CO_2 Enhanced Water Recovery in the Junggar Basin

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Abstract. The Junggar Basin, located in an arid area with scarce groundwater resources, is a crucial traditional energy supply region in western China. CO_2-enhanced brine recovery (CO_2-EWR) can both store CO_2 on a large scale and effectively exploit brine resources, and it has been adopted as an important carbon emission reduction technology in the Junggar Basin. This paper systematically analyzes and summarizes the application of CO_2 sequestration combined with water extraction strategy in this region. Key insights include: 1) The area features high-permeability conditions suitable for carbon sequestration, which can further increase CO_2 storage capacity and mitigate overpressure-induced risks, and meanwhile the low-permeability caprock prevents leakage risks; 2) Saline aquifers in the Junggar Basin are primarily composed of loose rock types like gravel and medium-coarse sand, with low cementation strength and poor mechanical stability. Under the combined effects of high permeability and weak mechanical strength, fluid flow intensifies shear and erosion on rock matrix particles, leading to particle detachment and migration, consequently causing sand production during CO_2-EWR implementation; 3) The mechanisms governing particle detachment during CO_2-EWR remain unclear, necessitating the related experimental and theoretical studies. Particularly, extensive experimental research should be conducted in conjunction with the aquifer lithology and hydrogeological conditions to understand the relevant processes and determine the associated influencing factors and critical conditions.

1. Introduction

Over the past few decades, excessive carbon emissions have led to a series of climate issues, including global warming, frequent extreme weather events, and environmental pollution [1]. To address global climate change, a series of carbon emission reduction measures have been implemented [2]. Among these measures, CO_2 geological storage is regarded as the one with the greatest potential [3]. There are various options for subsurface carbon sequestration sites (Figure 1), among which the favorable seepage characteristics and caprock sealing performance of deep saline aquifers have attracted considerable interest [4,5].

The Junggar Basin is rich in coal resources, with total reserves exceeding 390 billion tons, accounting for 7% of the national reserves and making it the largest integrated coalfield in China [7-9]. Focusing on coal resource development and utilization, the region has established an industrial system encompassing coal power, modern coal chemical industries, and coal-electrolysis metallurgy, with an annual output value surpassing 100 billion yuan [10]. However, large-scale coal resource exploitation and utilization have also led to severe challenges of high carbon emissions in the Junggar Basin, with its carbon emissions reaching 13222 Mt/a [11, 12], imposing substantial pressure on carbon emission reduction locally and even across China. As early as 2016, the China Geological Survey conducted research on the carbon storage potential of the Junggar Basin. Exploration data indicate that the eastern region of the Junggar Basin is underlain by high-quality saline aquifers with thicknesses exceeding 100 meters and maximum permeability reaching 400 mD, resulting in an estimated CO_2 storage potential of 14.5 million tons [13]. Additionally, low-permeability caprocks with permeability near 0.001 mD overlie the saline aquifers, effectively preventing the leakage of sequestered carbon dioxide [14]. Overall, the Junggar Basin possesses superior geological conditions for implementing CO_2 saline aquifer storage, making it an inevitable choice for promoting rapid and coordinated economic and social development in western China.

At present, there is a lack of systematic analysis and summary of the project and research of CO_2 saline aquifer storage in the Junggar Basin. In response to this research gap, this article conducted a corresponding review study with the following layout structure. Section 2 introduces necessity of implementing CO_2 enhanced saltwater recovery (CO_2-EWR) technology. Section 3 analyzed the present progress of studies on CO_2-EWR in Junggar. Section 4 presents the main engineering issues faced by

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the Junggar's CO_2-EWR project. Finally, we provided an outlook on future research in section 5.

