developments that address such public concerns is essential. In addition, there is a strong desire to be able to control or predict the occurrence of damaging earthquakes. In these regards, geophysical/geomechanical modelling is key in site selection, injection operation, and post injection management.

In geological CO2 storage, it is important to clarify the mechanisms and geomechanical conditions of worst-case events, such as damaging earthquakes and reservoir leakage, so that they can either be avoided or mitigated. It is most desirable to use an actual CO2 geological storage site in which such events have actually occurred and have been well monitored. However, many pilot projects are sited in places with good conditions for safely pressing CO2 into the reservoir. Thus it is valuable to carry out ”natural analogue research”, analysing similar phenomena caused by the activity of a natural CO2-quality fluid to examining the modelling technology. In the Matsushiro area, a series of more than 700,000 earthquakes occurred over a 2-year period (1965-1967). This swarm, termed the Matsushiro swarm, resulted in ground surface deformations (uplifts as large as 75 cm), cracking of the topsoil, enhanced spring outflows with changes in chemical compositions, and CO2 degassing. Ten million tons of CO2-rich saltwater seeped was estimated to have seeped out from underground along the cracks. Thus the Matsushiro swarm is believed to have been triggered and driven by high pressure CO2-rich fluid from deep sources. Data observed during the Matsushiro swarm can therefore be used as a natural analogue for examining the geomechanical modelling technology based numerical simulation using the coupled THM (heat transferring, fluid flow, rock mechanics) analysis. Here, we make a brief review of studies on the Matsushiro fluid-driven earthquake swarm based on TOUGH-FLAC approach.

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Keywords: CCS, Geomechanical modelling, Fault, Matsushiro seismic swarm, Deep fluid

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HRE28-16 Room:105 Time:May 25 15:00-15:15

On the Passive Geophysical Monitoring Research for CO2 Geological Storage at AIST

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[1]AIST

An appropriate monitoring program is indispensable for an individual geological carbon sequestration project to detecting subsurface changes within the reservoir, to provide for potential risk such as CO_2 leakage through the caprock, and to improve the predictive capability of reservoir simulation. Time-lapse seismic method is mainly used to monitor subsurface CO_2 plume and have demonstrated its capability to detect temporal and spacial changes of CO_2 plume in many geological storage site as Sleipner.

However, relatively high cost of time-lapse seismic requires some another monitoring choice, especially for sub-seabed storage typical in Japan. AIST have studied passive geophysical monitoring method to reduce the repetition of the seismic sounding, especially in post-injection period.

In order to investigate the feasibility of passive geophysical monitoring methods for CO_2 geoloical storage, we carried out reservoir simulations of CO_2 geological storage, and calculated the temporal changes in geophysical observables caused by subsurface changes due to CO_2 injection. We also carried out high-resolution gravity, self-potential and AE(passive seismic) monitoring in Farnsworth test site in USA, where large-scale field testing injecting of CO_2 is carried out by the Southwest Partnership on Carbon Sequestration (SWP). From 2014, we started baseline monitoring of gravity and SP in Tomakomai, where the first demonstration test will be planed from FY2016.

Acknowledgement
This research is funded and supported by Ministry of Economy, Trade and Industry (METI). Funding for the Farnsworth project is provided by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) through the Southwest Partnership on Carbon Sequestration (SWP) under Award No. DE-FC26-05NT42591. He authors also thanks to Chaparral Energy, University of Utah, New Mexico Institute of Mining and Technology, Japan CCS, Tomakomai city for their support for our monitoring.

Keywords: CO2 Geological Storage, monitoring, gravity, self-potential, passive seismic

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HRE28-17 Room:105 Time:May 25 15:15-15:30

The Micro seismic and well pressure monitoring system installation for Tomakoami CCS demonstration project

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[1]Japan CCS Co., Ltd., [2]JGI, Inc., [3]PrimeCast Co.,Ltd.

As a part of "the large-scale CCS demonstration project at the Tomakomai area", METI plans the micro-seismic monitoring and wellbore pressure/temperature continuous measurement, These monitoring data will be used in order to find out the distribution of CO_2 plume in the reservoir and to assess relations between micro-seismic activities and CO_2 injection. The installation of the measurement system has completed in the end of January 2015 and the baseline observation has been just started.

