



A model of cement-formation interface failure length in supercritical CO₂-ECBM and storage injection well considering the coal swelling effect under high pressure

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Received: 17 July 2018 / Accepted: 8 April 2019 / Published online: 17 April 2019
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Abstract

The swelling effect of high-pressure carbon dioxide (CO₂) in coal seam is obvious. In the restrained deep formation, it is converted to stress acting on the wellbore and the caprock. The action stress is concentrated near the wellbore and poses a threat to the cement-formation interface. Due to interface failure to micro-annulus, wellbore integrity will be lost and this will have an impact on carbon dioxide-enhanced coalbed methane recovery (CO₂-ECBM) and storage. In this paper, the pseudo-steady pressure distribution and steady pressure distribution of CO₂ injection process were established after considering the change in permeability of coal seam injected with high-pressure supercritical CO₂, and the vertical stress distribution model was derived. A one-dimensional radial numerical simulation formed by iterative method was established. A model for calculating the failure length at the cement-formation interface is obtained, and the shear stress and debonding length at the interface at various injection rates and times are calculated. The results show that the shear stress on the cement-formation interface has the maximum magnitude on the height of the interface between coal seam and caprock. The shear stress generated by coal swelling may break the fragile cement-formation interface into a narrow debonding interface. The injection rate has an influence on the interface failure length. For the same total injection amount, low injection rate is beneficial to protect the cement-formation interface integrity. This study provides a reference for the design of maximum injection speed for CO₂-ECBM and storage to avoid leakage.

Keywords Coal seam · Interface failure · Supercritical CO₂ · Coal swelling

Introduction

Fossil fuels such as coal, oil and natural gas provide above 80% primary energy of the world. However, the carbon dioxide emissions from fossil fuels represent about 60% greenhouse effect (Wang et al. 2018; Fang et al. 2017). One effective technology to reduce and utilize the emitted CO₂ is to inject it into the unmineable coal seam and increase methane production, or CO₂-ECBM in addition to CO₂ storage/sequestration (Zhang et al. 2015; Ibrahim and Hisham 2015). This technology can improve the recovery

of coalbed methane, realize the geological storage of CO₂, and achieve the purpose of easing greenhouse gas emissions. This method depends on the higher CO₂ adsorption/sorption capacity than CH₄ and most other adsorbing gases underground of coal seam and utilizes the injecting CO₂ from the ground to the bottom hole to replace the adsorbed CH₄ to free state (Haszeldine 2009; Mackay 2013). The injection of gas increases the pore fracture pressure and drives the free gas flowing out of the CBM production well, and thus increases the production and recovery of CH₄ (Mitra et al. 2008; Shi et al. 2014).

The technology of CO₂ injection into deep formation was widely used all over the world as a purpose of enhanced oil recovery (CO₂-EOR), natural gas recovery (CO₂-EGR) and CO₂ storage (Bryant 2007; Yang et al. 2014). It has been proved that injecting CO₂ into coal seams was a promising technique for improving coalbed methane recovery (Keim 2018; Cui et al. 2007; Kubus 2010). The first CO₂-ECBM pilot test was carried out in San Juan Basin of Colorado and

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Meridian in 1993 and 1995 (Gunter et al. 1997). A large-scale CO₂-ECBM field was performed in Allison Unit in San Juan Basin during 1995–2001 (Reeves et al. 2003). Since then, more than a dozen ECBM field trials have been orchestrated in reservoirs around the world (Pan et al. 2017), such as Western Canada Sedimentary Basin in Canada from 1998 (Mavor et al. 2004), three field projects in Qinshui Basin and one at the eastern margin of Ordos Basin in China from 2004 (Qin et al. 2017), Upper Silesian Coal Basin in Poland from 2004 (Van Bergen et al. 2009), Ishikari Coal Basin in Japan from 2004 (Yamaguchi et al. 2006) and Illinois Basin in USA from 2008 (Oudinot et al. 2011).

There is a significant difference in the formation medium between ECBM and other CO₂-enhanced recovery or storage technology. That is, coal seam swells/shrinks after absorbing gases, the adsorption of gas in the pores of coal results in the decrease in the free energy of coal surface, thus causing the swelling of coal (Pan and Connell 2007; Sakurovs et al. 2008). The swelling is much larger adsorbing CO₂ than that adsorbing CH₄, and the swelling effect becomes especially obvious under high-pressure condition (Vishal et al. 2013; Zhou et al. 2011). Shi and Durucan (2004) modified the standard geomechanical description by using the method of sorption-induced coal swelling strain. The resultant geomechanical relationships were used with the permeability models and developed permeability models that integrate strain and pressure effects. Cui and Bustin (2005) assuming that there is a linear relationship between porosity and strain difference, showed how this derivation should also include the effect of coal swelling, assumed that bulk and pore swelling strains were equal. Pan and Connell (2007) presented a theoretical model based on adsorption thermodynamics and elasticity theory; this model describes gas adsorption-induced swelling by assuming that the surface energy changes and it can describe coal swelling in different gases based on one set of coal property parameters and adsorption isotherms for different gases. Jikich et al. (2009) observed the internal structural changes of coal adsorbing various amount of CO₂ by X-ray computed tomography. Connell et al. (2010) derived from the general linear poroelastic constitutive law, presented analytical permeability models for tri-axial strain and stress conditions which distinguish between the sorption strain of the coal matrix, the pores (or cleats) and the bulk coal. Lu and Connell (2010) developed a predict model to describe the change of porosity, permeability and swelling strain of coal with CO₂ absorbed under at most 12.8 MPa and applied to the results from a series of laboratory tests. Pan and Connell (Pan and Connell 2011) presented a more general stress–strain relationship for anisotropic conditions. Directional swelling strain is considered as if it will have the same impact as thermal expansion in each direction. It is considered that the effect of directional expansion strain in all directions is the same as that of thermal expansion.

