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Research status of CO_2 as cushion gas in underground natural gas storage

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ABSTRACT

CO_2 as cushion gas of underground natural gas storage can not only effectively save the initial capital investment, but also slow down the greenhouse effect and realize the geological burial of CO_2. It has important strategic significance and social value for the development and construction of underground natural gas storage. Based on a large number of literature research at home and abroad, this paper summarizes and combs the differences in physical properties between carbon dioxide and natural gas, the mixing mechanism of carbon dioxide as cushion gas and natural gas in natural gas underground storage, the influence of multiple rounds of injection and production in the operation of natural gas underground storage and the influence on the capacity and stability of gas storage under fluid solid coupling, so as to provide reference for the implementation of CO_2 as cushion gas in natural gas underground storage. In addition, it also puts forward the deficiency of theoretical understanding of cushion gas in CO_2 as natural gas underground storage, including: ①High-speed non Darcy seepage of gas, the movement law of displacement phase front and the distribution characteristics of mixing zone under the action of alternating load; ②The accuracy of three-dimensional three-phase oil, gas and water injection production dynamic multi physical field coupling model is improved; ③For geological activities in the early stage of natural disasters, which may lead to gas leakage, specific measures shall be taken to deal with emergencies; ④ The geological conditions of gas storage construction are more complex, and its development is more difficult. In addition, the mathematical model of injection production operation evaluation in the whole life cycle of natural gas underground storage operation is established.

Keywords: Underground natural gas storage, Cushion gas, Mixing mechanism, CO_2 deep burial, Permeation-diffusion

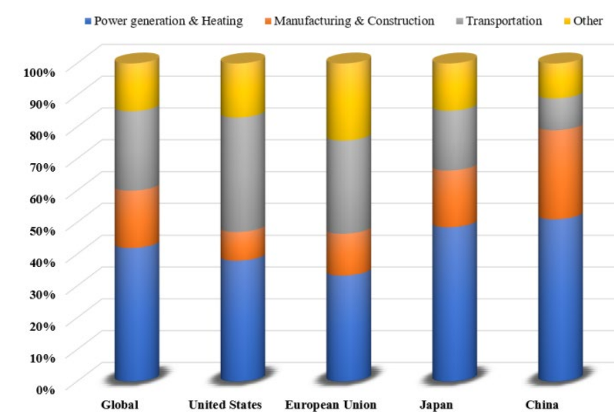

Fig. 1. Global and major sources of carbon emissions (Data source: IEA, Haitong Securities Research Institute)

1. INTRODUCTION

The "2021 China Natural Gas Development Report" pointed out that in the future, the development of the natural gas industry should be based on the "dual-carbon" goal and the new economic and social situation[1]. As an important strategic reserve energy source for the country, the advantages of natural gas are mainly reflected in high heating value, significant economic benefits, and small environmental pollution. The development and utilization of natural gas are of great significance to China's development and construction. However, due to seasonal, regional, and supply-demand contradictions, the significance of natural gas emergency peak regulation and strategic reserves is becoming more prominent. The construction of underground natural gas storage facilities can effectively solve supply-demand contradictions, adjust the energy structure, and mitigate greenhouse effects.

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The amount of natural gas that a gas storage facility can hold at a certain temperature and pressure is called its storage capacity, of which 25% to 75% must be kept inside the storage facility during operation as cushion gas to provide pressure for gas extraction work, suppress formation water flow, prevent water intrusion, and ensure the stability of the storage facility. Nitrogen (N_2) and natural gas (CH_4) are commonly used as cushion gases[2-9]. However, N_2 is prone to mixing with natural gas, increasing impurities in extracted gas, lowering its heating value, and affecting normal use of natural gas. As for natural gas itself used as cushion gas, the portion of natural gas used as cushion gas remains in the storage facility and cannot be extracted or sold, resulting in direct economic losses and energy waste.

Compared with CH_4 and N_2, the high-pressure compressibility and high viscosity of carbon dioxide in its supercritical state under storage conditions indicate that it is more suitable as cushion gas for natural gas storage[10, 11]. In addition, a large amount of CO_2 storage experience has been accumulated in oil and gas field development, providing important reference value for using CO_2 as cushion gas. In terms of enhanced oil recovery, CO_2 has also achieved certain economic benefits through experiments. Furthermore, the rapid development of the global economy has led to massive CO_2 emissions, posing a serious threat to the Earth's ecosystems and human social development. To address global climate change and achieve sustainable development of human society and the Earth's ecosystem, the 21st United Nations Climate Change Conference adopted the Paris Agreement, proposing to achieve carbon neutrality around 2030, that is, net zero emissions of carbon dioxide[12]. Therefore, deep burial of CO_2 as cushion gas in underground natural gas storage not only meets the needs of China's economic development for natural gas but also reduces greenhouse gas effects, providing a new way to achieve the "dual carbon" goal[11]. Therefore, the deep burial of CO_2 as cushion gas in underground natural gas storage not only meets the demand for natural gas in China's economic development, but also reduces greenhouse gas effects, providing a new pathway for achieving the "dual carbon" targets. Based on extensive research of domestic and foreign literature, this paper summarizes the feasibility and mechanism of using CO_2 as cushion gas in underground natural gas storage, providing a reference for the engineering practice of CO_2 as cushion gas.