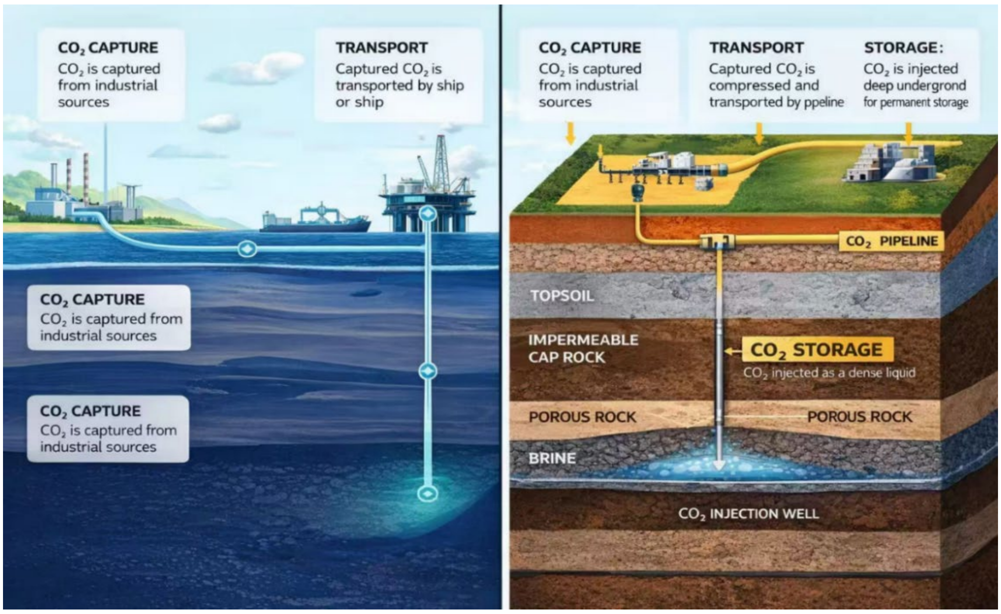

Figure 1. Main methods for CO_2 geological storage [6]

2. Necessity of Implementing CO_2-EWR in the Junggar Basin

The Junggar Basin is dominated by the Gobi Desert, desert grasslands, and adjacent loess regions, representing an arid zone with extremely scarce water resources. In recent years, industrial advancement not only aggravate carbon emissions but also further exacerbate water resource consumption in the region. In order to reduce CO_2 emissions and relieve the pressure of local industrial and agricultural water, China has carried out the first domestic carbon dioxide sequestration combined with saline water extraction in this region in 2016 (Figure 2) [15, 16]. This initiative is smoothly implemented under the leadership of China and with the assistance of Australia. The project assesses the exploitable water resources and carbon sequestration potential of the saline aquifer in this area, providing an important basis for the future implementation of long-term, large-scale carbon sequestration and saline groundwater extraction in this region. From the development history of CO_2 saline aquifer storage technology, the CO_2-EWR technology has significant advantages compared to the traditional storage method (only injecting CO_2). In terms of economic benefits, this technology not only achieves effective CO_2 storage, but also synchronously extracts underground saline water resources, improving the economic feasibility of the project. At the technical level, CO_2-EWR can effectively alleviate stress concentration and formation structure damage caused by CO_2 injection, thereby enhancing the safety of CO_2 injection and storage processes.

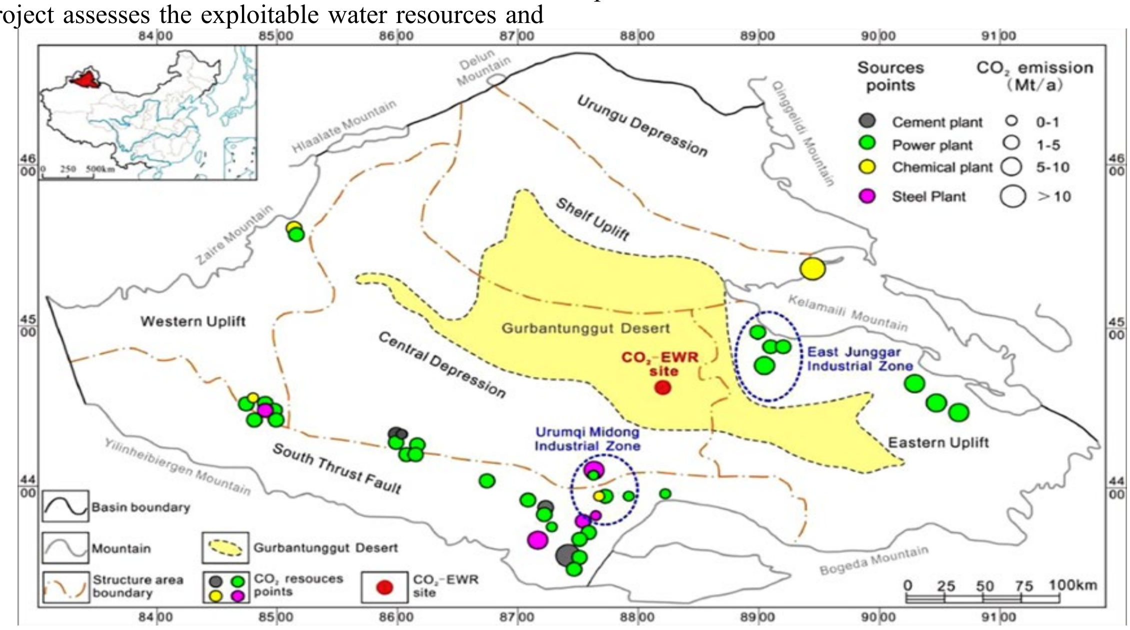

Figure 2. Major carbon emission areas and pilot pumping production sites at Junggar Basin [15]