The monitoring measurement system consists of an ocean bottom seismic cable, four ocean bottom seismometers, a land seismic observation station, seismic sensors in three observation wells, wellbore pressure/temperature sensors and three DTSs(distributed temperature Sensor) in each well.

Observed Data, excludes three OBS data, are gatherd to the JCCS Tomakomai Office at almost the same time. The monitoring data management system, which has been developed, will be able to check anomalies of the collected data immediately. If any seismic event is detected, hypocenter will be determined automatically.

This paper reports the overview of the monitoring data management system

Keywords: CO2 storage, CCS, monitoring

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HRE28-18 Room:105 Time:May 25 15:30-15:45

Geochemical monitoring of CO2 underground and an evaluation technique of geochemical features

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[1]RITE

Mechanism of carbon dioxide (CO2) geological storage is similar to accumulation of oil and natural gas deep underground (gas trapping). Additionally CO2 dissolves into water in the reservoir (solubility trapping). A part of dissolved CO2 precipitates as carbonate minerals (mineral trapping). Geochemical trapping such as solubility and mineral trapping prevent upward migration of CO2 by eliminating its buoyancy. Amounts of solubility and mineral trapping strongly depend on storage sites. Timing of mineral trapping is still unclear. In this study, we present an evaluation technique of geochemical features at a CO2 geological storage site, the Nagaoka site for an example. We collected core and water samples from the injection well before CO2 injection. After cessation of CO2 injection, formation water was collected twice from the observation well by Cased-hole Dynamics Tester (CHDT, Schlumberger). Monitoring results showed that solubility trapping occurred around CO2 bearing layer and a condition of CaCO3 precipitation was prepared below the layer. Laboratory experiments indicated that Ca containing silicate such as plagioclase provide Ca to precipitate with dissolved CO2. A preliminarily result of reactive transport modeling showed solubility trapping was the dominant mechanism for CO2 trapping and mineral trapping increased with time at the Nagaoka site. Details of an evaluation technique of geochemical features will be presented at the session.

HRE28-19 Room:105 Time:May 25 15:45-16:00

A method for assessing the impacts of leaked CO2 on the marine environment

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Carbon dioxide (CO_2) capture and storage (CCS) is promising technology that mitigates the global warming. Captured CO_2 from industrial processes is transported to a reservoir in the deep geological formations. Storage sites are selected so deliberately that CO_2 is believed to be stably stored in the reservoir. However, in case of a worst-case scenario, we should assess the impacts of leakage. In Japan, CO_2 will be stored under the seabed, so that CO_2 would leak out into the sea if unexpected leakage should occur. Therefore, we should assess the potential impacts on the marine environment. In this talk, we will introduce a method of the assessment that we have been developing. The method consists of two tools; a numerical model and a database of marine biological impacts. A numerical model predicts dispersion, i.e. distribution and concentration, of leaked CO_2 in the sea. Since leaked CO_2 is advected and diffused by ocean flow, the model should properly represent flow, temperature, and salinity fields in the sea. In addition, seasonal variation in the sea could be important for the simulation. Stratification in the sea strengthens in summer and weakens in winter, so that leaked CO_2 would be more likely to be mixed vertically in winter than in summer. We have been developing an ocean model for simulating leaked CO_2, taking consideration of those factors above. The model is based on a non-hydrostatic ocean model, called *kinaco*, developed by Matsumura and Hasumi (2008). In general, numerical cost of a non-hydrostatic model is very expensive. In *kinaco*, numerical cost is improved greatly, which enables a simulation in a relatively large area and of a relatively long period, as a simulation with a non-hydrostatic model. With this model, we conducted a numerical simulation in a gulf-like topography. A passive tracer, which is regarded as TCO_2 (total dissolved inorganic carbon) originating from leaked CO_2, is injected near the bottom. In order to represent seasonal variation, sea surface temperature (SST) is restored to temporally variable temperature from observational data, and temperature and salinity on a lateral boundary are also restored to observational data. Wind velocity data given at the sea surface, which are converted to wind stress in the model and drive the model ocean, are daily mean observational data. In order to access the potential impacts of leaked CO_2 on the marine organisms, we make use of a database of marine biological impacts of CO_2 concentration that RITE has been compiling. The biological impacts of CO_2 in the ocean are referred to not TCO_2 but partial pressure of CO_2 (pCO_2), and so the calculated TCO_2 in the simulation should be converted to pCO_2. With the resulting pCO_2 values and the database, we can estimate the potential area where marine organisms might be impacted.