Qu et al. (Qu et al. 2012) studied a permeability switching model to represent the evolution of coal permeability induced by CO₂ absorption under variable temperatures, and the result was consistent with typical laboratory and in situ observations available in the literature. Day et al. (Day et al. 2012) studied the swelling of CO₂ in the unconstrained coal seam at 55 °C and 15 MPa conditions by experiment. The swelling of coal seam sample is about 1–3% after CO₂ is completely absorbed. Harpalani et al. (2016) carried out a laboratory study and measured the permeability and volumetric strain of the coal caused by the swelling of absorbed CO₂ under the pressure among 2.41 MPa (350 psi) and 5.86 MPa (850 psi).

There are many leakage pathways in the process of CO₂ injection and storage. The leakage paths of geological factors include top and bottom cap fractures, formation faults, while borehole factors include cement and casing of the injection and abandoned wells (Guen et al. 2009). Huo and Gong (2010) simulated the CO₂ leakage rate from formation fracture and compared the rate of fractures in CO₂ injection formation versus in caprocks by using discrete fracture model. Papanastasiou et al. (2016) presented a leakage pathway induced by fracture slip based on the modeling work of hydraulic fracturing in weak formations. CO₂ can migrate upwards through non-sealing faults or through induced hydraulic fracturing if the CO₂ pressure exceeds the closure stress defined by the minimum in situ stress. One of the main risks identified with storing CO₂ in the subsurface is the potential for leakage through existing wells penetrating the caprock (Nygaard et al. 2014). Tao et al. (2014) developed a prediction model of CO₂ leakage rate along wellbore based on sustained casing pressure data. Loizzo et al. (2011) studied four leakage pathway classes of wellbore including mud channels, chimneys, micro-annuli and no cement, and quantified the risk of leakage. Haghghat et al. (2013) studied the CO₂ leakage rate from geologic and wellbore pathways prediction model based on big data and smart field technology.

However, the study of coalbed wellbore integrity induced by swelling of CO₂ adsorption was rarely reported. In fact, the swelling effect cannot be neglected. It is converted into internal stress under the stress constraint at deep coal seam condition. The calculated constraining stress was about 25 MPa based on the swelling parameters of Day's et al. (2012) measurement. The stress generated by high-pressure CO₂ swelling is concentrated near the wellbore which threatens the wellbore integrity.

The cement between the casing and coal seam was formed by cement slurry that was injected from the well and coagulated under the condition of underground. The cement-formation interface is relatively weak (Ai et al. 2014) and is one of the potential leakage pathways for CO₂ injection and geological storage. However, the

high-pressure injection swelling effect near wellbore increases the stress on the cement-formation interface. When the stress breaks the fragile interface and debonds, CO₂ will escape from coal seam and cause safety problems.

The CO₂ field injection time is short and there is no comprehensive monitoring system for CO₂ leakage (Li et al. 2016), so few cases of CO₂ leakage have been reported. In addition, the whereabouts of injected CO₂ cannot be fully informed, even injected CO₂ leaks from the wellbore of adjacent formations, the current technical means are difficult to know. As a result, there are very few data reports of CO₂ from the industry. The present study of geological integrity does not consider the cement-formation interface influenced by the effect of coal swelling which produce great stress under the consideration of high-pressure supercritical CO₂. In this study, considering the pore pressure distribution after CO₂ injection, combined with the swelling effect of supercritical CO₂ in the coal seam, the stress distribution and the shear stress value at the cement-formation interface of the caprock are obtained. The failure condition and debonding failure length of cement-formation interface were calculated.

The adsorption phenomena in coal seam

Adsorption is a physiochemical process, describing the adhesion of particles of a phase at the surface of another phase. Adsorbates are fluid, and adsorbents are generally a porous solid (Mukherjee and Misra 2018). As the gas molecules are adsorbed, the molar entropy of the system and the enthalpy between adsorbed phase and adsorbents both decreases. Coal swells during gas adsorption and shrinks during gas desorption. This sorption-induced coal matrix volume change is a unique phenomenon for coal reservoirs. Laboratory measurements have shown coal can swell up to a few percent volumetrically (Pan and Connell 2012). Methane exists in coal seams mainly in two different states, adsorbed phase and bulk gas phase, with a small portion of methane dissolved in formation water. The adsorbed phase of CBM usually accounts for more than 80% of the total gas in place content in sub-surface coal seams (Wang and Tang 2018). Gas adsorption behavior in different adsorbents depends on thermodynamic properties of gas and adsorbent interaction (Vishal et al. 2013). The affinity of CO₂ in coal is higher than methane, and the amount of CO₂ adsorbed in coal is always higher than methane at the same pressure (Tang and Ripepi 2017). For a system containing CO₂ and CH₄, differential strain develops due to excess strain caused by

dissolution of CO₂ in coal compared to that of CH₄, on unit concentration basis.

