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Research Progress on Carbon Dioxide Geological Storage

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Abstract. Carbon Capture, Utilization, and Storage (CCUS) technology is one of the key approaches to address global climate change and achieve carbon dioxide emission reduction. As a core component of the CCUS technology system, CO_2 geological storage will play a foundational supporting role in the process of achieving the carbon neutrality goal in China's energy industry. Currently, the main geological formations for CO_2 storage include deep saline aquifers, depleted oil and gas reservoirs, deep unmineable coal seams, and basalts. Due to differences in rock properties and geological conditions, different geological formations have formed distinct storage mechanisms and models. Based on a systematic analysis of CO_2 storage mechanisms in different geological formations, combined with typical domestic and international engineering cases, this paper summarizes the implementation effects and applicable conditions of various storage technologies. Additionally, aiming at the current technical bottlenecks and safety risks of CO_2 geological storage, this article discusses the future technical development directions and industrialization paths, in order to provide theoretical support and practical reference for promoting the large-scale application of CO_2 geological storage technology in China.

Keywords: CO_2 geological storage, storage mechanism, storage engineering cases, storage safety, CO_2 monitoring

1. Introduction

The emission of greenhouse gases such as CO_2 leads to global warming, which is a common problem facing the world. Reducing their emissions has become a major issue of common concern to the international community. Currently, there are many methods to reduce carbon dioxide emissions worldwide. Carbon Capture, Utilization, and Storage (CCUS) is an important technical means to reduce greenhouse gas emissions and address climate change. The United States, the European Union, the United Kingdom, Japan, and other countries have successively introduced relevant strategies to promote its development [1]. Recently, the International Energy Agency (IEA) released the report Credible Pathways to 1.5°C: Four Pillars for Action in the 2020s, pointing out that CCUS is one of the four pillars of action. According to the IEA report, the contribution of CCUS technology to emission reduction will increase from 3% of the total emission reduction in 2020 to 10% in 2030, and will reach 19% by 2050.

CO_2 geological storage refers to the process of storing captured CO_2 in deep formations through engineering and technical means and using it to enhance energy extraction, which is an important

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part of CCUS. The main storage sites include deep saline reservoirs, depleted oil and gas reservoirs, deep unmineable coal seams, and basalts. Currently, a series of geological storage projects have been carried out internationally and domestically, such as the Sleipner saline aquifer storage project in Norway, the proposed Porthos depleted gas reservoir storage project in the Netherlands, the Enping 15-1 oilfield group engineering project in China, and the planned basalt CO_2 in-situ mineralization storage project in the coastal areas of Guangdong Province. According to relevant statistics, there are more than 270 CCS/CCUS projects worldwide, and many countries and regions have deployed or are deploying carbon storage projects. CO_2 geological storage has been proven to be an effective method to reduce greenhouse gas emissions [2], and through this method, nearly millions of tons of CO_2 are stored in geological reservoirs globally every year. Based on a comprehensive analysis of geographical data such as sedimentary thickness, the global CO_2 geological storage potential is approximately 8,000~55,000 Gt .

This paper elaborates on the storage mechanisms in four different geological formations and analyzes the current challenges encountered by geological storage technologies, in order to contribute to the reduction of the global greenhouse effect. In recent years, significant progress has been made in the research field of CO_2 geological storage. To further effectively promote the development of CO_2 geological storage and utilization technology, this paper sorts out the global development trend and research progress in this field, analyzes the current research hotspots, and looks forward to the development of this field, aiming to assist in the realization of global carbon removal strategic goals.

2. CO_2 storage mechanisms, advantages, and disadvantages in different geological formations

As an important means of reducing carbon emissions, CCUS is divided into two parts: Carbon Capture and Utilization (CCU) and Carbon Capture and Storage (CCS).