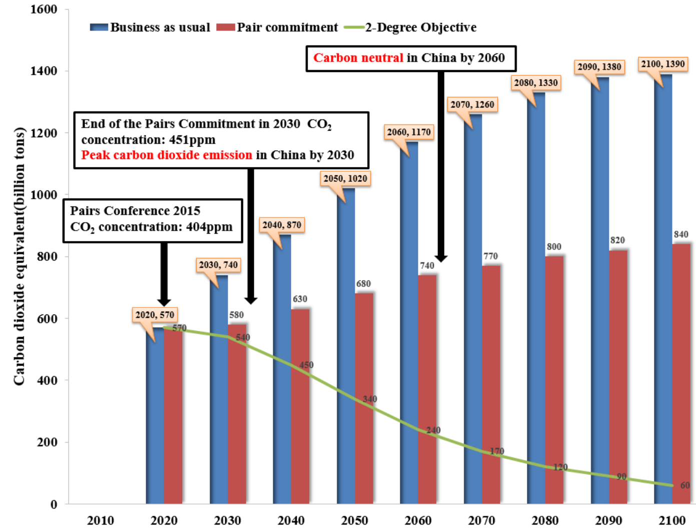

Fig. 2. Global carbon emissions predictions to 2100 (Data source: Science)

2. CURRENT STATUS OF UNDERGROUND NATURAL GAS STORAGE

According to the International Gas Union (IGU), there are currently 715 underground gas storage facilities operating in 37 countries and regions worldwide, with a total working gas volume of $3.53\times10^8 m^3$, accounting for approximately 11.7% of the global natural gas consumption. Of these, 549 underground gas storage facilities have a working gas volume of less than $5\times10^8 m^3$, accounting for 77% of the total. Among the four types of underground gas storage facilities, reservoir-type has the largest working capacity, accounting for about 75% of the total, followed by aquifer-type at 12%, salt cavern-type at 7%, and oil reservoir-type at 6% [13].

In the late 1960s, Daqing Oilfield conducted its first gas storage experiment, and in 1975, China's first reservoir-type underground gas storage facility, Lamadian Underground Gas Storage, was built and put into operation. In the late 1990s, the first commercial underground gas storage facility, Dagang Dazhangtuo Gas Storage, was completed and took on the task of "valley filling and peak shaving" for natural gas in the Beijing-Tianjin-Hebei region and winter peak regulation and supply guarantee for Beijing. This marked the beginning of China's underground gas storage construction and signaled a new development stage for China's underground gas storage facilities[14]. So far, China has built and operated 27 natural gas underground storage facilities, with a cumulative peak regulation and gas extraction volume of about 50 billion cubic meters, benefiting more than 200 million people in over 10 provinces and cities, and replacing 50 million tonnes of standard coal. Despite starting later compared to foreign countries, China's development in underground gas storage has been rapid, and after more than a decade of hard work, China's gas storage facility construction has entered a mature stage.

In terms of technology, since 2000, units such as China National Petroleum Corporation and Southwest Oil and Gas Field have independently innovated for over a decade, forming a complete set of technologies and standard systems with independent intellectual property rights in the geological evaluation of underground gas storage sites, drilling, injection and production processes, surface processes, equipment manufacturing, operation control. These achievements have gained worldwide attention, paved the way for China's industrialized construction of gas storage facilities, established the foundation for the strategic reserve pattern of natural gas, and promoted the historic transformation and upgrading of China's energy supply from gas production and transmission peak regulation to underground gas storage peak regulation. In October 2021, the Nanpu Gas Storage Project of Jidong Oilfield was put into operation smoothly, marking the successful transformation of China's gas storage construction from onshore to offshore, from reservoir-type to oil reservoir-type, broadening the ideas for constructing gas storage facilities in China, laying the theoretical foundation for converting oil reservoirs into gas storage facilities in the future, and having important reference and guidance significance.

Currently, there is limited research on using CO_2 as cushion gas in natural gas underground storage both domestically and internationally. The theoretical and methodological aspects of controlling the diffusion and migration of CO_2 in the storage facility are still in the conceptual stage, and related technical studies are not yet mature. There are many challenges that need to be addressed, such as the displacement front propagation under high-intensity injection and production, mixing of CO_2 and CH_4 under injection and production pressure differential, and multi-physical field flow-solidification coupling. In terms of technology, further research is needed on issues such as the risk of CO_2 leakage as cushion gas, the impact of geological activities such as natural disasters on CO_2 storage, and the strong corrosive reaction of CO_2 on metal materials during transportation and storage.

3. FEASIBILITY AND MECHANISM RESEARCH STATUS OF CARBON DIOXIDE AS CUSHION GAS IN UNDERGROUND NATURAL GAS STORAGE

Whether in depleted oil and gas fields, underground aquifers, or salt rock formations used as gas storage facilities, during the injection and production operations of gas storage peak regulation, a portion of gas must be kept in the storage facility, which is called cushion gas. Initially, natural gas itself was used as cushion gas in underground gas storage facilities. In China's Dazhangtuo Underground Gas Storage Facility, the volume of cushion gas accounted for 50% of the total gas storage capacity, approximately $7.23\times10^8m^3$. However, because the natural gas used as cushion gas could not be extracted, it caused serious financial burden and pressure on gas storage facility construction and operation companies. In 1986, the Gas Research Institute selected the Hansen Storage Facility of Texas Gas Transmission Corporation as an example to analyze the injection of N_2 into the west side of the storage facility[15]. Long-term simulation showed that no N_2 was detected in the extracted gas. However, this does not mean that inert gases are suitable for all gas storage facilities, such as those with very small total capacity (less than $8.5\times10^4m^3$), which results in insufficient economic benefits to recover expected economic effects due to inability to pay for data collection, engineering analysis, and other costs.

