Pressure variation law of CO_2 injection target area in coal seams

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Abstract. Gas outburst accidents are prone to occur during coal mining, and injecting CO_2 into the coal body can achieve the goal of gas displacement. At the same time, this method will cause changes in the permeability of the coal body, leading to deformation, fracture, and other factors affecting the stability of the coal body. Therefore, it is of great significance to study the pressure changes in the target area of CO_2 injection into coal. The COMSOL software was used to simulate the CO_2 injection process into coal. The research results showed that as the displacement process progressed, the range of CO_2 influence gradually increased, and the gas pressure in the target area decreased while the CO_2 pressure increased. The direction of drilling to the boundary of the coal body is affected by injection pressure and extraction, and the CO_2 and gas pressures are constantly decreasing. Some areas may experience gas pressure rising above the initial gas pressure.

Keywords: Rock and soil seepage; Carbon dioxide injection; Gas pressure; Numerical simulation; Quantitative analysis.

1 Introduction

Coal accounts for a relatively high proportion of China's primary energy consumption structure[1,2]. In order to meet the requirements of global climate change and the dual carbon target, China urgently needs to vigorously develop clean energy. According to statistics, the amount of coalbed methane resources buried below 2000 meters on land in China is as high as 36.81×10^{12} m^3[3]. However, the extraction of coalbed methane is relatively difficult. To solve this problem, some scholars[4,5] have injected CO_2 into non minable coal seams containing gas, which can not only increase gas production but also achieve long-term stable storage of CO_2. Many scholars have studied the characteristics of binary gas adsorption desorption seepage during CO_2 displacement of gas. Jiang[6] found that the CO_2 injection temperature has an important impact on the CH_4 displacement efficiency and CO_2 storage. The higher the CO_2 injection temperature, the

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greater the outlet mixed gas flow rate and CH_4 gas flow rate, showing a trend of first increasing, then decreasing, and tending to stabilize. Zhu[7] found that the correlation between coal deformation caused by CO_2 adsorption and desorption and gas pressure conforms to the Langmuir equation. Niu[8] found that as the CO_2 injection pressure increases, the internal expansion coefficient of the coal body increases, leading to a decrease in permeability. In terms of numerical simulation, Zheng[9] found that the decrease in coal permeability will result in a significant loss of gas migration velocity. Wang[10] simulated CO_2 displacement of gas in coal samples and found that the displacement efficiency of gas varies under different injection pressures.

In summary, although many scholars have conducted many studies on adsorption desorption seepage during the displacement process, they have not analyzed the pressure changes in the target area of the coal body. This article establishes a coupled physical field model for the CO_2 displacement gas process in the coal body and analyzes the pressure changes in the injected CO_2 target area.

2 Mathematical model of CO_2 displacement gas process

2.1 Gas diffusion control model

During the process of CO_2 displacement of gas, binary gas diffuses under pressure, and the gas satisfies the equation:

$$\begin{cases} \frac{\partial C_1}{\partial t} - \nabla \cdot (D_1 \nabla C_1) = -Q_1 \\ \frac{\partial C_2}{\partial t} - \nabla \cdot (D_2 \nabla C_2) = -Q_2 \end{cases} \tag{1}$$

where C_i is the concentration of the gas substance, mol/L; t is time, s; D_i is the gas diffusion coefficient, m^2/s; Q_i represents the binary gas source term, reflecting the mass exchange between CO_2 and gas (Q_1 represents gas, Q_2 represents CO_2).

2.2 Gas seepage control model

During the process of CO_2 displacement of gas, the gas seepage in the coal body satisfies the equation:

$$\begin{cases} \frac{\varphi M_1}{RT}\frac{\partial p_1}{\partial t} + \nabla \cdot \left(-\frac{M_1 k p_1}{RT\mu_1} \nabla (p_1 + p_2) \right) = Q_1 \\ \frac{\varphi M_2}{RT}\frac{\partial p_2}{\partial t} + \nabla \cdot \left(-\frac{M_2 k p_2}{RT\mu_2} \nabla (p_1 + p_2) \right) = Q_2 \end{cases} \tag{2}$$

