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Perspective

Mechanisms in CO_2-enhanced coalbed methane recovery process

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Abstract:
Injection of CO_2 and subsequent desorption of CH_4 is considered to be the most efficient enhanced coalbed methane (ECBM) recovery technique to date. Meanwhile, CO_2-ECBM is an excellent option for CO_2 geo-sequestration for an extended period. Despite ongoing research efforts and several field applications of this technology, the mechanisms of the process have yet to be fully understood. The coalbed heterogeneity, the fluid interactions with coal, the CO_2 induced swelling, and the continuous pressure and composition changes require outright insights for optimal application of the technique. Furthermore, intermolecular interactions of CO_2 and CH_4, their competitive adsorption on the dry/wet coal surface, and the dispersion and advection processes play an important role in defining the CO_2-ECBM recovery process. An attempt has been made here to understand the key mechanisms of CO_2-ECBM recovery in coalfields, particularly the adsorption of CO_2 in the supercritical state at the recommended sequestration depth.

1. Introduction

Coalbed methane (CBM) is an important unconventional gas resource under development today (Muther et al., 2022). Nevertheless, 60% to 80% of the adsorbed CBM emits into atmosphere during coal mining (Prabu and Mallick, 2015; Serikov et al., 2022), creating explosion risks, which is traditionally diluted by ventilation. Most of the CBM, e.g., as high as 98%, is adsorbed onto the internal pores with the rest remaining as free gas in cleats of dry coal seams (Naveen et al., 2017; Asif et al., 2019a). The content of gas generally increases with the coal maturity and the depth, i.e., deep high-rank coalbeds contain more gas than shallow coalbeds; however, deep coalbeds are challenging to mine with current technologies (Godec et al., 2014). Unmineable coalbeds, along with basalt formation, saline aquifers, and depleted oil and gas reservoirs, are considered as prospective sites for CO_2 storage to mitigate the rising greenhouse gas level (Bachu, 2000; Naveen et al., 2018; Asif et al., 2022b). CO_2 injection for enhanced coalbed methane (ECBM), as illustrated in Fig. 1(a), is an effective means to improve the storage economics in coal reservoirs by enhancing CH_4 production and ultimate recovery (Mazzotti et al., 2009). For example, Zheng et al. (2022) reported incremental CH_4 desorption of ~14%-26% from coal powder columns by CO_2 flooding with nuclear magnetic resonance monitoring as compared to natural depressurization; Zhang et al. (2023) tested CO_2-ECBM in a meter-scale coal specimen box and obtained enhancements of ~24%-27% on the basis of conventional CBM recovery. Typically, gases injected for ECBM include N_2 and CO_2. Compared to N_2, CO_2 is preferable owing to its much higher adsorption affinity and higher recovery ability, in addition to future windfalls associated with CO_2 mitigation. Also, CO_2 injection results in better sweep efficiency, whereas N_2 injection causes rapid deformations (Schepers et al., 2010). To date, there still exists a knowledge gap regarding ECBM recovery mechanisms due to complex fluid-solid interacting physics within pores and cleats under reservoir conditions (Asif et al., 2022a).

