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CO_2-assisted technologies for the development of tight gas reservoirs: The implication on CCUS

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1 Introduction

Tight gas reservoirs are non-conventional rock reservoirs with matrix permeability of less than 0.1mD and porosity of less than 15% (Kalam et al., 2021). The ultimate gas recovery rates in these reservoirs are very low due to the limited permeability and unfavourable reservoir characteristics which undermine the production of hydrocarbons (Syah et al., 2021). The recovery factor may be greatly elevated by using horizontal drilling and multi-stage hydraulic fracturing (Syed, Muther, Van, Dahaghi, & Negahban, 2022). Due to water shortages and contamination of subsurface water, fracturing fluids commonly used for water-sensitive formations face significant challenges (Shen et al., 2021). Therefore, a viable option is to combine carbon capture, utilization, and storage (CCUS) technology with enhanced gas recovery (EGR) technology using CO_2. This technique provides additional economic and environmental value because it uses existing infrastructure to increase gas recovery and permanently store CO_2 in depleted reservoirs (Ren et al., 2023).

2 Comprehensive analysis of CO_2-assisted technologies

2.1 CO_2 fracturing

The failure of water-based fracturing fluids in unconventional reservoirs, especially those with high clay content, led to the development of CO_2 fracturing technology (Zhao et al., 2021). With CO_2 fracturing, the reservoir rock and formation fluids undergo a variety of physical and chemical reactions. As a result of these reactions, reservoirs may become more porous and permeable, and the flow of natural gas commences. Gas recovery factor is enhanced and CO_2 is permanently stored in the geological formations (Tao et al., 2021). Tight reservoirs and other unconventionals are characterized by high temperature especially when the depth exceeds 1000 m where the temperature and

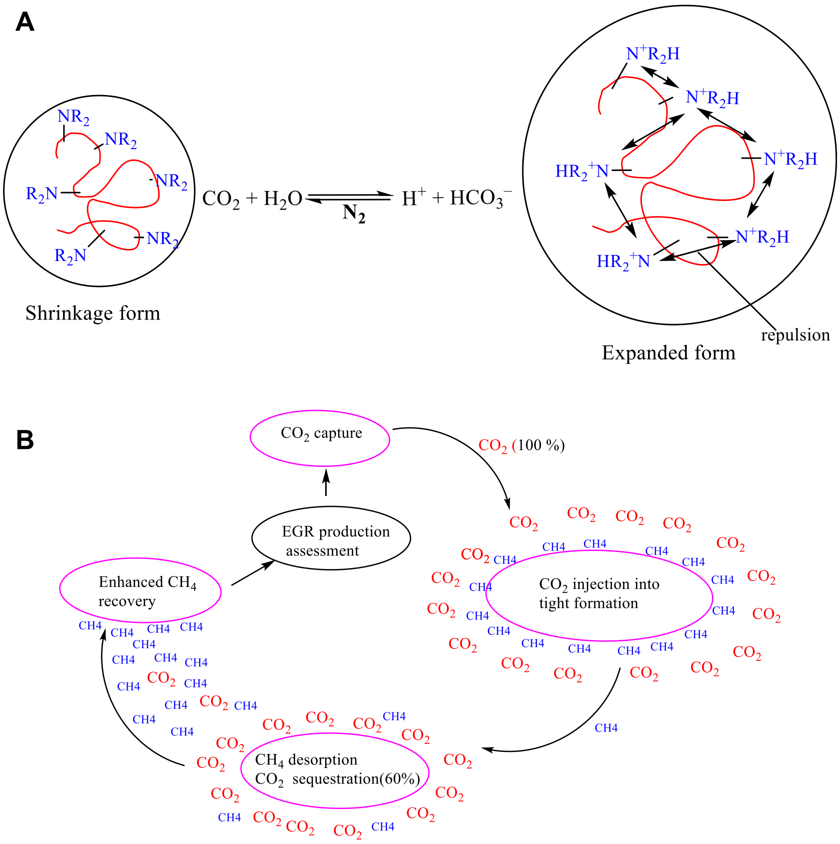

FIGURE 1
(A) Polymer CO_2 responsive gel expansion mechanism (Wu et al., 2023), **(B)** CO_2-CH_4 competitive adsorption.

pressure are above the critical point of CO_2 (31.1 C, 7.38 MPa, respectively). These formation conditions make CO_2 attain the supercritical state exhibiting superior properties such as low viscosity, strong diffusion, much higher density than gas, and almost no surface tension (He et al., 2022). CO_2 fracturing is significantly superior as it lowers the pressure required to initiate a fracture, connect micro-fractures, and create intricate fracture networks appropriate for rock formations with low pressure, low permeability, and high-water sensitivity. Additionally, liquid CO_2 can be used as a fracturing fluid and has several benefits over others, including quick well cleanup, removal of formation damage, and low cost. However, the widespread use of CO_2 fracturing fluids has been constrained by inadequate proppant transfer, significant friction loss, and high pump displacement associated with low fluid viscosity (Middleton et al., 2015).