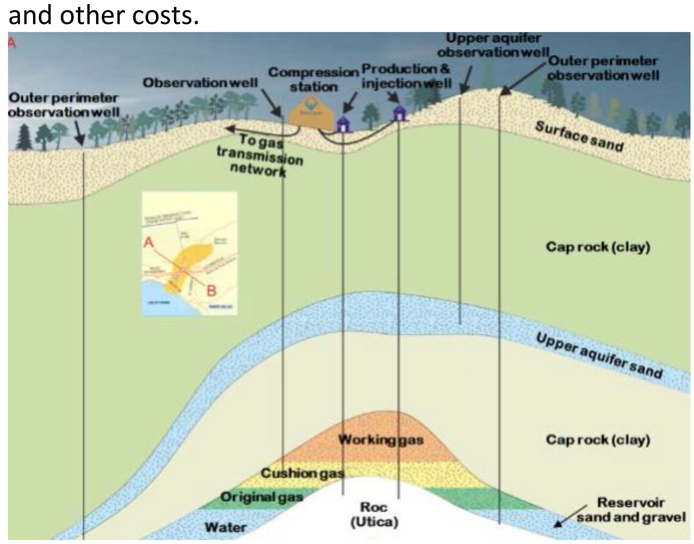

Fig. 3. CO_2 as cushion gas for underground natural gas storage (By Intragaz)

The injection of CO_2 into depleted oil and gas reservoirs has attracted great attention due to its potential for underground storage of greenhouse gases and enhance oil and gas recovery. The former Soviet Union's Gas Scientific Research Institute first proposed the possibility of using CO_2 as cushion gas in underground natural gas storage facilities, which received high attention and promotion from many countries[16]. However, because there is no engineering practice of using CO_2 as cushion gas in underground natural gas storage facilities in the world, related research at home and abroad has not formed a complete theoretical system for CO_2 as cushion gas. Scholars' research on the feasibility and mechanism of using CO_2 as cushion gas in underground natural gas storage mainly includes the differences in physical properties between CO_2 and CH_4, the mixing law of CO_2 and natural gas, and the flow-solid coupling during the operation of gas storage facilities [17-21].

3.1 Physical properties of CO_2 and CH_4

The selection of cushion gas for underground natural gas storage reservoirs should have physical properties that firstly, have a high compressibility to provide more storage space and greater gas support during the injection and withdrawal process. Secondly, it should have a large density difference with natural gas to greatly reduce the degree of mixing with natural gas under the action of gravity. Additionally, cushion gas should also have a large viscosity difference with natural gas to limit the flow of cushion gas during the gas recovery stage, prevent CO_2 impurities from mixing with the extracted gas, and affect the natural gas recovery rate. Therefore, to demonstrate the feasibility of using CO_2 as cushion gas in underground natural gas storage, it is necessary to conduct in-depth research on the physical property differences between CO_2 and CH_4 (the main component of natural gas).

Tan[16], Wang[22], Curtis[23], Liu[24] et al. analyzed the thermodynamic properties of mixed gases composed of different mole fractions of CO_2 and CH_4 using the BWRS equation, and studied the relationship between the density, viscosity, and compressibility factor of the mixed gas and pressure at different temperatures, and theoretically demonstrated that CO_2 could be used as cushion gas for gas storage reservoirs[25-30]. The results showed that at the same temperature and pressure, the viscosity of CO_2 was 10 times that of CH_4. In addition, Hu et al. proved through mixed gas experiments that supercritical CO_2 and CH_4 show a layered state and could be used as cushion gas for depleted gas reservoir-type gas storage reservoirs[31]. Oldenburg et al. obtained simulation experiment results indicating that when the formation temperature was slightly higher than the critical point of CO_2, its density and viscosity were both greater than CH_4. The relatively high viscosity of CO_2 is conducive to the migration of CH4, which reduces the tendency of interaction and mixing between CH_4 and CO_2. The relatively high viscosity of CO_2 is conducive to the migration of CH_4, which reduces the tendency of interaction and mixing between CH_4 and CO_2. The migration process in the gas reservoir is more inclined to CO_2 displacement of natural gas, forming a inclined miscible transition zone without large-scale mixing. It shows that CO_2 can not only be used as cushion gas in underground gas storage, but also improve gas recovery of gas reservoir[25,32]. Furthermore, Oldenburg conducted research on CO_2 flooding to increase natural gas recovery and noted that converted depleted gas reservoirs into underground natural gas storage reservoirs. In this context, CO_2 trapped in the reservoirs acted as cushion gas, which helped reduce the initial investment required for building underground gas storage reservoirs[32]. Although the successful engineering practices of using inert gases as cushion gas for underground gas storage reservoirs exist, to demonstrate that CO_2 has advantages over N_2 and CH_4 as cushion gas, Zhang et al. compared the changes in compressibility factor, density, and viscosity of CH_4, CO_2, and N_2 under reservoir conditions. The study found that: 1) The compressibility factor of CO_2 is much higher than that of CH_4 and N_2, indicating that CO_2 can provide more storage space and driving force during injection and extraction stages when used as cushion gas; 2) The density of CO_2 is much higher than that of CH_4 and N_2, and under the influence of gravity, CO_2 as cushion gas tends to concentrate at the bottom of the reservoir, reducing the degree of mixing with natural gas; 3) The viscosity of supercritical CO_2 is between gas and liquid phases and significantly different from that of CH_4. This reduces the degree of mixing, providing better mobility for CH_4[34].