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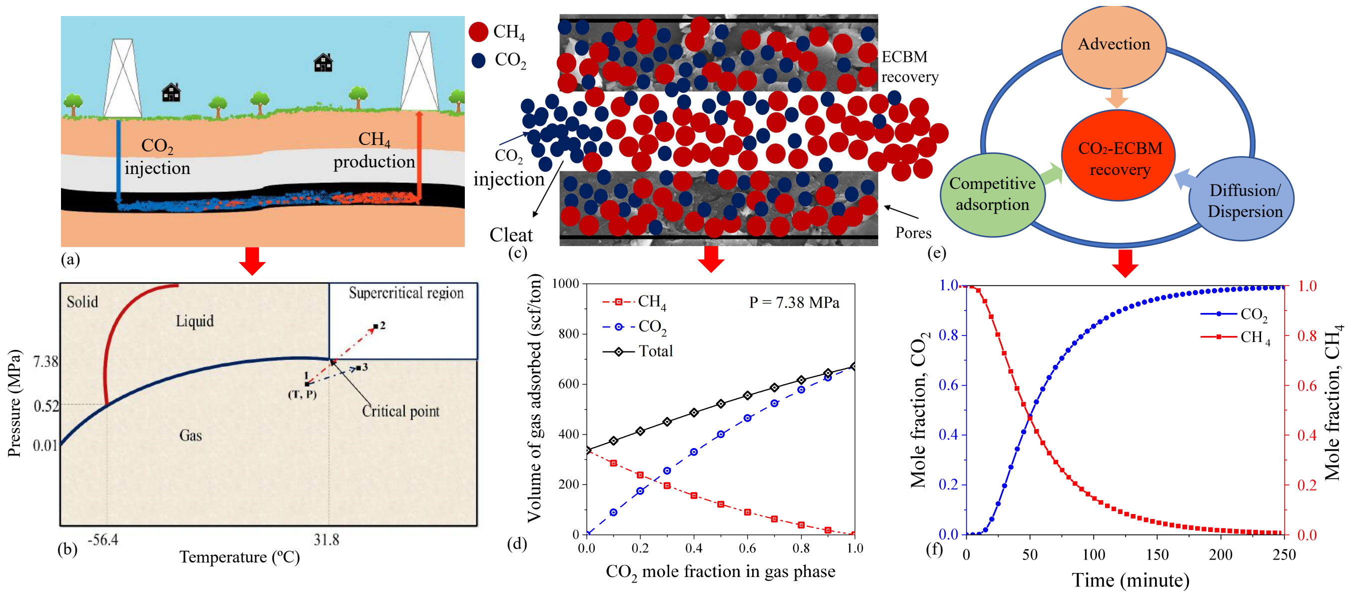

Fig. 1. Key mechanisms in the CO_2-ECBM recovery process (Fig. 1(b) modified after Perera et al. (2011b)).

2. Competitive adsorption in CO_2-CH_4 displacement

To fully understand the CO_2-ECBM recovery process, competitive adsorption in coal should be clarified (Qin et al., 2022). When coal interacts with CH_4 or CO_2, the imbalanced intermolecular forces between the coal atoms on surface enable attraction of other molecules, serving as potential adsorption sites. Competitive adsorption occurs given variations in affinity of different gases towards coal (Ottiger et al., 2008; Asif et al., 2019b). Without decreasing the overall reservoir pressure, the partial pressure of CH_4 can be decreased after CO_2 injection (Shi and Durucan, 2005; Perera et al., 2012), which leads to faster CH_4 desorption from coal surfaces.

2.1 CO_2 phase changes during injection

The recommended minimum depth of coal seams for CO_2 sequestration is around 800 meters, as deeper coal seams provide high enough pressure to keep CO_2 supercritical (Pashin and Mcintyre, 2003). There could exist an optimal CO_2 injection pressure in terms of CH_4 recovery and CO_2 storage from the wettability perspective in presence of water (Zheng et al., 2020). Injection modes of constant pressure or stepwise pressurization also affect CBM recovery (Bai et al., 2022). Fig. 1(b) shows the phase diagram of CO_2 with the supercritical pressure and temperature of 7.38 MPa and 31.8 °C. Both temperature and pressure of CO_2 increase with depth from surface conditions (point 1 of Fig. 1(b)) to reservoir conditions, e.g., in deep reservoirs, CO_2 can reach the supercritical state (viz. point 2), whereas in shallow reservoirs, CO_2 would remain as a gas with lower density and storage capacity (viz. point 3). Supercritical CO_2 has a more significant potential to displace CH_4 and acquires higher adsorption capacity than gas state (Perera et al., 2011a).

2.2 Van der Waals equation

The competitive adsorption of CO_2 over CH_4 on coal surface stems from their different physical and chemical properties. The smaller kinetic diameter of CO_2 (0.33 nm) in contrast with CH_4 (0.38 nm) allows CO_2 to enter into all pores where CH_4 molecules reside. In coal matrix, CO_2 or CH_4 molecules adhere to the coal molecules by the weak van der Waals force, their properties can be described by:

$$\left(P+\frac{a}{V^2}\right)\times(V-b)=RT \tag{1}$$

where P is pressure in atm, T is temperature in K, V is gas volume in L/mol and R is the gas constant in L·atm·K^{-1}·mol^{-1}. The van der Waals constant, a, is larger for CO_2 (3.658 L^2atm/mol^2) than CH_4 (2.30 L^2atm/mol^2), signifying that CO_2 is preferred over CH_4 for adsorption by molecular attraction. The molar volume of molecules, b, has close values for CO_2 and CH_4.