3. Current Research on CO_2-EWR in the Junggar basin

Chinese scholars have carried out some studies assessing carbon sequestration potential and groundwater extraction feasibility in this region (Figure 3). For earlier work, Ma et al. numerically simulated the CO_2 transport process and distribution pattern in underground saline aquifer under pure carbon sequestration. Based on those simulation results, they speculated that the carbon sequestration stock in this area could reach 145 million tons without long-term leakage risk [15]. On this basis, Ma et al. further evaluated the impact of saline water recovery on carbon sequestration capacity, showing that, when combined with saline water extraction, the sequestration volume is over three times higher than that under single carbon dioxide injection [17]. Besides to significant improvement in carbon sequestration capacity, further research find that the peak saline water recovery efficiency can attain 3% of the reservoir's accessible pore volume, with roughly 1.3 tons of subsurface water recoverable for each ton of carbon injected [18]. The substantial potential for saline water extraction can effectively alleviate industrial and agricultural water stress in this region. To further improve the efficiency and economic performance of the CO_2-EWR system, Chen et al. comprehensively compared multi-vertical-well systems in terms of their performance in comprehensively improving CO_2 sequestration capacity and reducing drilling costs. The simulation results showed that, compared with the three-well system, the costs associated with well deployment and water extraction in the five-well system far exceed the benefits gained from the increased water production [19]. Additionally, the numerical simulation results of Liu et al. show that injection schemes operating under fixed pressure constraints deliver significantly enhanced CO_2 storage performance when benchmarked against strategies governed by fixed flow rate controls [20]. Besides to focusing on injection and recovery efficiency, the evolution of formation pressure throughout the CO_2-enhanced water recovery process has also been extensively examined, which directly controls the in-situ stress distribution and affects production safety. Mi et al. pointed out that, under CO_2 injection alone, although it will not have a significant impact on the development and utilization of nearby groundwater resources, the formation pressure still requires more than 10 years to recover to its initial level even after CO_2 injection is halted [13]. However, after long-term water extraction, the formation pressure around CO_2 injection wells can decrease by up to 20%, significantly reducing the risk of overpressure in the formation [14]. In summary, the geological conditions of the underground saline aquifer in this region generally favor the implementation of water extraction throughout carbon dioxide sequestration. Compared to the traditional CO_2 injection mode, this strategy will further elevate the rate of carbon sequestration and alleviate safety issues such as overpressure induction.

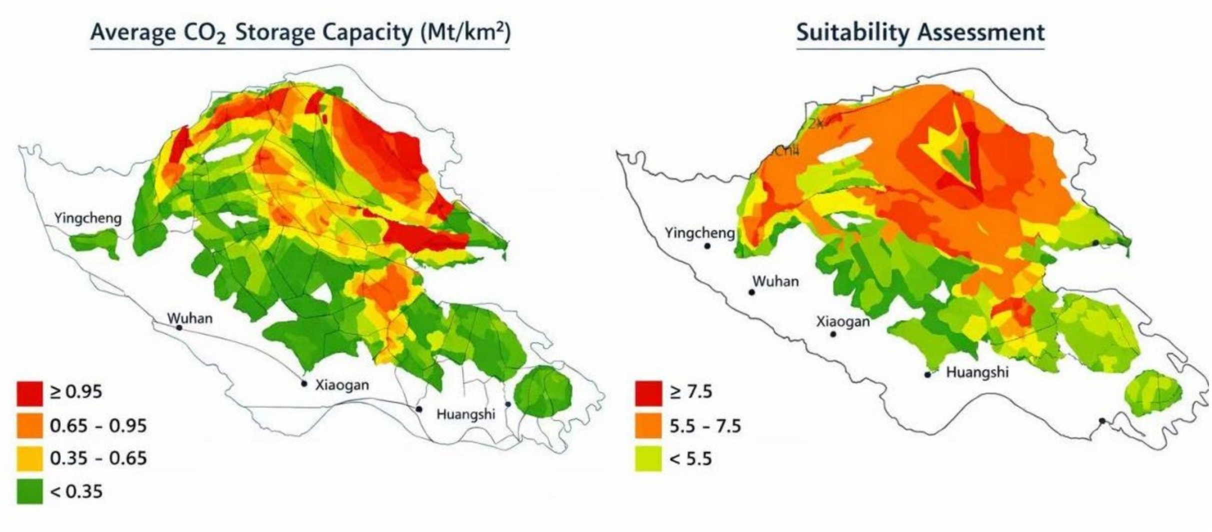

Figure 3 Carbon storage potential and CO_2-EWR suitability evaluation in the Junggar Basin [20, 21]

