An experimental study on the permeability changes of anthracite reservoirs in different depths of Qinshui Basin induced by supercritical CO₂ injection

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Abstract

Geological sequestration of supercritical CO₂ (ScCO₂) in deep coal seam has been considered as one of the most promising options for reducing greenhouse gas emission. The permeability of a coal seam, a key parameter estimating the CO₂ injectivity, determines the success of ScCO₂ storage in the deep coal seam. The deep coal seam has a low initial permeability and a further permeability loss induced by the adsorption-swelling effects of coal during ScCO₂ injection. This paper presents a set of measurements on the permeability changes of anthracite reservoirs in different depths of Qinshui Basin induced by ScCO₂ injection. The results indicate that the change in anthracite permeability presents a negative exponential decrease with the buried depth increase. The depth of anthracite reservoir increases from 800 to 1400 m, and its permeability will decrease from 4.59 × 10⁻² to 8.04 × 10⁻⁴ mD. The permeability change induced by ScCO₂ injection is the combining effects of temperature, pressure, and adsorption-swelling, and the permeability change can be described by a negative exponential model during ScCO₂ injection to anthracite reservoir in different depths. The loss coefficient of permeability is up to three magnitudes induced by ScCO₂ injection to the anthracite reservoir in the depth of 800 m, 2-3 magnitudes in 1000-1200 m, and 1-2 magnitudes in 1400 m. Although the initial permeability of anthracite reservoirs in the same depth exists differences, the permeability loss coefficient almost has the same magnitudes induced by ScCO₂ injection. Comparing with the permeability loss coefficient of the anthracite reservoir in different depths, the permeability variation of the shallow coal seam is more sensitive than the deep induced by ScCO₂ injection. However, the deep coal seam has a relatively large fracture pressure, so the allowable ScCO₂ injection pressure in the deep coal seam is greater than the shallow.

KEYWORDS

deep anthracite reservoir, geological sequestration, permeability, supercritical CO₂
1 INTRODUCTION

Carbon dioxide (CO₂) is a kind of greenhouse gas affects atmospheric temperature, and geological sequestration of CO₂ has been considered as one of the most promising options for reducing greenhouse gas emission.1-3 The permeability of a coal seam, a key parameter reflecting the ability of fluids to flow inside the coal seam and a critical parameter estimating the CO₂ injectivity, determines the success of CO₂ storage in coal seam.4-6 The deep coal seam and coal bed methane (CBM) exploration and development are difficult, but the deep coal seam is one of the geological media to potentially store huge amounts of CO₂.7-10 However, deep coal seams with a low in situ permeability and CO₂ injection to the deep coal seam will be in the supercritical state, that is, ScCO₂, which affect the permeability of coal seam induced by ScCO₂ adsorption-swelling. Coal swelling will further reduce the deep coal permeability, so the technical implementation of ScCO₂ injection to deep coal seam becomes more difficult.11-13

Scholars have made great achievements on the factors that affect the coal permeability, including stress, temperature, and adsorption-induced coal swelling, and they have developed models to describe coal permeability variation account to these factors.14-17 Coal permeability is highly sensitive to the effective stress. Some tests are conducted to study the effects of effective stress changes in coal permeability. The test results depicted an exponential reduction of coal permeability to gas when effective stress increases, and some empirical correlations to represent the effect of stress on permeability are developed.18-21 Another important factor that influences coal permeability is temperature, and the effect of temperature on the coal permeability has also been investigated experimentally. The experimental results indicated that the permeability trend to be a negative exponential declining with the temperature increases.22-25 Coal is a special porous medium, coal matrix swells, and shrinks during induced by gas adsorption and desorption.26,27 The effect of matrix swelling and shrinkage on cleat permeability of coal has been investigated by several researchers.28,29 Pan et al30 proposed that coal swells with gas adsorption and shrinks with gas desorption, which changes the coal cleat apertures and thus the permeability under reservoir conditions. Kiyama et al31 have conducted laboratory tests to understand the change in the physical properties of coal for continuous injection of liquid/ScCO₂ and N₂ by measuring strain and permeability, and they suggested that coal swelling is likely to be the main cause for the permeability change.

A number of permeability models have been developed for predicting coal seam permeability changes, some widely used permeability models, including ARI model,32 P&M model,33 and S&D model.34 In addition, Wang et al35 developed an improved permeability model accounts for the stress-dependent deformation using a stress-strain correlation, which allows determination of directional permeability for coals. Pan and Connel36 presented an anisotropic swelling model based on adsorption thermodynamics and elasticity theory, and the anisotropic swelling model was incorporated a permeability model to describe permeability behavior during CBM and ECBM process.