The calculation model of cement-formation interface debonding failure length

Whether it is the supercritical CO₂ flooding or storage process, the pore pressure of coal seam reaches the pseudo-steady state in a short period of time. According to the basic pseudo-steady pressure distribution model of seepage mechanics, the CO₂ injection and displacement process of near wellbore pressure distribution is as follows:

$$p(r) = p_i + \frac{q_c \mu_c}{4\pi K_s h_s} \ln \left[-\text{Ei} \left(-\frac{r^2 \mu_s C_t}{4K_s t} \right) \right] \quad (1)$$

where $p(r)$ is the pore pressure at location r (Pa), p_i is the initial pore pressure (Pa), q_c is the CO₂ injection rate (m³/s), μ_c is the CO₂ viscosity (Pa s), C_t is coalbed comprehensive compressibility (1/Pa), K_s is the permeability of coal seam (m²), h_s is the seam thickness (m), t is the injection time (s), and r is the distance from borehole (m).

The Ei in Eq. (1) is the power integrator function which is shown as:

$$\text{Ei}(-x) = - \int_x^\infty \frac{\exp(-x)}{x} dx \quad (2)$$

With the injection time increasing, ECBM gradually enters the pressure steady state. When the seepage is stable, according to the basic steady pressure distribution model of seepage mechanics, the pressure distribution of the coal seam is as follows:

$$p(r) = p_i + \frac{p_{in} - p_i}{\ln(r_e/r_w)} \ln \frac{r}{r_w} \quad (3)$$

where p_{in} is the bottom hole injection pressure (Pa), r_w is the wellbore radius (m), and r_e is the equivalent supply radius (m) which can be converted according to the single well control area of the production well.

The permeability of coal seam changes after the injection of supercritical CO₂. Shi et al. (2014) studied the permeability of coal seam injected CO₂. This coal seam permeability model has the same form in the cylindrical coordinates and considered the effect of pore press and strain of coal seam changes as:

$$K_s = K_{si} \exp \left\{ 3C_p \left[\frac{v}{1-v} (p_c - p_i) + \frac{E_s \epsilon_f}{3(1-v)} \right] \right\} \quad (4)$$

where K_{si} is the original permeability of coal seam (m²), E_s is the Young's modulus of coal seam (Pa), C_p is the coal particle compressibility (1/Pa), p_c is the average pore pressure

(Pa), ν is the Poisson's ratio of coal seam, and ϵ_f is the free swelling strain of coal under unconstrained condition.

The average pore pressure can be calculated by weighted mean as:

$$p_c = \frac{\int p(r)dA}{\int dA} \quad (5)$$

where A is the area of the single well control area of the production well (m^2).

In the process of ECBM or geological storage by injecting CO_2 coal seam through perforation tunnels from injection well, the injected CO_2 swells the coal seam. As is known to all, only the unmineable coal seam may conduct the ECBM or CO_2 geological storage. Whatever, the coal seam that meets the above condition is always being bounded by the higher burial depth of the strata, which gives rise to almost no space for formation swelling and then the swelling produced by the adsorption of CO_2 on coal seams is limited. As a result, this part of the original swell amount is converted into stress and stored in the coal reservoir. Thus, the internal coal stress increases. At the same time, the added stress acts upon the injection wellbore, and on the top and bottom coal cover layers as well. The inner stress is caused by swelling effect as radial extrusion stress to the injection wellbore and a longitudinal compressive stress to the caprock. In the action of these two stresses above, it makes a great shear stress on the cement-formation interface which may be destroyed under certain conditions, and the CO_2 escape channels are formed (Fig. 1). This can result in some unexpected situations, such as the cross-flow layers of CO_2 -ECBM, CO_2 escape after storage.

In general, the formation temperature is about $60\text{ }^\circ\text{C}$ in terms of the deep coal seams for CO_2 -ECBM and geological storage, which is above the CO_2 critical temperature of $31.04\text{ }^\circ\text{C}$. The drilling fluid temperature is low during the formation of wellbore. When the wellbore is formed, the surrounding rock was cooled by drilling fluid while the drilling fluid is warmed by whole formation. Compared with the initial state of the surrounding rock, the temperature difference when injecting CO_2 is small, and the degree of temperature reduction and contraction of CO_2 injection are significantly smaller than the expansion. In addition, considering that the study of temperature calculation brings great difficulties, the influence of temperature change is neglected.

As for the coal seam internal swell after the injection of CO_2 , by theoretical analysis and combined with Cui's (2007) experimental results verification, Zhou et al. (2011) developed an unconstrained free swelling under high pressure is as follows:

$$\epsilon_{f(i)} = -\frac{3}{(1-\phi)E_s} \int_0^p \epsilon_{f(i)} dp - \frac{\rho_s}{E_s} V_{L(i)} RT \ln(1 + b_{(i)} p) \quad (6)$$

where $\epsilon_{f(i)}$ is the strain of coal adsorbed on i type single component gas, ϕ is the coalbed porosity, ρ_s is the density of the coal seam (kg/m^3), $V_{L(i)}$ is the Langmuir volume of i type single component gas (m^3/kg), R is the gas constant ($J/mol/K$), T is the coal seam absolute temperature (K) and $b_{(i)}$ is the adsorption coefficient of i type single component gas