Deep saline aquifers have enormous storage potential, accounting for 90% to 95% of the total CO_2 storage capacity. Since the density of injected CO_2 is lower than that of saline water, CO_2 will move upward, displacing the saline water. After the completion of CO_2 injection, the previously displaced saline water returns to displace part of the CO_2. This part of CO_2 is adsorbed in the pores of porous storage under the action of capillary force, and some of the CO_2 also reacts with the saline water.

Depleted oil and gas fields have good sealing performance and huge storage space. This technology is also known as CO_2-enhanced oil recovery (CO_2-EOR). CO_2 is easily soluble in crude oil, which can increase the expansion coefficient of crude oil, reduce the interfacial tension of crude oil, and significantly reduce the viscosity of crude oil, thereby improving the flow capacity of crude oil. Based on the practice of CO_2 oil recovery technology, many scholars have proposed CO_2 miscible flooding technology to further improve efficiency.

Deep coal seams are potential geological formations for CO_2 storage. Storing CO_2 in them can not only reduce carbon emissions but also displace methane gas in coal seams. However, this scheme is technically complex and still faces a large number of theoretical and practical challenges.

Basalt mineralization technology refers to storing CO_2 using mafic-ultramafic igneous rocks. They contain minerals such as olivine and pyroxene that easily react with CO_2. The principle is that CO_2 first forms carbonic acid with water in the rock formation, prompting hydrogen ions to dissolve the primary minerals in the basalt matrix, release cations, which then react with dissolved CO_2 to form stable carbonate minerals, enabling permanent storage.

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2.1. Basalt mineral carbonation storage

Basalts are widely distributed globally, accounting for approximately 70% of the ocean floor area and more than 5% of the land area, making them one of the main rock types on the Earth's surface [3]. Mafic-ultramafic igneous rocks are considered ideal CO_2 storage media due to their high content of minerals such as olivine and pyroxene that readily react with CO_2, offering excellent mineralization storage capacity and low leakage risk [4]. As a typical mafic extrusive rock, basalt forms in various geological periods and has a mafic mineral content of 45%-85%. The bubble and fracture structures generated during lava cooling and tectonic movements further enhance the rock's porosity and permeability. These characteristics make basalt formations an economically reliable, safe, and long-term carbon storage site, which is of great significance for achieving the carbon neutrality goal.

2.1.1. Storage mechanism

After CO_2 is injected into the basalt formation, it first dissolves in formation water to form carbonic acid. Subsequently, H^+ ions in carbonic acid react with surface cations of carbon-sequestering minerals in basalt, breaking the original bridge bond structure and releasing divalent cations such as Ca^{2+}, Mg^{2+}, and Fe^{2+}. At the same time, CO_3^{2-} and HCO_3^- in water combine with these cations. The reaction process can be expressed as:

$$3H^+ + 2H_2O + CaMgSi_2O_6 \rightarrow Ca^{2+} + Mg^{2+} + 2H_4SiO_4 \tag{1}$$

On one hand, this reaction consumes H^+ ions, increasing the pH value of the system and promoting the precipitation of carbonate minerals. On the other hand, it drives the continuous dissolution of silicate minerals, continuously providing cations such as Ca^{2+} and Mg^{2+}. These ions ultimately combine with CO_2 to form stable carbonate minerals such as calcite, magnesite, and siderite, realizing the long-term fixation of CO_2.

2.1.2. Engineering cases

CarbFix Project

The CarbFix project, located 3 kilometers south of the Hellisheidi Geothermal Power Plant in Iceland, injects CO_2 into a basalt reservoir at a depth of 400-800 meters. The reservoir has a porosity of 8.5%, horizontal and vertical permeabilities of 300 mD and 1700 mD respectively, a temperature range of 20-50 °C, and a pH value of 8.4-9.4, mainly composed of basalt lava and hyaloclastite. From January to August 2012, the project injected a total of 175 tons of pure CO_2 and 73 tons of mixed gas containing H_2S and H_2, and used ^{14}C isotope tracing to monitor CO_2 migration. Monitoring data showed that the peak concentrations of dissolved inorganic carbon and ^{14}C were significantly lower than the theoretical mixed values, and approximately 95% of the injected CO_2 achieved mineralization storage within two years.