The binary gas source phase satisfies the equation:

$$\begin{cases} Q_1 = \tau \cdot \left(C_1 - \frac{\rho_{g1} \rho_c a_1 b_1 p_1}{1 + b_1 p_1 + b_2 p_2} \right) \\ Q_2 = \tau \cdot \left(C_2 - \frac{\rho_{g2} \rho_c a_2 b_2 p_2}{1 + b_1 p_1 + b_2 p_2} \right) \end{cases} \tag{3}$$

where φ is the porosity of the coal body; M_i is the molar mass of the gas, g/mol; R is the gas constant, 8.314 J/(mol·K); T is gas temperature, K; p_i is gas pressure, MPa; k is coal permeability, 10^{-15}m^2; μ_i is the gas dynamic viscosity, Pa·s; τ is the adsorption desorption coefficient, with a value of 1.42ms; ρ_{gi} is the density under gas standard conditions, kg/m^3; ρ_c is the coal density, kg/m^3; a_i is the maximum gas adsorption capacity, m^3/kg； b_i is the gas adsorption pressure constant, MPa^{-1}.

3 Establishment of displacement model

Using COMSOL software to simulate the process of CO_2 displacement of gas in coal, the coal model was simplified to clearly observe the displacement effect and pressure changes, and to shorten the calculation time. Coal body size is 5 × 5 meters, with CO_2 injection port at the center of the borehole and gas extraction port around it, as shown in Figure 1.

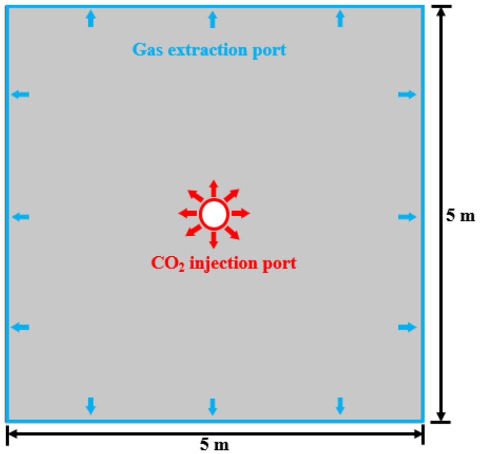

Fig. 1. Schematic diagram of CO_2 displacement gas model.

The simulation parameters during the displacement process are shown in Table 1.

Table 1. Setting of displacement model parameters.

Parameter	Initial porosity	Initial permeability /m^2	Initial gas pressure /MPa	Gas dynamic viscosity /Pa·s	CO_2 dynamic viscosity /Pa·s	Gas diffusion coefficient /m^2·s^{-1}	CO_2 diffusion coefficient /m^2·s^{-1}
Value	0.049	4×10^{-16}	0.05	1.08×10^{-5}	1.38×10^{-5}	2×10^{-6}	3×10^{-6}

4 Simulation results and analysis

4.1 Change pattern of CO_2 pressure in the target area

0.4 MPa CO_2 was injected from the borehole, and the change in CO_2 pressure in the target area is shown in Figure 2.

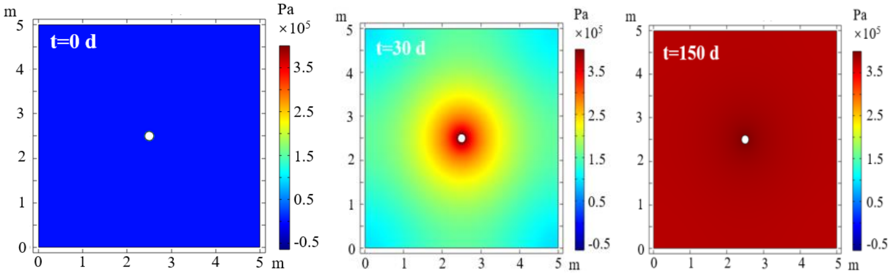

Fig. 2. CO_2 pressure variation diagram during displacement process.

From Figure 2, it can be seen that as the displacement process progresses, the CO_2 pressure continues to increase, the migration range continues to expand, and the CO_2 pressure continuously decays from the borehole to the coal body boundary.