In depths greater than 800 m, CO₂ injection is likely to behave like supercritical fluid inside the coal seam. The transition of CO₂ from a subcritical to supercritical state occurs at 7.38 MPa and 31.8°C.7,37 Many scholars have found that the effect of ScCO₂-induced swelling on coal permeability changes significantly, and some experimental results not only show that the coal permeability declining with effective stress increases but also indicate that coal permeability will restore after injection for a long time. Massarotto et al38 conducted measurements on the properties of coal before and after treatment with ScCO₂, and they proposed that both micro- and mesoporosities for coal show significant increases after reactions with the ScCO₂ and H₂O mixture. Liu et al3 suggested that the ScCO₂ sequestration into coal appears to have the potential to increase significantly the anthracite microporosity, which is very advantageous for CO₂ storage. The effects of subcritical CO₂ adsorption-induced coal matrix swelling are different from ScCO₂ on the coal permeability. Perera et al11 found that the swelling process continues longer under ScCO₂ adsorption, and they concluded that ScCO₂ adsorption could induce more matrix swelling than subcritical CO₂ adsorption under the same adsorption pressure. Moreover, the change in pore structure is one reason for influencing permeability. Fractal theory is one of the methods of nonlinear mathematics and has become increasingly popular in studying the effect of pore structure on transport properties of fluid in porous media.39-42 Liu et al43 conducted a fractal analysis on the pore structure of coals before and after the ScCO₂-H₂O treatment, and they found that micropores in coal are highly developed which leads to a reduced permeability of the coal after ScCO₂-H₂O treatment. Therefore, the ScCO₂ storage in a deep coal seam is more complex than the shallow.

In China, the deep high-rank anthracite reservoir is development compared with the coal-bearing basin in other countries. The deep anthracite reservoir presents the low in situ permeability, and the permeability variation of different deep coal seams induced by ScCO₂ injection is different. In this paper, we conducted a series of simulation experiments on the permeability variation induced by ScCO₂ injection to different deep anthracite reservoirs, and we developed a model for describing the permeability variation induced by ScCO₂ injection to different deep anthracite reservoirs in Qinshui Basin.
2 | SAMPLES AND EXPERIMENTAL SCHEME

2.1 | Sample preparation

Anthracite samples are collected from Shanxi Formation No. 3 coal seam in ZZ, CZ, and SH colliery in Qinshui Basin, Shanxi, China (Figure 1). Data of exploratory wells (buried depth range from 559.9 to 1122.3 m) show the Shanxi Formation coal seam at temperature 27.0–45.4°C and at pore pressure 5.10–12.08 MPa (Table 1). The vitrinite reflectance \( R_{\text{O,max}} \) of anthracite range from 2.44% to 3.33%. In order to study the characteristics of permeability variation of different deep anthracite reservoirs during ScCO\(_2\) injection, we have conducted a set of simulation experiments on anthracite permeability variation induced by ScCO\(_2\) injection under different depth conditions. Samples are cored from large lumps of coal and sample preparation reference to the size of \( \phi50 \times 100 \) mm. The initial geometric parameters of samples, including the length, diameter, mass, and fracture and porosity, are measured and listed in Table 2.

Figure 2 shows the correlation between reservoir temperature/pressure and buried depth, and it indicates that the temperature and pressure of No. 3 coal seam present linear increase with the buried depth increase. The fitting formula for temperature and depth is \( y = 0.032x + 9.444 \), and the temperature gradient of the coal seam is about 3.2°C/100 m. The fitting formula for pressure and depth is \( y = 0.0114x - 1.1736 \), and the temperature gradient of the coal seam is about 1.14°C/100 m. The fitting formulas for the correlation between temperature/pressure and buried depth will provide theoretical guidance for setting initial conditions of simulation experiments.

2.2 | Apparatus

The testing system was developed with the capacity to carry out fluid flow and gas adsorption measurement at high confining pressures and injection pressures and under conditions of elevated temperature (Figure 3). Jia et al.\(^{44}\) reported the structure of the testing system for testing adsorption-induced swelling in detail and also illustrated the method for testing ScCO\(_2\) adsorption-induced swelling. Moreover, the flow meter was employed to test the gas flow rate at the outlet of sample cell, and the test results were used to calculate the coal permeability (Figure 3). Therefore, the testing system caters for the experimental studies on permeability and adsorption-induced swelling of coal during ScCO\(_2\) injection.

2.3 | Methods

The approach to CO\(_2\) adsorption measurement was conducted, by volumetric method, according to Chinese National Standard GB/T19560-2008.\(^{45}\) The liquid displacement method (ie, the
confining pressure liquid displacement induced by coal swelling), capable of directly measuring CO₂/ScCO₂ adsorption-induced swelling to the whole anthracite core, was employed, and the detail experimental methods refer to the literature reported by Jia et al. The steady-state method was used to test coal permeability, and the flow rates were obtained and used to calculate permeability with Darcy’s Equation:

\[
k = \frac{2P_0L\mu g Q}{A(P_2 - P_1)D}
\]

where \(k\) is sample permeability, mD; \(L\) is sample length, mm; \(P_0\) is atmospheric pressure, MPa; \(\mu\) is gas viscosity, Pa·s; \(Q\) is the flow rate at the outlet of cell, mm³/s; \(A\) is specimen cross-sectional area, mm²; \(P_1\) is injection pressure, MPa; \(P_2\) is outlet pressure, MPa.