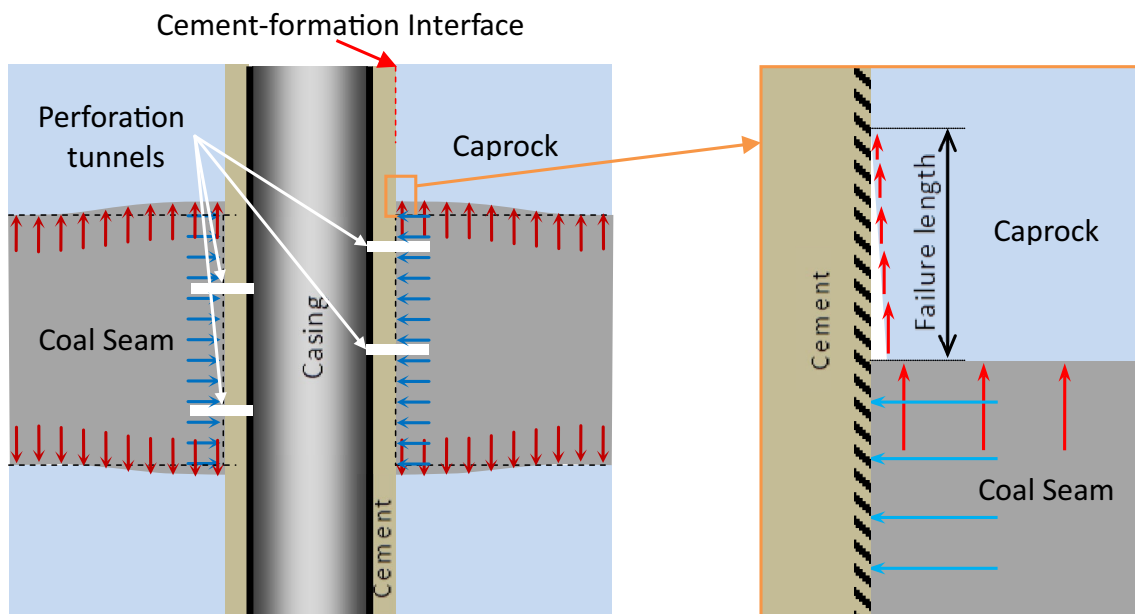


Fig. 1 Location conditions of the casing, cement, interface, caprock and coal seam

(1/Pa), and $b_{(i)} = 1/p_L$ where p_L is the Langmuir pressure of i type single component gas (Pa).

From the saturated adsorption of CH_4 to the adsorption of CO_2 , the additional strain produced by the coal seam is as follows:

$$\varepsilon_f = \frac{3}{(1-\phi)E_s} \left[\int_0^{p_i} \varepsilon_{f(\text{CH}_4)} dp - \int_0^p \varepsilon_{f(\text{CO}_2)} dp \right] + \frac{\rho_s RT}{E_s} \left[V_{L(\text{CH}_4)} \ln(1 + b_{(\text{CH}_4)} p_i) - V_{L(\text{CO}_2)} \ln(1 + b_{(\text{CO}_2)} p) \right] \quad (7)$$

The swelling of the coal seam causes compression to the surrounding rock and the wellbore, so the pressure stress and length reduced strain are taken as positive value in this paper.

The physical equation of the coal seam adsorbed by CO_2 can be shown as:

$$\begin{cases} \varepsilon_r = \frac{1}{E_s} [\sigma_r - \nu(\sigma_\theta + \sigma_z)] + \varepsilon_f \\ \varepsilon_\theta = \frac{1}{E_s} [\sigma_\theta - \nu(\sigma_r + \sigma_z)] + \varepsilon_f \\ \varepsilon_z = \frac{1}{E_s} [\sigma_z - \nu(\sigma_r + \sigma_\theta)] + \varepsilon_f \end{cases} \quad (8)$$

where ε_r , ε_θ and ε_z are radial strain, circumferential strain and vertical strain, respectively, and σ_r , σ_θ and σ_z are radial stress, circumferential stress and vertical stress (Pa), respectively.

Under the constraint of deep underground formation, the strain in each direction of coal seam can be considered as 0, or $\varepsilon_r = \varepsilon_\theta = \varepsilon_z = 0$. The stress can be obtained combined with Eq. (8) as:

$$\sigma_r = \sigma_\theta = \sigma_z = \frac{E_s \varepsilon_f}{1 - 2\nu} = \sigma(r) \quad (9)$$

The coal seam swells after CO_2 injected, but the cement sheath, casing and coal caprock do not. The radial stress generated by the expansion of the coal seam acts on the cement, so that the casing and cement are fixed, and the vertical stress is formed at the interface between the seam and cap. Therefore, on the cement-caprock interface, the cement is fixed by the radial stress and the cap is subjected by the longitudinal stress, which causes the coal swelling effect acting as the shear stress on the cement-formation interface.

When $\tau(z) > s_c$, where $\tau(z)$ is the shear stress on the cement-formation interface (Pa) and s_c is the shear strength of cement-formation interface (Pa), the interface debonds. Since the pore stress in the caprock is equivalent to that of the coal seam, the effect of the pore pressure variation on the effective stress can be ignored.

The upper and lower layers of deep coal seams can be regarded as infinite strata. In the infinite stratum, the vertical stress in the axial direction is as follows:

$$\sigma_z = q \left[1 - \frac{z^3}{(z^2 + a^2)^{\frac{3}{2}}} \right] \quad (10)$$

when the radius is a and the uniform stress is q .

The shear stress of cement-formation interface formed by the whole plane vertical stress can be deduced as:

$$\tau(z) = \int_0^\infty \left\{ 1 - \frac{z^3}{[z^2 + r(q)^2]^{\frac{3}{2}}} \right\} dq \quad (11)$$

where $r(q)$ is the inverse function of pseudo-steady or steady state pressure distribution and z is the vertical distance from coal seam.

In order to calculate the debonding failure length of the fracture surface, it is assumed that the fractured debonding surface can be extended under the influence of the vertical stress produced by the swelling of the coal seam. At the end of the extension, the shear stress is equal to the shear strength as

$$\tau(z) = s_c \quad (12)$$

The shear stress decreases with the increase in the distance to the coal seam. When the shear stress equals to s_c , the corresponding z is the cement-formation debonding failure length.