The development of mixed gas experiments is beneficial for a better understanding of the mixing mechanism between CO_2 and natural gas. Hu et al. designed an intermediate container mixing gas experiment. The experimental results showed that significant gas mixing occurred between the two gases when the experimental environment was at the low-pressure subcritical point of CO_2. When the experimental conditions were near the high-pressure subcritical point of CO_2, the gas chromatograph detected only 0.05% CO_2 in the extracted CH_4 gas at the outlet end, indicating that near the critical point of CO_2, the CO_2 gas maintained a good stratification state with the upper CH4 and did not undergo extensive mixing. However, this experiment did not consider the diffusion mixing of CO_2 and CH_4 in porous media, which requires overcoming capillary forces and takes a long time to form[34]. Therefore, Li added two groups of CO_2 displacement natural gas long core diffusion experiments based on the experiments of Hu et al. One group continuously injected CO_2 to displace natural gas, and the other group injected CO_2 at a volume ratio of 0.2 PV and held it under pressure for 2 hours. The experimental results showed that the process of CO_2 displacement of natural gas has some characteristics of piston-type displacement. Although the molecular diffusion strength of CO_2 and CH_4 in the long core is weak after holding under pressure, it cannot be completely ignored, and ultimately presents a pure natural gas flow zone, a mixed zone of CO_2 and natural gas, and a pure CO_2 flow zone[35]. The experimental results are consistent with the results of gas property analysis when CO_2 is used as a cushion gas.

Although CO_2 as a cushion gas for underground natural gas storage has not yet been implemented in practice, the comparative analysis of the physical properties between CO_2 and CH_4 shows that CO_2 has significant advantages and potential as a cushion gas. It can not only "activate" the "dead gas" in underground gas storage, but also alleviate the greenhouse effect.

3.2 The feasibility of using carbon dioxide as cushion gas in underground natural gas storage was studied by numerical simulation

Numerical simulation technology is commonly used to study the gas migration behavior inside gas storage facilities. In 1968, Henderson et al. used a three-dimensional two-phase gas flow model to simulate the injection-production operation dynamics of natural gas storage facilities, which was the earliest report on numerical simulation of gas storage facilities[36]. So far, researchers have developed three main types of mathematical models, including three-dimensional gas flow models, three-dimensional gas-water displacement models, and two-dimensional gas-oil mixture models [37, 38]. ① The three-dimensional gas flow model was primarily used to simulate the injection-production operation of depleted gas reservoirs with a closed volume and no water drive. The model assumed that the reservoir contained only single-phase gas and considered the non-Darcy effect of fluids and the compressibility of gas and rocks, which could simulate the injection-production dynamics of single-phase gas. ② The three-dimensional gas-water displacement model was mainly used to simulate the injection-production operation of underground aquifer-type gas storage facilities and water-driven depleted gas fields. When coupled with the three-dimensional gas diffusion model, it could be used to study the mixing problem of cushion gas and working gas in gas storage facilities[39-45]. However, solving the model was relatively difficult[46-48]. Wang et al. established an integral averaging model for the dynamic migration of natural gas in underground aquifer-type gas storage facilities. Compared with the three-dimensional two-phase gas-water seepage model, this model was easier to solve and had higher computational accuracy[49, 50]. ③ The two-dimensional gas-oil mixture model was primarily used to simulate the injection-production operation of non-water-driven depleted oil reservoir gas storage facilities. However, currently, the vast majority of oil reservoirs are developed using water injection. Therefore, this model is not applicable to simulating the injection-production operation of water-driven depleted oil reservoir gas storage facilities.

The interaction between CO_2 as cushion gas and CH_4 in gas reservoirs is affected by a variety of factors including molecular diffusion, microscale convection and diffusion, reservoir properties, operating conditions of the gas reservoir, injection methods, and injection rates of the cushion gas. The process of gas mixing displacement between cushion gas and working gas under multiple cycles of high-speed injection and extraction conditions is substantially different from the mechanisms of gas-liquid displacement and liquid-liquid displacement, presenting a unique seepage-diffusion coupling problem. Tan et al. pointed out that the mixing process between cushion gas and working gas in underground gas storage reservoirs is a complex and nonlinear process, accompanied by phenomena such as microscale mixing, viscous fingering, and gravity override, exhibiting obvious spatiotemporal chaotic behavior. Therefore, chaos theory can be used to describe the internal uncertainty changes caused by the action of multiple factors in porous media. This research approach fills a theoretical gap in the gas storage system and provides important academic value for further research on gas mixing mechanisms. However, the study of the chaos theory in the mixing of CO_2 as cushion gas and natural gas has only stayed at the feasibility stage[51].

In terms of mathematical model solving, the traditional Cartesian orthogonal grid and finite difference (FD) algorithm are generally used to solve the established mathematical models mentioned above. However, they have poor adaptability for complex boundaries and suffer from grid orientation issues. Zhang et al. established a three-dimensional compositional model that coupled convection and diffusion to describe gas mixing in porous media surrounding a water well, and investigated the effects of fluid flow and immiscible displacement on the process. The solution method employed an unstructured prism mesh and a mixed control volume finite element (CVFE) and finite difference (FD) approach for increased flexibility. By measuring the mole fraction of CO_2 gas in the upper, middle, and lower layers, the researchers analyzed the degree of mixing and concentration distribution between CO_2 cushion gas and working gas. The results indicated that during the injection period, the mole percentage of CO_2 in the lower layer gradually decreased as CO_2 was displaced to the bottom of the well, forming a distinct zone of CO_2-natural gas mixture. During natural gas extraction, the mole percentage of CO_2 in the middle layer gradually increased, showing that the mixture zone of CO_2 and natural gas moved upward, with most CO_2 concentrated in the lower layer, providing power for natural gas extraction. Additionally, if the mixture zone was located at a mid-high position, CO_2 recovery rates were enhanced; if it was located at a low position, injected CO_2 could be used as cushion gas to provide power for gas production and achieve deep burial of CO_2. However, the pure ideal model used to study the theoretical and methodological aspects of CO_2 diffusion and transport in gas storage facilities mentioned above neglected many geological and engineering factors[34]. To address this issue, Cao et al. simulated 15 operating cycles using geological data from the East China Sea gas reservoir and analyzed the detailed effects of geological and engineering parameters on reservoir pressure, gas mixing characteristics, and CO_2 content in extracted gas. The results showed that the mixing zone curve was divided into four stages throughout the entire operating cycle: an increasing stage, a smooth stage, a sudden increase stage, and a cyclic variation stage. The thickness of the mixing layer was negatively correlated with reservoir temperature, permeability, and residual water. The CO_2 component in the cushion gas, reservoir permeability, and production had a significant impact on the breakthrough of CO_2 in the production well, while the effects of water saturation and temperature were relatively small[52].