Wallula Project

The Wallula project in the United States injects supercritical CO_2 into the Columbia River Basalt Group at a depth of 800-900 meters. This area belongs to continental flood basalt, and the overlying dense caprock provides good structural trapping conditions for the injected CO_2. From July to August 2013, the project continuously injected supercritical CO_2 at a daily rate of 40 tons, with a total injection volume of 1000 tons within 25 days [5]. In recent years, the United States has focused on two offshore basalt storage areas on the east and west coasts. Among them, the offshore basalt

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formation in the Cascadia Basin on the west coast is located 300-500 meters below the seabed, and it is planned to store approximately 0.5×10^8 tons of CO_2 within 20 years. This CO_2 will be transported to the target reservoir about 200 miles off the Pacific coast for storage.

2.2. CO_2 Storage in depleted oil and gas reservoirs

Depleted oil and gas reservoirs are regarded as one of the most potential CO_2 storage sites. After the exploitation of oil and gas resources, these reservoirs become ideal storage locations due to their good sealing performance and huge storage space. Meanwhile, detailed exploration of oil and gas reservoirs has accumulated rich geological data and complete infrastructure, providing strong support for CO_2 storage work [6]. In addition, the injected CO_2 can expand crude oil, reduce its viscosity and interfacial tension, thereby significantly improving the flow capacity of crude oil. This technology is also known as CO_2-enhanced oil recovery (CO_2-EOR). Due to its ability to achieve carbon storage while improving the recovery efficiency of low-permeability oil reservoirs, it has received widespread attention in the oil and gas industry.

2.2.1. Storage mechanism of CO_2 in depleted oil and gas reservoirs

In depleted gas reservoirs, the mechanisms of using CO_2 to improve natural gas recovery mainly include the following aspects: ① Compared with natural gas, CO_2 with higher density can drive natural gas from the bottom of the gas reservoir through gravity differentiation, thereby improving recovery efficiency; ② The injected CO_2 can supplement gas reservoir energy, enhance the pressure gradient, and accelerate the natural gas production rate; ③ When the gas reservoir pressure rises to approximately 8 MPa, CO_2 transforms into a supercritical state, whose viscosity is significantly higher than that of natural gas, helping to maintain a stable displacement mobility ratio; ④ For gas reservoirs with edge and bottom water, injecting CO_2 can also effectively inhibit water intrusion and extend the water-free or low-water production stage.

2.2.2. Engineering cases

SACROC Project (United States)

The SACROC oilfield, located in the Scurry area of western Texas, is the largest Pennsylvanian oilfield in the Midland Basin, discovered in 1948. Since 1972, the oilfield has launched CO_2 capture and storage, which is the largest and longest-running CO_2 flooding project in the United States and the world's first large-scale CO_2-EOR project. The reservoir of the oilfield is carbonate rock, showing significant heterogeneity affected by sea level changes, tectonic subsidence, and karstification. Chevron Oil Company completed the first well of the project, with a depth between 1930 and 1954 meters. Due to the decline in reservoir pressure and the failure of water injection pressure maintenance measures, the operator launched the first phase of CO_2 injection in 1972. To date, a total of 255 million tons of CO_2 have been injected, of which 100 million tons have been stored. Approximately half of them are recovered after being produced with crude oil and reinjected to further improve recovery efficiency. Subsequent monitoring results show that the injection and storage of CO_2 have no significant impact on the environment, the geochemical properties of groundwater remain stable, and the shallow aquifers are not disturbed.