In order to observe the displacement rate of CO_2 under different injection pressures, the injection pressures were determined to be 0.4 MPa, 0.6 MPa, and 0.8 MPa. The curve of CO_2 pressure over time under different pressure conditions is shown in Figure 3.

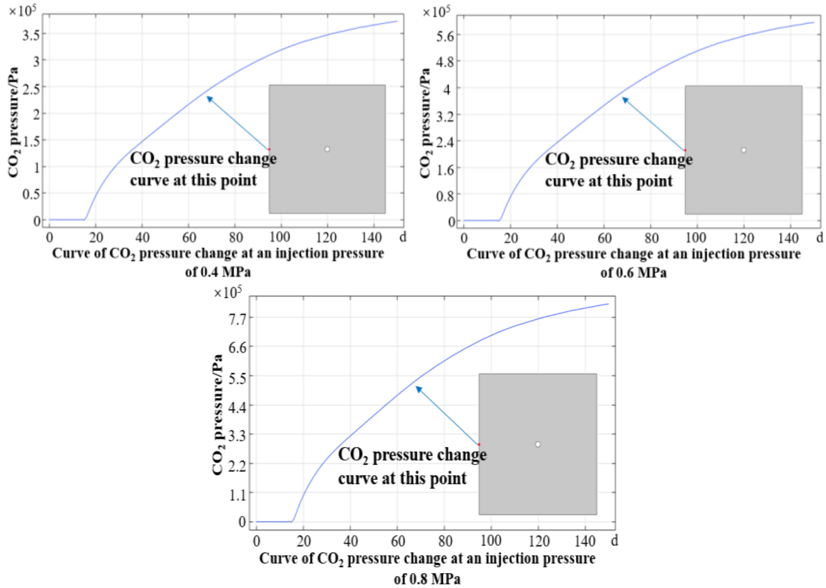

Fig. 3. CO_2 pressure variation curve under different pressure conditions.

From Figure 3, it can be seen that as the injection pressure increases, the CO_2 infiltration diffusion rate increases. When the injection pressure of CO_2 is 0.4 MPa, CO_2 reaches the coal boundary after 18 days; When the injection pressure of CO_2 is 0.6 MPa, CO_2 reaches the coal boundary after 17.5 days; When the injection pressure of CO_2 is 0.8 MPa, CO_2 reaches the coal boundary after 17 days. Increasing injection pressure is an important way to improve the efficiency of gas displacement.

4.2 Change law of gas pressure in the target area

During the process of CO_2 injection to replace gas, the gas pressure changes are shown in Figure 4.

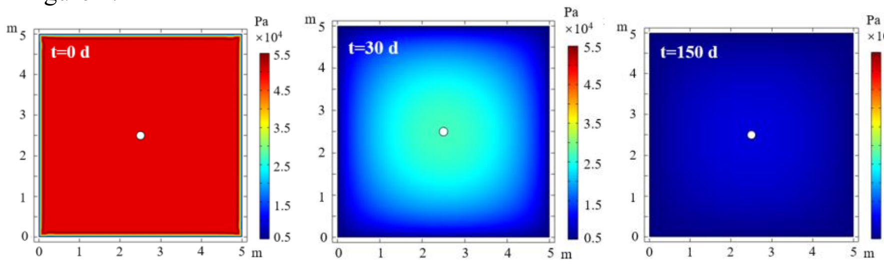

Fig. 4. Gas pressure variation diagram during displacement process.

From Figure 4, it can be seen that as the CO_2 displacement process progresses, the gas pressure gradually decreases over time until the coal body is completely displaced. Due to the fact that the boundary of the coal body is the extraction boundary, the closer the gas is to the boundary, the lower the gas pressure.

To observe the variation of gas pressure in the coal body, a reference point 0.5 m away from the borehole was used to record the changes in gas pressure at that point, as shown in Figure 5.

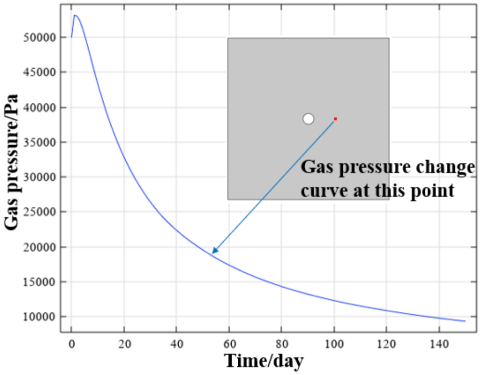

Fig. 5. Gas pressure variation curve at reference point.