4. IMPACT OF CARBON DIOXIDE CUSHION GAS ON THE CAPACITY AND STABILITY OF UNDERGROUND NATURAL GAS STORAGE.

CO_2 has a certain solubility. Injecting CO_2 into the reservoir will react with the reservoir rocks and formation water to generate mineral precipitation, resulting in changes in reservoir properties, increased complexity of fluid migration, and impact on injection and production capacity as well as storage capacity. In addition, the alternating load of injection and production will change the mechanical parameters of the rock, such as compressive strength, tensile strength, and Young's modulus, affecting the stability of the gas storage. Therefore, fully understanding the impact of CO_2 deep burial as cushion gas on the storage capacity and stability of the gas storage is essential for ensuring efficient and safe operation of the gas storage.

The results of CO_2 core displacement experiments conducted by Gu et al. showed that when CO_2 was injected into the top of the core, the dissolution of minerals in the upper part of the core was the most significant, while the relative solubility of minerals in the middle part of the core was less. The pore volume was influenced by the solubility of minerals and increased accordingly, resulting in an increase in porosity in the upper part and a slight increase in porosity in the middle part. However, during the displacement process, some precipitation and particles generated by geochemical reactions moved downward and counteracted the increase in pore volume caused by mineral dissolution. The upper and lower parts of the core were blocked by precipitation generated during the reaction, which significantly reduced their permeability due to the influence of mineral dissolution[53]. Zhao et al. core displacement experiments also confirmed that the pore structure changed significantly during CO_2 injection, and triaxial rock tests showed a significant decrease in rock mechanical strength. This was due to the relationship between tensile strength and cementing strength of the rock. The CO_2 dissolution eroded the rock cementing material, causing the core to become loose and even produce micro-cracks, resulting in a significant decrease in rock mechanical strength. The impact of CO_2 dissolution was very significant, ultimately leading to a decrease in rock stability. As for CO_2 as cushion gas, the gas used as cushion gas is not extracted. When the underground natural gas storage is abandoned, CO_2 is directly buried underground for storage. The above experiments were conducted under conditions where the geochemical reaction cycle between gas, water, and rock was relatively short. However, CO_2 storage requires thousands of years, making long-term geochemical reaction experiments between gas, water, and rock challenging to carry out [54]. The results of the numerical simulation by Kihm[55], Zhang et al.[30] indicate that the effectiveness of CO_2 geological storage is largely influenced by the mineral composition of the geological strata, and significant changes in the composition of iron ions and magnesium ions occur under long-term geochemical reactions. There are very few specific research cases for CO_2 storage as cushion gas for natural gas underground storage, although the above research is focused on the impact of CO_2 geological storage on geological strata, it also provides a theoretical basis and scientific basis for studying the impact of CO_2 as cushion gas on reservoirs.

On the other hand, whether it is a depleted oil and gas reservoir or an aquifer gas reservoir, the essence of its injection-production operation is a gas-driven water process, with only a higher intensity than a general gas-driven water process. During the multi-round injection-production process in the gas storage, some pores that were originally occupied by water and crude oil are filled with injected gas, and frequent injection and production causes changes in reservoir temperature, pressure, geological structure and so on, resulting in changes in injection and production capacity and storage capacity[56-58]. Researchers obtained the following conclusions through multiple rounds of "gas-water" interdrive experiments: 1) Wettability had a significant effect on the characteristics of gas-water co-driving and infiltrating flow; 2) Multi-cycle gas-water co-driving could cause an increase in the relative permeability of the gas phase, a decrease in the relative permeability of the water phase, and an increase in the residual gas saturation in the coexisting zone of gas and water; 3) The reciprocating movement of water during the operation of the gas storage caused the formation of a large number of dead zones in the pore space of the reservoir, resulting in a decrease in the availability of the pore space and storage capacity utilization; 4) For reservoirs with widely developed fractures, multi-cycle gas-water co-driving produced certain water blockage damage, reducing the effectiveness of storage capacity utilization[59-65]. However, the above conclusions may not necessarily apply to the gas storage of CO_2 as cushion gas. In the research of gas storage expansion and injection-production operation laws, Xiong et al. studied the variation of rock core gas storage space based on gas-driven indoor experiments. The results indicated that after three rounds of injection-production operations, the gas saturation of the gas storage could only reach about 40%, and it tended to reach its capacity after five rounds, with the gas saturation reaching around 50%. This shows that due to the influence of water and oil content, the maximum storage capacity of depleted oil reservoirs could reach only half of the entire storage space of the depleted oil reservoir[66]. Furthermore, the gas and water at the gas-water front always remained in contact, and the infiltrating flow characteristics of the two-phase mutual drive and displacement occurred at the gas-water transition zone formed by the cyclic operation of the gas storage[67]. He et al. conducted experiments on the changes in gas-water phase seepage during multiple injection-production cycles, and investigated the migration and distribution laws of gas and water in the multi-cycle gas-water interaction displacement at the gas-water transition zone[60]. From the perspective of micro-scale displacement mechanisms, during the gas-water co-driving process, the combined effects of driving pressure difference, capillary force, frictional force that liquid flow must overcome, and the high compressive elastic force of gas make it difficult to remove gas after water intrusion into the two-phase zone. As a result, the storage capacity and working gas volume of the gas storage are reduced. Additionally, related research results have shown that the expansion effect is better in the early stages of multi-cycle injection-production, but the expansion effect deteriorates in later stages. The research mentioned above provides good guidance for the initial expansion and construction of underground natural gas storage in depleted oil reservoirs. However, there is currently a relative lack of related research on the reconstruction of depleted oil reservoirs as natural gas underground storage facilities and their subsequent expansion in China. Additionally, there is relatively little quantitative research focused on the gas saturation during the construction process of such facilities.