Keywords: marine environmental impacts, Carbon dioxide Capture and Storage, numerical model, database of marine biological impacts

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HRE28-20 Room:105 Time:May 25 16:15-16:30

Wellbore integrity assessment of CO2 sequestration site from the geochemical reaction using well composite samples

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[1]Research Institute of Innovative Technology of the Earth

We studied to the geochemical interaction between CO_2, well cement and sandstones for the long-term wellbore integrity in a CO_2 sequestration. To simulate the wellbore system, we prepared well composite samples consisting of steel casing, Portland cement (API ClassA), and sandstone. Using the samples, batch experiments were conducted at 50 ℃ and 10 MPa of CO_2 pressure corresponding roughly 1 km below the ground surface. The well composite samples were exposed to the CO_2 saturated brine and the supercritical CO_2 and for 56 days.

After the reaction with CO_2, cement alteration zone were clearly observed along the cement-sandstone interface under CO_2 saturated brine condition and wet-CO_2 condition. The cement alteration zone was visibly divided into two layers; one is an orange-colored layer (carbonation zone) in the outer cement, and another is white-colored layer in the inner cement. The carbonation depth under wet-CO_2 condition was larger than that under CO_2-saturated brine condition. However, the carbonation depth was a few millimeters and inner part of cement did not altered within 56 days of the reaction. Based on the results the predicted 30 years carbonation depth evaluated by a logarithmic approximation was estimated at 4.5 mm for wet-CO_2 condition and 0.76 mm for CO_2-saturated brine condition, respectively. The Ca concentration in the carbonation zone increased 13% in comparison to that in the unaltered cement zone while the Mg, Si, and S concentrations decreased significantly. The predominant crystalline phases in the carbonation zone were $CaCO_3$ (calcite, aragonite, and vaterite). On the other hand, focusing on the sandstone side, it was observed that small points rich in Ca distributed in the pore spaces of the sandstone. This suggests that the precipitation of calcium carbonate is as result of Ca^{2+} diffusion out of the cement coupled with inward diffusion of carbonate ion. The formation of $CaCO_3$ reduces cement permeability and increases its compressive strength. These results indicate that the formation of fine carbonate provides an effective barrier to further CO_2 attack.

Keywords: CCS, well integrity, cement, carbonation

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HRE28-21 Room:105 Time:May 25 16:30-16:45

Preliminary simulation for the behavior of aqueous solution of carbon dioxide in abandoned coal mine

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In order to realize the scenario by the Ministry of the Environment to reduce 80% GHG emissions by 2050, even minor corporations which emit less than 108 kg-CO_2/year will have to implement CO_2 capture and storage. Therefore it is necessary to develop and prepare various ways of CO_2 storage to be adaptive to various geological conditions.

We conducted preliminary simulation for the behavior of aqueous solution of CO_2 injected by CMS (Carbon Dioxide Micro Bubble Storage) project. We particularly examine the case applying CMS to abandoned coal mine because the geological condition has been well investigated and relatively high porosity is expected around the past panels.For a case study, we developed a model for Shimizusawa coal mine in Yubari city, Hokkaido, Japan.

The simulated results from the standard model based on the range of existing data and practical injection rate showed that the aqueous solution of CO_2 was stored in the past panels. Even if we assumed the upper formations were as permeable as sandstones, aqueous solution of CO_2 was stored in the past panels. These results suggest the stability of CO_2 storage by the form of aqueous solution. On the other hand, if we assumed the thinner panels, aqueous solution of CO_2 did not spread well and aqueous solution of CO_2 reached the inclined access shaft. This result suggests that aqueous solution of CO_2 possibly flows to permeable pass preferentially to surface if the balance of reservoir condition and injection rate is not appropriate.

These results are expected to contribute to the design of CMS project or evaluation of solubility trapping.

Keywords: CO2 geological storage, CMS, aqueous solution of CO2, numerical simulation, abandoned coal mine