K12-B Project (Netherlands)

The K12-B gas field in the Netherlands is the world's first field test case of CO_2 reinjection into abandoned gas reservoirs to improve recovery efficiency and achieve storage. The gas field is

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located in the North Sea, approximately 150 kilometers off the northwest coast of the Netherlands, with a water depth of about 26 meters. The sandstone reservoir is buried at a depth of 3800 meters, belonging to an anticlinal fault block trap, with medium-low reservoir permeability (5~30 mD) and geological reserves of approximately 144.1×10^8 cubic meters. After development, the gas reservoir pressure decreased from the original 40 MPa to 4 MPa. The CO_2 content in the produced gas is 13%. Since 2004, the separated CO_2 has been reinjected into the Slochteren reservoir above the gas-water interface through well K12-6; from May 2004 to January 2005, a total of approximately 20,000 tons of CO_2 were injected, increasing the average pressure of the gas reservoir by about 1 MPa. The practice of the K12-B gas field first verified the technical feasibility of reinjecting associated CO_2 into the original gas reservoir, which not only improved the gas field recovery efficiency but also realized the geological storage of CO_2. The project has been running smoothly, confirming the technical adaptability and operational safety of CO_2 storage in depleted gas reservoirs on the Dutch continental shelf.

2.3. CO_2 storage in deep unmineable coal seams

Storing CO_2 in the pore structure of coal rocks is a technical path with dual benefits. It can not only effectively reduce carbon emissions but also improve natural gas production by displacing methane gas in coal seams, showing good application prospects in reducing energy waste. China is rich in coalbed methane resources, but basic theoretical research and engineering practice in this field still face many challenges. Compared with depleted oil and gas reservoirs, coal seams are usually shallower in burial depth, but due to their ancient age and high degree of metamorphism, they generally exhibit characteristics such as low permeability, low porosity, and complex geological structures. How to achieve efficient CO_2 injection and ensure long-term storage stability is the core difficulty of current technological development.

2.3.1. Storage mechanism

The main mechanisms of CO_2 storage in deep unmineable coal seams include adsorption by coal matrix and residual gas storage caused by dual porosity structure. This dual porosity structure is formed during deep geological evolution and coalification processes. Gas migration in this medium is manifested as diffusion and adsorption in the coal matrix and laminar and steady flow in the cleat system [7]. When CO_2 is injected into deep coal seams, it first contacts the coal surface, forming a strong adsorption layer at a high concentration on the coal matrix surface through competitive adsorption with water molecules and surface prockstial energy [8]. Under water-bearing conditions, capillary tension also promotes the dual porosity structure to further trap CO_2 in the form of residual gas. Since coal has a significantly stronger adsorption capacity for CO_2 than methane, the injected CO_2 can effectively displace methane through competitive adsorption mechanisms, promoting coalbed methane recovery. Therefore, CO_2 storage in deep unmineable coal seams is essentially a multiphase coupling process of interactions between CO_2, coal matrix, and coalbed methane.

2.3.2. Engineering case

The San Juan Basin project in the United States is located in New Mexico, with the target horizon being the Late Cretaceous Fruitland Formation coal-bearing strata, with an average depth of approximately 900 meters. In 1995, to evaluate the CO_2 storage potential of this coal seam, a CO_2-ECBM (CO_2-Enhanced Coalbed Methane Recovery) pilot test was carried out. The Fruitland

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Formation coal reservoir can be divided into four different types of areas, and the test area belongs to a high-pressure, high-yield coalbed methane area. The coalbed methane production reached its peak one year before the test. Implemented by Burlington Resources, this project is the world's first field test of combined nitrogen and CO_2 enhanced coalbed methane recovery (ECBMR), achieving the goal of storing CO_2 in unmineable coal seams while improving coalbed methane recovery efficiency. CO_2 injection started in July 2008 and ended in August 2009. During the 12-month injection period, a total of approximately 9 million cubic meters of CO_2 were injected into the Fruitland coal seam, and the actual injection volume was a quarter of the original plan.