5. CONCLUSIONS AND PROSPECT

This paper systematically summarizes the development of underground natural gas storage in China, as well as explores the feasibility of using CO_2 as cushion gas for natural gas underground storage through physical properties and numerical simulations. In addition, the "gas-water-rock" interaction has a significant impact on reservoir structure and stability. Although the study of CO_2 as cushion gas is still in the conceptual stage, the current research provides important reference value for the implementation of natural gas underground storage projects, while also providing new ideas for CCUS.

In the process of accelerating the implementation of the "2030 peak carbon emissions" and "carbon neutrality by 2060" goals, high-quality and efficient natural gas is playing a critical role in China's energy transition and has become the optimal choice for promoting high-quality economic development in China. Drawing on the construction of gas storage facilities abroad, China's strategic natural gas reserves should mainly rely on underground storage. The dual requirements of peak shaving and strategic reserve have determined the importance of natural gas storage. Using CO_2 as cushion gas in underground natural gas storage not only meets the demand for natural gas in China's economic development, but also achieves geologic carbon sequestration to mitigate greenhouse gas emissions. This can lay a foundation for the country's long-term and sustained high-speed economic development. However, there is still room for improvement in the theoretical understanding and specific implementation plan of using CO_2 as cushion gas in underground natural gas storage, and there are certain shortcomings in commercial software used for storage facility construction.

Therefore, the following issues need to be urgently researched in the future:

(1) In terms of gas storage facility construction, the high-quality resources for building new facilities are becoming increasingly scarce in China. The geological conditions for developing new storage facilities are more complex, and the difficulty of constructing new facilities continues to increase. Existing technologies may not be able to meet the demand for efficient construction. Additionally, existing facilities that have already been put into operation are in the late stage of expansion, making it increasingly difficult to expand production capacity significantly;

(2) Under gas storage conditions, the impact of parameters such as displacement front motion, density, and injection speed on the movement of the displacement front and the distribution of CO_2 and natural gas mixing zones is not yet fully understood. This is particularly true when there is a presence of oil, gas, and water three-phase fluids, where underground seepage does not follow conventional Darcy flow completely. Additional constraints are required to simulate these conditions, which can result in significant uncertainty and greatly affect the simulation accuracy;

(3) In terms of engineering implementation, injecting CO_2 as cushion gas has a significant impact on surface injection and gas processing, requiring higher anti-corrosion standards for injection and production pipelines. Additionally, a series of geological activities, such as earthquakes or ground subsidence or uplift, can lead to the formation of numerous micro-cracks in the reservoir, potentially causing CO_2 leakage. Once leaked, the large amount of CO_2 entering the atmosphere or water layer could have unimaginable impacts on the Earth. Therefore, there is no comprehensive solution for handling emergencies related to gas storage facilities yet.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Tian, G. (2021). 《China Natural Gas Development Report (2021)》. Natural Gas Industry, 41(08): 68.

[2] Ding, G. S., Wei, H. (2020). Review on 20 years' UGS construction in China and the prospect. Oil & Gas Storage and Transportation, 39(01): 25-31.

[3] Laille, J. P., Coulomb, C., Tek, M. R. (1986). Underground Storage in Cerville-Velaine, France: A Case History in Conversion and Inert Gas Injection as Cushion Substitute. SPE Annual Technical Conference and Exhibition.

[4] Bai, M. X., Song, K. P., Li, Y. et al. Development of a novel method to evaluate well integrity during CO_2 underground storage. SPE Journal, 20(3): 628-641, 5.

[5] Bai, M. X., Sun, J. P., Song, K. P. et al. (2015). Well Completion and Integrity Evaluation for CO_2 Injection Wells. Renewable and Sustainable Energy Reviews. 45: 556-564.

[6] Foh, S. E. (1991). The use of inert gas as cushion gas in underground storage: Practical and economic issues. United States.

[7] Cao, W., Liu, X. H. (2004). Take cheap inert gas as cushion gas of gas storage with salt caves. Natural Gas Industry. 24(9): 136-138.

[8] Li, J. J., Jiao, W. L., Wang, Z. S. (2007). Discussions on inert gas taken as cushion gas in underground gas storage with aquifer. Petroleum Planning & Engineering. 5: 40-42.

[9] Lekkala, S. R. (2009). Impact of injecting inert cushion gas into a gas storage reservoir, West Virginia University, USA.

[10] Iskandar, C. S., Biyanto, T. R. (2023). Optimization of CO_2 enhanced oil recovery operating conditions:

A case study of El morgan oil field reservoir. Gulf of Suez, Egypt.

[11] Shah, P. G. (2023). Improving CO_2 enhanced oil recovery in unconventional formations via the dissolution of wettability altering CO_2-soluble nonionic surfactants (Doctoral dissertation, University of Pittsburgh).

[12] Zou, C. N., Xue, H. Q., Xiong, B. et al. (2021). Connotation, innovation and vision of "carbon neutral". Natural Gas Industry. 41(08): 46-57.