Methodology and calculation parameters

The shearing stress on cement-formation interface depends on the stress and pore pressure of wellbore surrounding rock which are coupling effect on permeability, pore pressure and coalbed stress. A one-dimensional radial numerical simulation formed by iterative method and established by a Visual Basic program.

Assuming a reasonable value for ε_f and p_c , the K_s can be calculated according to (4), and then calculate $p(r)$ of pseudo-steady state or steady state by (1) or (3), respectively. Then, the p_c can be calculated according to (5) and replace the p_c assumed first. Iterate p_c until the accuracy is satisfied. ε_f is calculated according to (7) and replaced by ε_f and returned to the beginning. The calculation is recalculated until the accuracy is satisfied. Finally, the shear stress can be calculated according to Eqs. (10) and (11).

The parameters refer to the parameters of the coal seam in Niu's thesis (Niu 2016) as shown in Table 1.

Under isothermal conditions, the viscosity of supercritical CO_2 can be simplified by a fitted equation. The viscosity was fitted according to the experimental data of Wang (2008) under 60 °C as:

$$\mu_c(p) = 1.726 \times 10^{-20} p^2 - 8.770 \times 10^{-14} p + 1.828 \times 10^{-6} \quad (13)$$

Table 1 Calculation parameters of the coal seam

Calculation parameters	Value
Porosity of coal seam	0.03
Young's modulus of coal seam (GPa)	3.00
Density of coal seam ($\times 10^3$ kg/m ³)	1.4
Langmuir volume of CO ₂ adsorbed by coal seam (m ³ /t)	32.2
Temperature of coal seam (K)	300
Adsorption coefficient of CO ₂ (1/MPa)	1.20
Borehole radius of coal seam injection well (m)	0.1
Initial permeability of coal seam ($\times 10^{-3}$ μ m ²)	0.1
Thickness of coal seam (m)	12
Comprehensive compressibility of coal seam (10^{-6})	14
Compressibility of coal seam (10^{-6})	0.5
Initial pore pressure of coal seam (MPa)	10
Poisson's ratio of coal seam	0.3
Langmuir volume of CH ₄ adsorbed by coal seam (m ³ /t)	34.21
Adsorption coefficient of CH ₄ (1/MPa)	0.476

in which pressure value ranged from 5 to 15 MPa with a correlation coefficient of 0.99 by using the SI unit.

In combination with the above parameters and the calculation method in this paper, the corresponding computer program is compiled. The vertical stress distribution, shear stress distribution and the two interfacial debonding failure lengths of the coal seam after supercritical CO₂ swelling are calculated.

The integral of Eq. (2) used the approximate solution as:

$$\text{Ei}\left(-\frac{r^2\mu_s C_t}{4K_s t}\right) = \ln \frac{2.25\mu_s C_t}{K_s r^2} \quad (14)$$

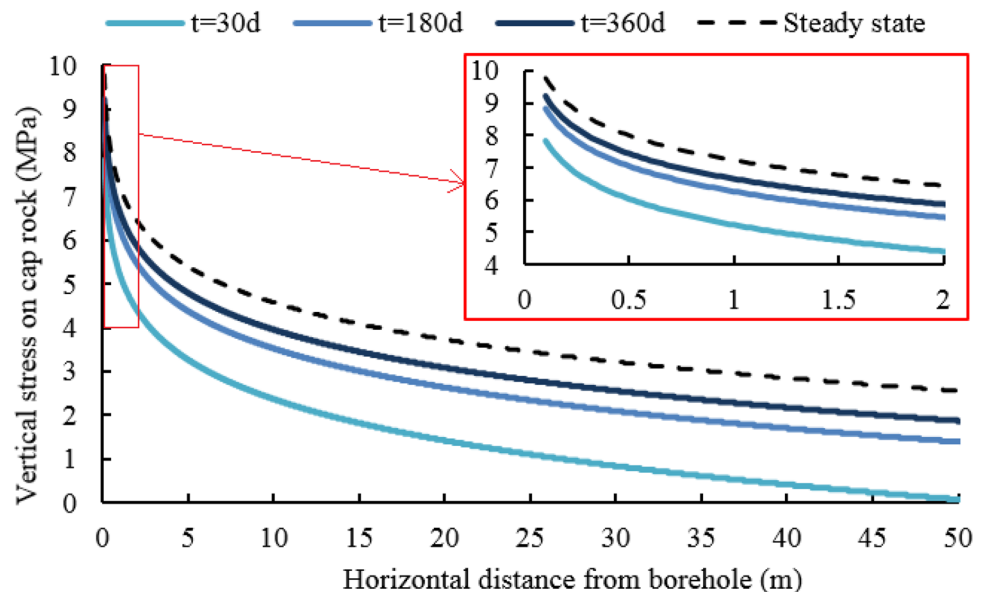
when $r^2\mu_s C_t/4K_s t < 0.01$. The integral of Eq. (6) used the cumulative method, and the step was 0.01 MPa. The inverse pressure function of Eq. (11) was calculated according to the pressure distribution, and the step was 0.02 m. The integral of Eq. (11) also used the cumulative method, and the step was 0.02 m.

The effect of injection time on debonding failure length of cement-formation interface

With the injection of CO₂, the pore fracture pressure in the coal seam increases. When the coal seam adsorbs CO₂, the swelling occurs and the vertical stress is formed. Assuming the injection rate is 2500 m³/day, the vertical stress on caprock was calculated in various injecting times and is shown in Fig. 2.