2.4. CO_2 storage in deep saline aquifers

Deep saline aquifers are composed of porous and permeable reservoir rocks (mainly sandstone and carbonate rock). Their good permeability is conducive to CO_2 injection, and the pores developed between rock particles provide storage space for CO_2. The water in such aquifers is usually non-drinkable, and they have superior structural sealing conditions. Coupled with their wide global distribution, they have become important storage sites for addressing climate change. Deep saline aquifers refer to deep rock formations saturated with saltwater. When CO_2 is injected to a depth of 800 to 3000 meters underground, it will maintain a supercritical state. In this state, CO_2 has both liquid properties and gas-like fluidity. Under supercritical conditions (approximately 89°F and 7.38 MPa), CO_2 has a high density, which reduces the buoyancy difference between it and the in-situ formation fluid, thereby optimizing storage capacity and reducing escape risk. In addition, the injected CO_2 can dissolve in saltwater and react with surrounding rock minerals to form stable mineral storage. This method also requires the deep saline aquifer to be overlain by a low-permeability caprock to ensure the safety of long-term CO_2 storage. Therefore, deep saline aquifers are regarded as ideal geological media for CO_2 storage.

2.4.1. Storage mechanism

The storage mechanisms of CO_2 in deep saline aquifers mainly include physical storage dominated by structural storage and residual gas storage, and chemical storage dominated by dissolution storage and mineralization storage. The migration and storage process of CO_2 in saline aquifers involves thermo-hydro-mechano-chemical (THMC) multi-field coupling effects [9]. Since the density of injected CO_2 is lower than that of saltwater, it will migrate upward under the action of buoyancy until it is blocked by low-permeability caprocks or closed structures such as anticlines and faults, thereby being stored in deep saline aquifers in a supercritical state. In the initial stage of injection, most of the CO_2 is stored in a structural form; as the concentration increases, the saltwater is displaced by CO_2. After the injection is completed, part of the saltwater displaces back, causing part of the CO_2 to be adsorbed in the reservoir pores under the action of capillary force, forming residual gas storage. At the same time, part of the CO_2 will dissolve in saltwater, and its solubility is affected by temperature, pressure, and salt content. Approximately 1% of the CO_2 reacts with formation water to form carbonic acid, which then decomposes into hydrogen ions and carbonate ions. The latter combines with cations such as Ca^{2+} and Mg^{2+} in saltwater to form carbonate precipitates, realizing the mineralization storage of CO_2.

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2.4.2. Engineering cases

Typical domestic and international deep saline aquifer storage projects include the Sleipner project in Norway and the Shenhua project in Ordos, China. In the process of selecting the target reservoir for the Sleipner project in Norway, key parameters such as structural characteristics, porosity, permeability, and storage pressure were comprehensively evaluated, and the Utsira Formation was finally selected as the storage site. The formation is overlain by a thick layer of shale, which can effectively prevent CO_2 leakage, and achieve long-term and safe CO_2 storage through the combined action of multiple storage mechanisms. The project stably injects approximately 1 million tons of CO_2 into the Utsira saline aquifer 800–1000 meters deep in the North Sea seabed every year, not only setting regular injection cycles but also implementing continuous geophysical monitoring [10].

The CO_2 for the Shenhua project in Ordos, China comes from the Shenhua coal direct liquefaction plant. The project adopts an integrated technology of capture, transportation, and storage. After fully evaluating the source-sink matching, a deep saline aquifer 10 kilometers west of the carbon source was selected as the storage site. The preliminary environmental impact assessment was completed in May 2010, systematically analyzing the storage potential, injection scheme, and theoretical maximum storage capacity. The project was completed and put into operation in December 2010, with the capacity of capturing and storing 100,000 tons of CO_2 per year. Since January 2011, the project has continuously injected supercritical CO_2 into the target saline aquifer for engineering tests. By the end of the injection in 2014, the cumulative storage capacity was approximately 300,000 tons.