[13] Natural gas industry special series report: pipeline network, LNG receiving station and gas storage industry enter a rapid development period. China Gas Network Website. (2019). http://www.chinagas.org.cn/qingjie/other/2019-03-28/45516.html.

[14] Li, J. J. (2006). Simulation research of use of inert cushion gas in underground gas storage reservoir in aquifer. Harbin Institue of Technology.

[15] Lin, T. (2008). Dynamic simulation and optimal operation control of carbon dioxide as cushion gas injection and production of gas storage reservoir. Harbin Institute of Technology.

[16] Tan, Y. F., Lin, T. (2008). Analysis on the single-well capacity of injection withdrawal in underground gas storage reservoir. Oil & Gas Storage and Transportation. 27(3) : 27-29.

[17] Cao, L., Tan, Y. F. (2009). Dynamic simulation research on injection and withdrawal performance of underground salt cavern natural gas storage. Journal of Harbin Institute of Technology (New Series). 16(5): 633-637.

[18] Niu, C. K., Tan, Y. F., Feng, L. Y. (2014). Stability analysis of multi-well gas injection for storing CO_2 in underground aquifer. Advanced Materials Research. 869 /870: 803-807.

[19] Niu, C. K., Tan, Y. F. (2014). Numerical simulation and analysis of migration law of gas mixture using carbon dioxide as cushion gas in underground gas storage reservoir. Journal of Harbin Institute of Technology (New Series). 21(3): 121-128.

[20] Starling, K. E., Savidge, J. L. (1992). Compressibility factors of natural gas and other related hydrocarbon gases. New York: Operating Section, American Gas Association.

[21] Bai, M. X., Reinicke, K. M., Song, K. P. (2014). An overview of hydrogen underground storage technology and prospects in China. Journal of Petroleum Science and Engineering. 124: 132-136.

[22] Wang, Y. J. (2014). The feasibility study of CO_2 as cushion gas in depleted gas storage. Southwest Petroleum University.

[23] Curtis, M. (2003). Carbon dioxide as cushion gas for natural gas storage. Energy＆Fuels. 17.

[24] Liu, A. (2015). Numerical simulation study of CO_2 as cushion gas in aquifer-type underground gas storage. Southwest Petroleum University.

[25] Oldenburg, C. M. (2003). Carbon dioxide as cushion gas for natural gas storage. Energy&Fuels. 17(1): 240-246.

[26] Van der Meer, L. G. H. (2008). Is carbon dioxide in case of natural gas storage a feasible cushion gas. TNO Built Environment and Geoscience, Netherlands.

[27] Wang, X. Y., Huang, X. S., Wang, X. et al. (2005). Availability study of carbon dioxide as cushion gas for underground gas storage. Pipeline Technique and Equipment. (1): 22-24.

[28] Li, G. T., Song, G. H., Zhang, J. et al. (2008). Theoretical discussion of carbon dioxide as cushion gas for underground gas storage tank. Natural Gas Exploration and Development. 31(2): 61-63.

[29] Oldenburg, C. M., Pan, L. (2013). Utilization of CO_2 as cushion gas for porous media compressed air energy storage. Greenhouse Gases: Science and Technology. 3(2), 124-135.

[30] Oldenberg, C. M., Pruess, K., Benson, S. (2001). Process modeling of CO_2 injection into natural gas reservoirs for carbon sequestration and enhanced gas recovery. Energy Fuels. 15, 293-298.

[31] Hu, S. Y., Hu, X. R., Li, Y. K. et al. (2018). Feasibility analysis about taking CO_2 as cushion gas for gas storage rebuilt upon depleted reservoirs. Reservoir Evluation and Development. 8(5): 56-59.

[32] Oldenberg, C. M., Benson, S. (2002). CO_2 injection for Enhanced Gas Production and Carbon Sequestration. In Proceedings of the SPE International Petroleum Conference an Exhibition, Villahemosa, Mexico. SPE 74367.

[33] Olendburg, C. M. (2003). Carbon sequestration in natural gas reservoirs: enhanced gas recovery and natural gas storage. Lawrence Berkeley National Laboratory. 1(10): 1-8.

[34] Zhang, R., Chen, S., Hu, S. et al. (2021). Numerical simulation and laboratory experiments of CO_2 sequestration and being as cushion gas in underground natural gas storage reservoirs. Journal of Natural Gas Science and Engineering. 85: 103714.