The three solid lines in Fig. 2 represent the vertical stresses formed by coal swelling adsorbed CO₂ at various injection times, the dashed line is the stress distribution when the injecting pressure enters the stable stage. Coal seam swells caused by CO₂ replace absorbed CH₄. The increased pore pressure comes from the injected CO₂. For the one-dimensional radial model of single point source, the injection pressure decreases rapidly with increasing distance, as the vertical stress formed by the swelling also decreases rapidly with increasing distance. Under the given calculation parameters, the vertical pressure of coal seam and caprock interface near the wellbore reach 7.8 MPa in 30 days, 9.2 MPa in 360 days and 9.8 MPa in infinite time. With the increase in injection time, CO₂ diffuses to the coal seam, the influence scope gradually increased, the vertical stress distribution of stratum is increased overall. Through

Fig. 2 Vertical stress formed by the swelling of CO₂ injection at the interface between coal and caprock



comparison of 30 days, 180 days and 360 days, the vertical stress increase speed gradually slowed down. However, this stress can only represent the stress magnitude at the cement-formation interface at the boundary between coal and caprock, and the swelling stress is decreased with the distance from the coal seam.

For the CO₂-ECBM, the pore fracture pressure of the coal seam will eventually become stable, shown as the dashed line in the diagram. Under the condition of CO₂ storage, when the injection pressure is close to the formation fracturing pressure, the injection pressure will be controlled under the fracturing pressure in order to protect the formation. Subsequently, the wellbore pressure differential effect is reduced, the formation stress distribution is more average, and the formation becomes safer. Combining the integral method Eq. (11) and assume the cement-formation interface strength is 3 MPa, the results of the drawing above, the shearing stress on the cement-formation interface is shown in Fig. 3.

The ordinate in Fig. 3 is the distance from the interface between the seam and the cap, and the abscissa is the shear stress at the cement-formation interface. As the wellbore is under the influence of the lateral pressure caused by the horizontal swelling of the coal seam, it can be considered that the relative injection well does not displace. Therefore, the vertical stress at the cement-formation interface formed in the form of shear stress under the vertical stress at the interface of the coal seam and the caprock. In fact, the shear stress curve is not the shear stress distribution along the cement-formation interface, but rather the curve joined with the shear stress value which if the cement-formation interface debonds to a certain height. When the stress is greater than the cement-formation interface debonding

failure strength, the interface will continue to debond. On the contrary, if this stress is less than the strength, the cement-formation interface will not reach at this position. It is considered that the cement-formation interface debonding failure length is exactly the height where the shear stress equals to the strength.

Because of the extremely low viscosity of supercritical CO₂, it can flow at a narrow debonding interface. The debonding interface becomes the CO₂ high-velocity leakage pathway, which influences injection and storage process. As can be seen from Fig. 3, with the increase in CO₂ injection time, the vertical stress due to the swelling of coal seam increases, and the shearing stress on the cement-formation interface gradually increases. Taking 3 MPa as the cement-formation interface strength for instance, it can be seen that the failure length of the cement-formation interface will gradually increases, and will reach 45 m when the injection enters steady state.

The effect of various injection rates

With the same parameters, the injection rate from 1500 to 3000 m³/day and the distribution of the coal swelling stress at the interface between the coal and the cap are calculated under the condition of 180 days. The vertical stress on the coal seam and caprock interface with various injection rates is shown in Fig. 4.

The four curves in Fig. 4 represent the stress distributions at the same injection time with various injection rates. With the increase in injection rate, the amount of injected CO₂ volume increases. The absorbed CO₂ volume increases with coal seam pore pressure and CO₂ amount,

Fig. 3 Shearing stress on the cement-formation interface under various CO₂ injecting times by assuming the cement-formation interface strength is 3 MPa