2.3 Competitive adsorption

The schematic diagram for the CO_2-ECBM displacement and competitive adsorption is shown in Fig. 1(c). The co-adsorption isotherm of CO_2 and CH_4, drawn at the critical pressure and temperature of CO_2, is shown in Fig. 1(d), providing the information about the mole fraction of CO_2 needed for effective ECBM recovery. From Fig. 1(d), it can be deduced that at least 25% of CO_2 in gas phase is required for relatively efficient ECBM recovery, in other words, a 25%/75% CO_2/CH_4 mixture should be expected for the CO_2-ECBM recovery. Moreover, the CO_2 adsorption capacity is 2 to 10 times higher than CH_4 (Gaucher et al., 2011).

2.4 CO_2-ECBM displacement process

As briefly depicted in Fig. 1(e), competitive adsorption, dispersion/diffusion and advection play an important but tangled role together in the displacement process. The dispersion of CO_2 and CH_4 happens in coal matrix during the gas molecule movement between matrix and cleat. In cleat, the advection of CO_2 and CH_4 becomes dominant due to CO_2 injection and movement of mixture (Raoof et al., 2013). The coupled advection and dispersion transport during CO_2-ECBM can be quantified by the well-known advection-dispersion equation, as embodied by the breakthrough curve in Fig. 1(f).

2.5 Leakage risk

Adsorption of CO_2 to coal significantly reduces the chances of backward migration of CO_2 into atmosphere. The leakage of CO_2 may lead to severe accidents similar to the CO_2 gas eruption happened in Lake Nyos in Cameroon in 1986 (Kling et al., 1987). It's desirable to evaluate the fundamental properties of caprock, such as its mineralogy, strength and pore structure, as CO_2 induced reactions, e.g., with calcite, may increase its permeability (Zhang et al., 2019; Xu et al., 2022).

2.6 Matrix swelling and shrinkage

Another key consequence of CO_2 injection into coal is coal matrix swelling, which has profound effects on CO_2 injection, displacement, spreading and sequestration. The matrix swelling or pore space shrinkage is also referred to as a gas sorption-induced strain that reduces the coal cleat width and pore sizes, thereafter decreasing coal porosity and permeability (Reucroft and Patel, 1986; Pekot and Reeves, 2002; Zhou et al., 2011). The sorption-induced strain can contribute up to 60% of the total variation of coal permeability during CBM production (Robertson and Christiansen, 2007; Lu and Connell, 2010). CO_2 influences coal permeability more dramatically than CH_4 on the same concentration basis, e.g., over 90% of permeability reduction could occur after CO_2 injection (Pekot and Reeves, 2002). On the contrary, coal matrix shrinkage happens during N_2 injection, due to its lower adsorption than CH_4. Hence, injection of CO_2-N_2 mixture has been considered as a technical option for ECBM as N_2 suppresses matrix swelling and permeability damage (Zhou et al., 2011).

3. Conclusions and remarks

CO_2-ECBM recovery is a technology that can improve CH_4 recovery as a bridge for energy transition and concurrently sequester CO_2, but knowledge gaps still exist in understanding competitive adsorption and its influential factors. Molecular dynamics is a fast-developing means suitable for visualizing and quantifying the relevant physics in nanoscale processes. Geomechanics, i.e., local changes in porosity and permeability affecting both dispersion and advection in the CO_2-ECBM process. Mineralogy of caprock should be analyzed to have a better strategy to minimize the risks of CO_2 leakage. Matrix swelling and shrinkage could dominate the permeability variation during the injection process, to balance the CO_2 and N_2 percentage becomes necessary for maintaining the injectivity. How injection and production parameters affect the recovery lacks of thorough investigation. On the whole, more in-depth analyses, experiments, and modeling of CO_2-CH_4-coal interactions are required to more adequately comprehend the promising CO_2-ECBM recovery technology before field implementation.

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Conflict of interest

The authors declare no competing interest.

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