From Figure 5, it can be seen that after CO_2 injection displacement, the gas pressure at the reference point first increases, leading to a local area where the gas pressure is higher than the initial gas pressure, and then continuously decays until it reaches zero. During the process of gas displacement, CO_2 injection is faster, and the initial gas migration speed is slower, leading to local accumulation and abnormal increase in gas pressure.

To explore the variation law of gas pressure at this reference point, the gas pressure data at this point was processed and analyzed, as shown in Figure 6.

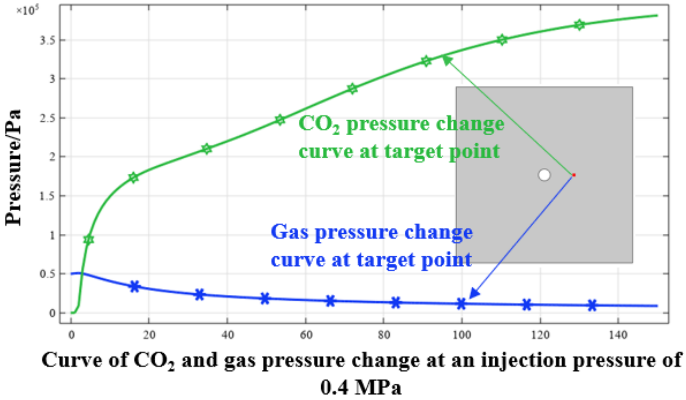

Fig. 6. Change curves of CO_2 and gas pressure at the reference point.

From Figure 6, it can be seen that after injecting CO_2 pressure, the gas pressure at the reference point continuously decreases, and the gas is displaced to the boundary of the coal body. At the same time, the CO_2 pressure at the reference point continues to increase, and the CO_2 content in the coal body increases.

To determine the area of abnormal increase in gas pressure, the reference line from the borehole to the boundary of the coal body was selected to study the temporal variation of gas pressure at different locations, as shown in Figure 7.

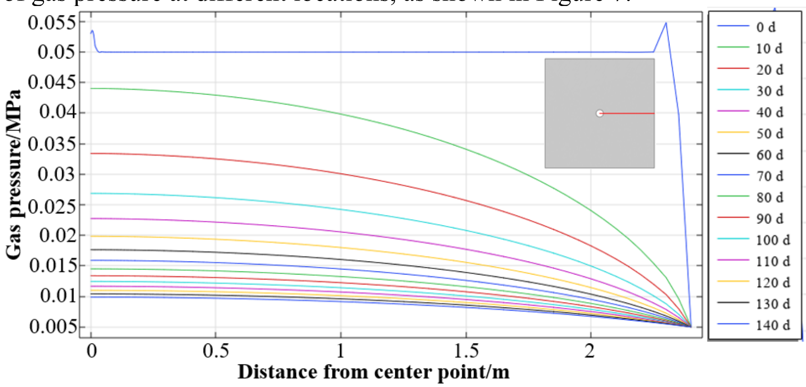

Fig. 7. Gas pressure change curves at different locations on the reference line.

From Figure 7, it can be seen that the abnormal increase in gas pressure occurs at the beginning of the displacement process, and the abnormal range is small, with a radius of approximately 0.05 m.

5 Conclusion

1) In the process of CO_2 injection to displace gas, the volume of CO_2 in the coal body increases, the CO_2 pressure increases, and the CO_2 pressure gradually decreases from the drill hole to the coal body boundary. The volume of gas in the coal body decreases, the gas pressure decreases, and gas accumulates in local areas, leading to an increase in gas pressure.

2) Increasing CO_2 injection pressure can significantly improve displacement efficiency. The higher the injection pressure, the faster the rate of CO_2 pressure increase, and the faster the gas displacement rate.

3) During the CO_2 injection displacement process, the radius of the abnormal increase in gas pressure area in this model is 0.05 m, and the duration is relatively short.

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