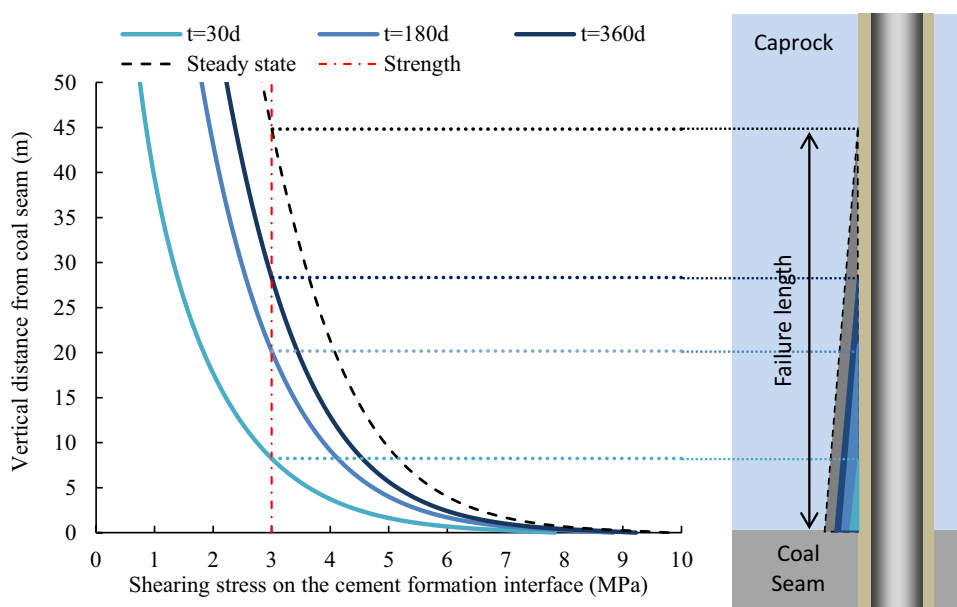
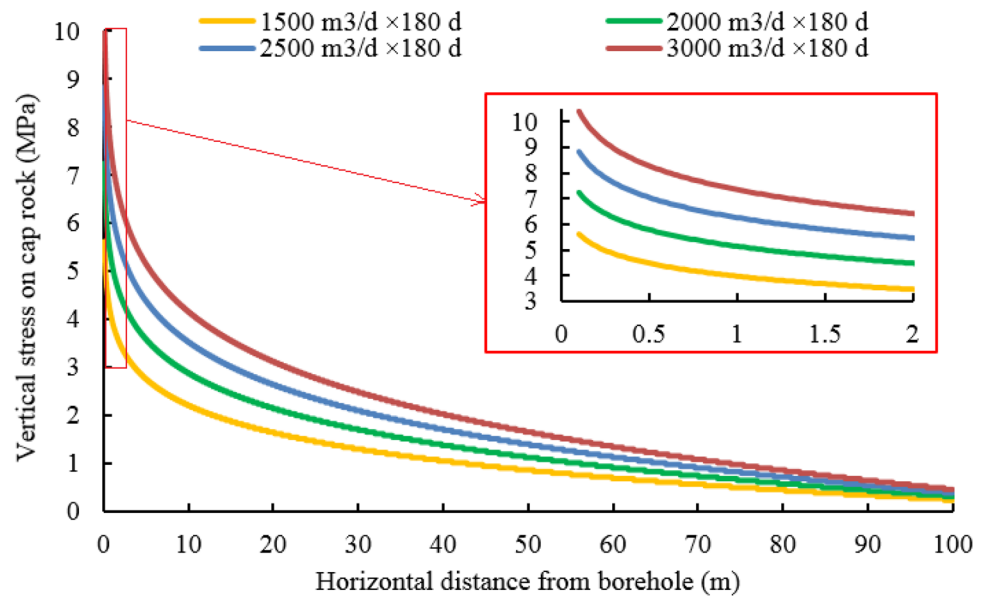


Fig. 4 Vertical stress formed by the swelling of CO₂ injection at the interface between coal and caprock interface under various injection rates



so the coal swelling effect increases with the increase in injection rate. Hence in constrained underground confining strata, this differential swelling will act as a vertical stress in the caprock. The flow rate increased two times from 1500 to 3000 m³/day, and the stress distribution increased by about 1.3 times. However, it is easy to infer that the faster CO₂ injection rate is, the greater the vertical stress formed under the same conditions. Setting the same injection amount of CO₂ is 450×10^3 m³, the vertical stress on caprock was calculated with the various injection rates and corresponding injection times as shown in Fig. 5.

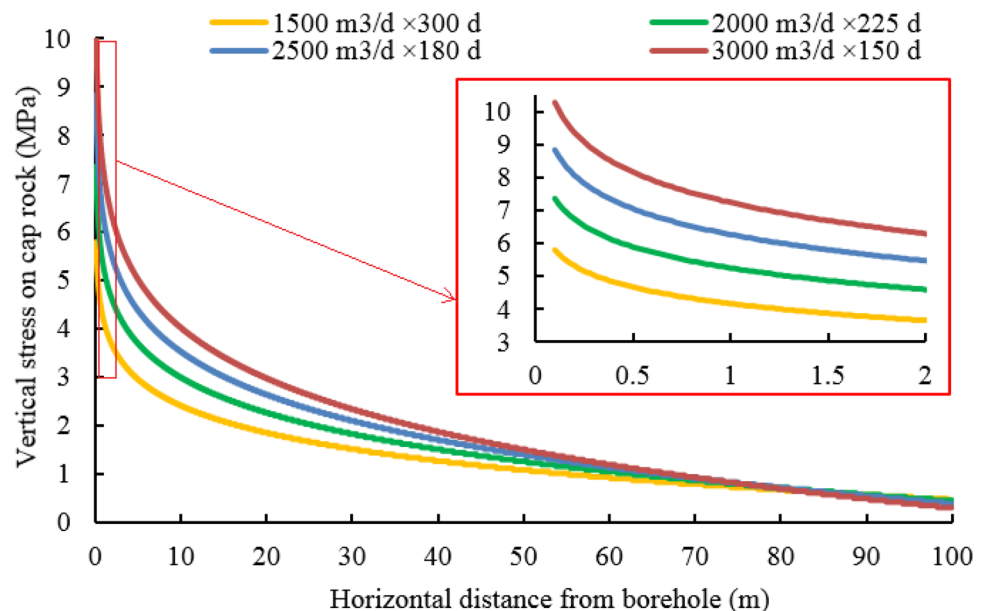
With the same CO₂ injection amount, the time is longer in the low injection rate, so the CO₂ in the coal seam is

more dispersed, and the radial pressure distribution is more balanced when the coal seam adsorbed CO₂. Fast injection causes stress concentration near wellbore and leads to more shear stress on cement-formation.

In order to calculate the debonding failure length of the interface, the shearing stress on the cement-formation interface is calculated according to Fig. 6 results.