3. Potential issues and prospects

In 2019, MIT Technology Review listed carbon storage as one of the top ten global technological challenges. The most critical scientific issue is the research and development of Monitoring, Measurement, and Verification (MMV) technologies during CO_2 geological storage, thereby evaluating the risks and storage capacity of CO_2 geological storage and ensuring the safety of long-term underground CO_2 storage. The U.S. Department of Energy has funded CCS/CCUS research since 1997, with early investments mainly focusing on CO_2 geological storage research. Safety risk control has always been the core issue of research, and the potential negative environmental impacts and storage costs have also attracted increasing attention. Based on the latest research trends, the four main directions for future research and development in the field of CO_2 geological storage include: storage safety research, advanced CO_2 monitoring technologies, cost reduction of storage, and deep saline aquifer storage.

3.1. Research on storage safety

Existing studies have confirmed that CO_2 injection into geological reservoirs will disturb the stress field, affect the permeability of the caprock, and then induce surface deformation and earthquakes, resulting in large faults. In fact, in many cases, faults with large slip distances can act as seals and have no impact on permeability, because the faults themselves act as seals rather than channels for fluid migration, and have trapped migrating oil and gas to form reservoirs during geological periods. The Geological Survey of Australia is leading research on the safety of fault sealing [11]. This research is part of the field-scale CO_2 injection carried out at the CO_2CRC Otway Scientific Test Site, and no CO_2 leakage along faults has been found.

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3.2. CO_2 Monitoring technologies

With the rapid development of CO_2 geological storage technology, the importance of efficient monitoring technologies has become increasingly prominent. Currently, seismic methods such as surface reflection and tomography are the main means to monitor underground CO_2 migration and leakage outside the storage area, while gravity and deformation measurements provide low-resolution migration indicators. Where appropriate, tracers, fluid composition analysis, and electromagnetic monitoring technologies are also used to evaluate the CO_2 storage status. Due to the weakening of pressure gradient and CO_2 dissolution reactions after storage, the leakage risk decreases with time, the long-term storage safety improves, and the demand for continuous monitoring decreases accordingly [12]. Future research will focus on the comprehensive analysis and comparison of monitoring technologies in terms of cost-effectiveness, efficiency, time span, and project adaptability.

3.3. Reducing CO_2 storage costs

It is estimated that by 2025, capturing each ton of CO_2 will account for approximately two-thirds of the CCUS cost. In addition to the capture cost, the transportation and storage cost per ton of CO_2 may range from tens to hundreds of US dollars, depending on the storage type. To achieve the 2°C temperature control target of the Paris Agreement, approximately 1250 Gt of CO_2 needs to be stored by 2100. The cost of directly capturing CO_2 from the air is 200~350 USD/t, but it is expected to decrease through technological progress. Incentive policies such as the U.S. 45Q policy, carbon pricing mechanisms, and emission restrictions promote cost reduction of carbon storage and commercialization of CCS/CCUS.

3.4. Deep saline aquifer storage

The key direction for the future development of CO_2 geological storage is deep saline aquifers. The advantage of saline aquifer storage is that more types of high-carbon emission sources can be stored nearby, thereby reducing the cost of constructing long-distance CO_2 transportation pipelines, and there is no need to capture CO_2 as high-purity CO_2, thereby reducing costs. From the current research progress, the future research directions of deep saline aquifer storage will mainly focus on key issues such as ensuring that the injected CO_2 can effectively flow into the saline aquifer, the storage capacity of the saline aquifer, and the long-term safety of storage.

4. Conclusions

Driven by both the carbon neutrality goal and energy transition, the development of CCUS has received unprecedented attention. Countries around the world have actively deployed relevant strategies to promote the implementation of CO_2 geological storage and utilization, effectively promoting the progress of project construction and scientific research. Against the background of global carbon neutrality and energy transition, it is expected that research results in this field will continue to emerge in the future. Current research hotspots mainly focus on depleted oil and gas reservoir storage, induced seismicity mechanisms and monitoring, leakage monitoring and environmental assessment, synergistic development and utilization of CO_2 storage and energy resources, and rapid mineralization storage.

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