4. Main Engineering Issues of CO_2-EWR in Junggar

During the implementation of the CO_2-EWR project, sand production occurred commonly, which tends to induce plugging in both formation pores and wellbores, and severely restricting the efficient and safe operation of the project. For example, the Australian government has implemented the largest-scale CO_2-EWR project worldwide in the Gorgon region [22]. During the promotion of the CO_2-EWR project in the Gorgon area, serious sand blockage problems occurred in both the pumping and injection wells, resulting in the paralysis of the entire underground pumping system. The annual carbon sequestration capacity only reached 1 million tons, far below the 4 million tons/year sequestration target and emission reduction requirements. The underground saline layer in Junggar Base primarily comprises unconsolidated rocks such as sand, gravel, and medium coarse sand. Although its high permeability and wide distribution give it great potential for CO_2 sequestration, the formation has low bonding strength and poor mechanical stability [23]. The reduction of pore pressure caused by water extraction leads to a rise in the effective stress, exacerbating the risk of shear failure. Under the action of hydraulic drag forces, the skeleton particles that undergo shear failure detach from the rock framework, and are transported by water flow and produced from production well, leading to frequent sand production problems during CO_2-EWR pumping, seriously affecting the normal operation of the project. In the field of petroleum engineering, some existing sand production prediction methods have provided a reference for establishing sand production prediction models applicable to the CO_2-EWR process. Among these prediction methods, formation sand production is divided into two processes: the detachment of rock framework particles and the transport of the detached particles. In particular, the description of the particle detachment constitutes the core of the modeling. There are two predominant prediction models at present. One is based on the fluid erosion criterion, which takes the critical water flow velocity as the initiation condition for particle detachment [24-26]. The other is founded on the shear failure theory, adopting the critical plastic shear strain as the initiation criterion [27-29]. When these prediction models are applied to the CO_2 sequestration integrated with saline water recovery, the critical flow velocity or formation shear deformation conditions corresponding to initiation of particle detachment require further identification. The empirical equations characterizing the correlations between water flow velocity, shear deformation magnitude and particle detachment extent should be calibrated accordingly. In addition, supercritical CO_2 exhibits liquid-like properties under certain high-pressure conditions, and its influence on particle detachment still requires further investigation.

5. Conclusion and prospective

As a major industrial base in the western region of China, with rapid development of society and economy, the Junggar region has become one of the regions with the most serious carbon emissions in the western region of China, facing huge pressure on carbon emission reduction. Underground saline aquifer is widely distributed in this region, which primarily comprises loose rocks such as sand gravel and medium coarse sand. It has the characteristics of large thickness, high permeability and good sealing conditions. It is an ideal place for CO_2 storage. In addition, in the Junggar Basin as a whole is in a desert and arid environment, and the problem of water shortage is serious. CO_2-enhanced water recovery is the preferred technology for implementing CO_2 saline aquifer storage in the region, which can achieve large-scale CO_2 storage and effectively alleviate the severe shortage of water resources. Both in terms of economic cost and technological utility, CO_2-EWR technology has significant advantages over traditional storage methods that only inject CO_2.

During the implementation of the CO_2-EWR project, sand production has seriously affected the efficiency and safety of CO_2-EWR technology, becoming a major obstacle to its application and development. Currently, the mechanisms governing sand production during CO_2-EWR remain unclear. It is urgent to conduct systematic experimental and theoretical studies on the physical mechanism, influencing factors, critical conditions, and calculation models of skeleton particle detachment. In particular, the critical conditions (such as the critical hydraulic gradient) and mechanism model for the occurrence of CO_2-EWR-induced sand production in the the Junggar Basin are the basis for evaluating the sand production behavior and its harm degree in the process of carbon sequestration. Substantial experimental research should be performed in combination with the local rock characteristics and hydrogeological conditions, understand the relevant process, and determine the relevant parameters.

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