2.2 CO_2-responsive gel blockage

Due to CO_2 poor mobility control, phase segregation, and extremely low viscosity, gas has the propensity to finger and break through into production wells easily bypassing unswept oil zones (Dai et al., 2017). To address these challenges and improve sweep efficiency, CO_2-responsive gels were developed to plug and divert CO_2 into oil zones. These chemicals have special functional groups (amines, amidines, guanidines, and carboxylic acids) on either surfactant or polymer chains that activate their responses based on the pH change caused by the presence of CO_2 (Yang, He, Sui, He, & Li, 2019). The interaction of CO_2 and water in the formation produces carbonic acid leading to protonation of the responsive tertiary amines, electrostatic repulsion among the polymer particles, and an increase in the particle size (Du D. et al., 2022). The injection of N_2 induces a reversible reaction by changing the pH of the system leading to CO_2 release and gel particle shrinkage (Y. Liu & Liu, 2022).

(Shen et al., 2021) investigated CO2-responsive worm-like micelles (WLMs) called N, N-dimethyl erucamide tertiary amine (DMETA) as a novel plugging agent where a recovery factor was enhanced by 21.7%. Furthermore (Wang et al., 2021), reported the ternary system comprising of cetyltrimethylammonium bromide (CTAB), sodium salicylate

(NaSal), and *N*, *N*-dimethylcyclohexylamine (DMCA) as plugging agent with improved gas recovery. Their mechanism involved protonating DMCA by CO_2 injection to induce a structural change from spherical micelles to WLM, reverting to a spherical state upon addition of NaOH Although this technology has been successful, its effectiveness is hindered by surfactant/polymer loss caused by surface adsorption, retention, thermal degradation, and precipitation in a high-temperature and saline environment (Massarweh & Abushaikha, 2022).

2.3 CO_2-CH_4 competitive adsorption

In tight reservoirs, CH_4 is found adsorbed to organic matter and clay minerals, in a free state in fractures and pores, and trace amounts as a dissolved gas in the liquid phase. Initially, quick gas is produced from free-state gas while the remaining gas (85%) is accessed by other advanced EGR techniques, like a gas CO_2 injection (S. Liu, Sun, Xu, Li, & Wang, 2020). For technical and economic reasons, CO_2 injection for enhancing gas recovery is coupled with CO_2 sequestration in geological formations. Geological sequestration of CO_2 in depleted reservoirs is widely considered as one of the most effective techniques to reduce greenhouse gas emissions (Du X. et al., 2022). This is due to the fact that kerogen and formation minerals have higher adsorption capacity to CO_2 (Ma, Yue, Li, Xu, & Niu, 2019). The adsorption capacity of CO_2 and CH_4 can be estimated by using experimental and simulation results and then fitted in various isothermal models (Langmuir) (Bemani, Baghban, Mohammadi, & Andersen, 2020). Most findings indicated that more than 60% of the injected CO_2 was adsorbed and the pre-adsorbed CH_4 ejected as shown in Figure 1B. However, the efficacy of CO_2-CH_4 competitive adsorption is still limited by both the reservoir and surrounding environments such as the amount of TOC, kerogen, pressure, and high temperature Adsorption increases with increasing pressure to the optimum level and a higher amount of kerogen since it contains more surface adsorption sites (Kang, Zhang, Kang, Guo, & Zhao, 2020).

3 Conclusion

To extract gas from tight reservoirs, a variety of CO_2-assisted systems have been developed. CO_2 as a fracturing fluid has many advantages over water. These include suitability for complex rock formations with low pressure, low permeability, and strong water sensitivity.

Even though CO_2-fracturing fluid has shown better performance as reported elsewhere, it still needs more research to determine how nanoparticles could improve its viscosity and thereby minimize friction losses, higher pumping pressures, and proppant carrying failures.

CO_2-responsive gel blockage has been successfully applied in the US, China, and other countries due to the careful selection of surfactants/polymers that are compatible with reservoir conditions and optimized formulation ratios. Certain setbacks must be addressed as well, such as unexpected retention, temperature-induced instabilities, or phase separation in the reservoir. Field-scale modeling and simulation of the phase behavior of ternary systems are advocated.

CCUS technology and CO_2-EGR are required to lower CO_2 emissions while enhancing natural gas output in order to make it commercially feasible. The viability of coupled approaches, in which CO_2-CH_4 competitive adsorption plays a key role, is assured by an increase in global gas prices.

Author contributions

XZ: investigation and research, writing manuscript draft; KX: resources and conceptualization; CW: modify analysis; XL: typesetting; AOM: supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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