Under the condition of the same CO₂ injection amount, the debonding failure length of the cement-formation interface is the shortest with low injection rate although it needs the longest time. Under the given parameters, the debonding length of the cement-formation interface at 1500 m³/day

Fig. 5 Vertical stress at the interface between coal and caprock interface under various CO₂ injection rates with same injection amount



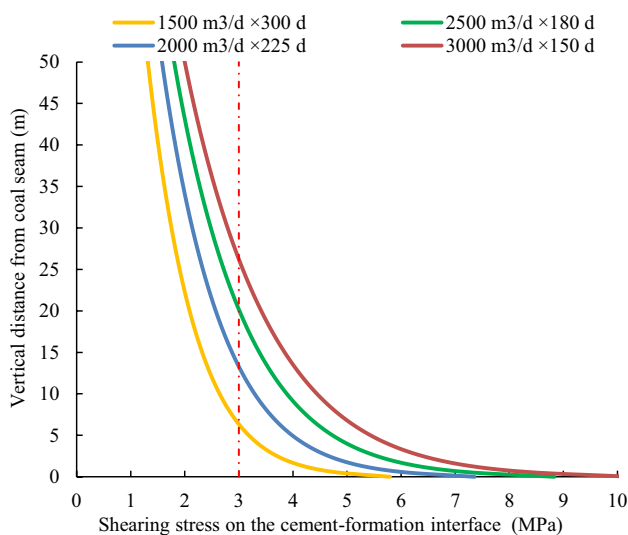


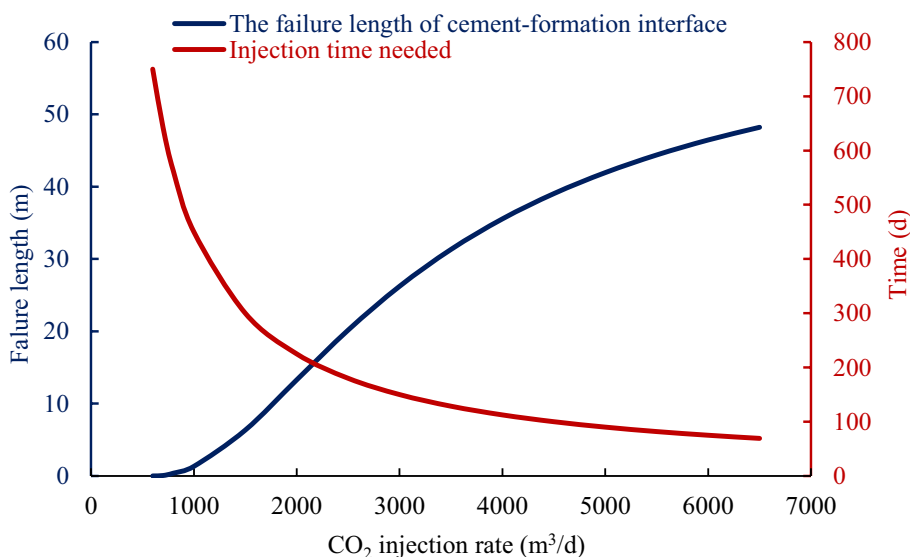
Fig. 6 Shearing stress on the cement-formation interface under various CO₂ injecting rates with same injection amount

injection rate is 5.3 m, while the 3000 m³/day injection rate is 26.0 m, increasing 4.9 times.

In order to study the relation between the injection rate and the failure length of cement-formation interface, various injection rates were calculated according to the same injection amount of 450 × 10³ m³ CO₂ with corresponding time.

The two curves in Fig. 7 are the cement-formation interface debonding failure length and the corresponding injection time with various injection rates, respectively. For the given parameter, when the injection rate is less than 700 m³/day, the cement-formation interface does not damage, but the injection time is relatively long. With the increase in CO₂ injection rate, the debonding failure length

Fig. 7 Debonding failure length of cement-formation interface and the CO₂ injecting time needed under various injection rates with same injecting amount



of the cement-formation interface increases rapidly, and the failure length increases and the speed slows down when it reaches more than 4000 m³/day. In order to ensure CO₂ cannot escape from injection coal seam, it is suggested that the injection rate should be reasonably designed according to the thickness of caprock.

The limitation of the mode

This model considered the coal swelling effect in the process of CO₂ injection including the formation pressure and permeability changes, while does not account for some secondary factors.

The differential swelling strain buildup in a transversely isotropic medium of coal seam is neglected and the release of vertical stress caused by vertical deformation after coal seam swell is neglected. This paper also does not consider the temperature effect and cannot analyze the effect of temperature reduction caused by the change in CO₂ injection rate on coal swelling. Assuming that the coal seam is pure methane and the injected gas is pure CO₂, the influence of other gas components is not considered. The difference of permeability after CO₂ injection into coal seam is neglected, and the average permeability is used to replace the different permeabilities at different locations.

Conclusions

1. With the injection of CO₂, the swelling take place on coal seam and the vertical stress is formed along the interface between coal seam and caprock as the coal

restrained at deep stratum condition. In the case of the contribution of wellbore confinement by the coal swelling radial stress, the vertical stress acts in the form of shear stress on the cement-formation interface.

2. The shear stress on the cement-formation interface has the maximum magnitude on the height of the interface between coal seam and caprock. The shear stress generated by coal may break the fragile cement-formation interface into a narrow debonding interface. The debonding interface becomes the CO₂ high-velocity leakage pathway, which influences injection and storage process.
3. With the same CO₂ injection amount, the lower CO₂ injection rate causes more dispersed CO₂ in the coal seam and the radial pressure distribution is more balanced when the coal seam adsorbed CO₂. There is an appropriate injection rate that does not destroy the cement-formation interface.

Acknowledgements This work was supported by Natural Science Foundation of China (No. 51774094), National Science and Technology Major Project of China (No. 2016ZX05016-002-003), Youth Foundation of Heilongjiang Province (Grant No. QC2018047) and Youth Science Foundation of Northeast Petroleum University (No. 2018NL-19).

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