[35] Li, Y. K. (2017). The impact of reservoir properties and operating conditions on mixing of CO_2 cushion and natural gas in storage reservoirs. Southwest Petroleum University.
[36] Henderson, J. H. (1968). Use of numerical models to develop and operate gas storage reservoirs. Journal of Petroleum Technology. 20(11), 7-14.
[37] Tan, Y. F., Lian, L. M., Yan, M. Q. (1997). The technology and development of foreign underground natural gas storage. Oil & Gas Storage and Transportation. 16(12): 17-19.
[38] Tan, Y. F., Lian, L. M., Yan, M. Q. (1998). Numerical simulation study of foreign natural gas underground gas storage. Gas industry. 18(6): 108-109.
[39] Kiliner, N., GÜmrah, F. (2000). A numerical simulation study on mixing of inert cushion gas with working gas in an underground gas storage reservoir. Energy Sources. 22(10), 869-879.
[40] Tan, Y. F., Chen, J. X. (2001). Simulation research of mixing problem to the cushion gas and work gas. Journal of Harbin Institute of Technology. 33(04): 546-549.
[41] Tan, Y. F. (2003). Numerical solution of gas mixing questions in underground gas storage. Natural Gas Industry. 23(02): 102-105.
[42] Tan, Y. F., Bu, X. B. (2008). Simulation of mixed effect of CO_2 deep burial as cushion gas of gas storage. China Petroleum Society International Symposium on Underground Gas Storage (Oil) Storage Engineering Technology. Beijing. 4-6.
[43] Wang, B. H., Yan, X. Z., Yang, X. J. (2013). Study on the dynamic migration law of inert cushion gas during injection-production process in underground natural gas storage reservior. Science Technology and Engineering. 13(31), 9184-9189.
[44] Feldmann, F., Hagemann, B., Ganzer, L. (2016). Numerical simulation of hydrodynamic and gas mixing processes in underground hydrogen storages. EES, 75(16), 116.
[45] Li, G. (2007). Calculation of storage capacity of gas storage and study on diffusion model and simulation of CO_2 cushion gas mixture. Southwest Petroleum University.
[46] Zhan, C. H., Yan, M. Q., Lian, L. M. (2001). Simulation pf aquifer underground gas storage reservoir with FEM. Gas & Heat. 21(4): 294-298.
[47] Li, P. M., Li, J. J. (2013). Numerical simulation of using inert gas as cushion gas in aquifer underground gas storage reservoir. Gas & Heat. 32(5): 47-54.
[48] Wang, L. J., Zheng, Y. L., Li, W. Y. et al. (2007). Gas-water drive mechanism of establishing aquifer underground gas storage. Natural Gas Industry. 27(11): 100-102.
[49] Wang, B. H., Yan, X. Z., Yang, X. J. et al. (2011). Equivalent seepage model of natural gas migration in underground gas storage reservoir. Journal of China University of Petroleum (Edition of Natural Science). 35(6): 127-130.
[50] Wang, B. H., Yan, X. Z., Yang, X. J. et al. (2012). Natural gas dynamic in an underground gas storage in aquifer beds. Acta Petrolei Sinica. 33(2): 327-331.
[51] Tan, Y. F., Zhan, C. H., Cao, L. et al. (2005). Gas mixing mechanism taking CO_2 as cushion gas and feasibility of operation control. Natural Gas Industry. (12): 105-107+4.
[52] Cao, C., Liao, J. X., Hou, Z. M. et al. (2020). Utilization of CO_2 as cushion gas for depleted gas reservoir transformed gas storage reservoir. Energies. 13(3): 576.
[53] Gu, L. B., Li, Z. P., Hou, X. L. (2007). Experimental research of reservoir physical changes induced by CO_2 flooding. Journal of Oil and Gas Technology. 29(3): 258-260.
[54] Zhao, R. B., Sun, H. T., Wu, Y. S. et al. (2010). Indoor study on the effect of carbon dioxide storage on stratigraphic rocks. Scientia Sinica (Technologica). 40(4): 378-384.
[55] Kihm, J. H., Kim, J. M. (2011). Numerical simulation of impacts of mineralogical compositions on trapping mechanisms and efficiency of carbon dioxide injected into deep saline formations.
[56] Tong, D., Trusler, J. M., Vega-Maza, D. (2013). Solubility of CO_2 in aqueous solutions of $CaCl_2$ or $MgCl_2$ and in a synthetic formation brine at temperatures up to 423K and pressures up to 40MPa. Journal of Chemical Engineering. 58(7): 2116-2124.
[57] Kutchko, B. G., Strazisar, B. R., Lowry, G. V. et al. (2008). Rate of CO_2 attack on hydrated Class H well cement under geologic sequestration conditions. Envirinment Science & Technology. 42: 6237-6242.
[58] Niu, C. K., Tan, Y. F. (2016). Stability analysis of gas-water interface using carbon dioxide as cushion gas for gas storage in low permeability gas reservoir. Journal of Harbin Institute of Technology. 48(8): 154-160.
[59] Wang, X. M., Guo, P., Jiang, F. G. (2006). The physuical simulation study on the gas-drive

multiphase flow mechanism of aquifer gas storage. Natural Gas Geoscience. 17(4): 597-600.
[60] He, X. L., Huang, S. J., Sun, C. W. et al. (2015). Gas-Water relative permeability variation in muti-cycle injectionproduction of underground gas storage in flooded depleted gas reservoir. Oil & Gas Storage and Transportation. 34(2): 150-153.
[61] Zhang, Q. (2015). Experimental study of seepage law of fractured carbonate gas storage injection and production. Chinese Academy of Science (In stitue of Seepage Fluid Mechanics).
[62] Ding, Y. H., Zhang, Q., Zheng, D. W. et al. Seepage laws in converting a microfissure-pore carbonate gas reservoir into a UGS. Natural Gas Industry. 35(1): 109-114.
[63] Shi, L., Liao, G. Z., Xiong, W. et al. (2012). Gas-water percolation mechanism in an underground storage built on a water-drive sandstone gas reservoir. Natural Gas Industry. 32(9): 85-87.
[64] Xie, J., Liang, H. Z., Guo, R. et al. (2018). Research status of the fluid displacement mechanism during the multi-rounds strong injection-production for the carbonate rock underground gas storage. Periodical of Ocean University of China. 48(6): 88-95.
[65] Wang, J. K., Zhang, J. L., Ding, F. (2014). Initial gas full component simulation experiment of Ban-876 underground gas storage. Journal of Natural Gas Science and Engineering.18(5), 131-136.
[66] Xiong, Y., Xu, H. G., Li, H. et al. (2015). Indoor experimental study on the mechanism of capacity change of gas storage in waste oil reservoirs. Science Technology and Engineering. 15(6): 173-176.
[67] Izgec, O., Demiral, B., BertinERTIN, H. et al. (2008). CO_2 injection into saline carbonate aquifer formations: laboratory investigation. Transport in Porous Media. 72(1): 1-24.