### 2.4 Experimental schemes and procedures

#### 2.4.1 Experimental schemes

The experimental schemes, testing the swelling strain and permeability under the condition of different deep anthracite reservoirs before and after ScCO₂ injection, are listed in Table 2.

#### 2.4.2 Simulating anthracite adsorption-swelling and permeability changes induced by ScCO₂ injection for different times

ZZ3, CZ3, and SH3 samples were used to simulate anthracite adsorption-swelling strain and permeability changes induced by ScCO₂ injection for different times, and the experiment consisted of five consecutive procedures: (a) sample preparation and airtightness testing: The coal core was enclosed into the sample cell and then tested the system airtightness by helium at 8 MPa, including reference cells, sample cell, and pipelines. Then, the system was degassed for at least 24 hours prior to the measurement start. (b) Setting experimental condition: CO₂ and helium were injected into reference cells at high pressure (about 15 MPa). The temperature of sample cell and gas reference cells was set to 40°C. The confining pressure and the liquid displacement valve working pressure were set to 10 MPa. After temperature and pressure of system in balance, pipelines and sample cell were degassed once again. (c) Testing the free-space volume calibration and original permeability: The free-space volume was tested by helium at pressure 8 MPa, then opened the valve (V10) and measured the pressure and flow rate at the outlet of sample cell, and the results were used to calculate the original permeability. (d) Adsorption-swelling and permeability measurements; testing the adsorption-swelling induced by ScCO₂ injection for 100 minutes. The variation of pressure and temperature of the sample cell and gas reference cells were consecutively monitored by the online-monitoring system. An electronic balance was employed to monitor the water displacement in real-time during ScCO₂ injection. After this procedure, open the valve (V10) and measure the pressure and flow rate at the outlet of sample cell, and the results were used to calculate the coal permeability. (e) Changing experimental condition: After the implementation of ScCO₂ injection for 100 minutes, repeat the procedures (b), (c), and (d). The same procedures were performed on adsorption-induced swelling and permeability for 500, 1000, 1500, 3500, and 5000 minutes in sequence (Figure 4A).

#### 2.4.3 Simulating adsorption-swelling and permeability changes induced by ScCO₂ injection to different deep anthracite reservoirs

ZZ4, CZ4, and SH4 samples were used to simulate anthracite permeability changes induced by ScCO₂ injection under the condition of different depths. According to the fitting formulas for temperature/pressure and depth in study area (Figure 2), the conditions of temperature and pressure for anthracite reservoir in the depth of 800, 1000, 1200, and 1400 m were set to 35.2°C/8.2 MPa, 41.5°C/10.6 MPa, 47.8°C/12.5 MPa,
and 54.2°C/14.8 MPa, respectively. The experimental methods for testing anthracite adsorption-swelling strain and permeability changes were conducted the same with the experimental simulation on ScCO2 injection for different times (described in the above section). Simulating adsorption-swelling strain and permeability changes was induced by ScCO2 injection to anthracite reservoir in the depth of 800 m, and then 1000, 1200, and 1400 m in sequence (Figure 4B).

3 | RESULTS

3.1 | Anthracite adsorption-swelling induced by ScCO2 injection for different times

Anthracite sample adsorbed volume and volumetric strain induced by ScCO2 injection for 500, 1000, 1500, 3500, and 5000 minutes under the condition of temperature 40°C, confining pressure 10 MPa, and injection pressure 8 MPa are shown in Figure 5. For a specific sample, under the same condition of confining pressure, temperature, and ScCO2 injection pressure, the adsorbed volume and volumetric strain of sample increase with the ScCO2 injection time lapses (Figure 5A). After ScCO2 injection for 5000 minutes, ZZ, CZ, and SH sample's adsorbed volume and volumetric strain are 59.32 mL/g and 3.26%, 64.32 mL/g and 2.96%, and 69.31 mL/g and 3.40%, respectively. The relationship between adsorbed volume/volumetric strain and ScCO2 injection time presents a Langmuir-like curve, namely the adsorbed volume and volumetric strain increase rapidly and the grow amplitude is large at the early period of ScCO2 injection. Shi and Durucan34 used a Langmuir-like equation to describe CO2 adsorption-induced swelling to coal. The variation amplitude of adsorbed volume and volumetric strain decreases with ScCO2 injection time lapses, and different samples present the same behavior. The correlation between adsorbed volume and the volumetric strain shows a nearly linear change, the volumetric strain increases with adsorbed volume increase, and different samples also present the same change law (Figure 5B).

3.2 | Anthracite permeability changes induced by ScCO2 injection for different times

The changes in anthracite permeability induced by ScCO2 injection for 500, 1000, 1500, 3500, and 5000 minutes under the condition of temperature 40°C, confining pressure 10 MPa, and injection pressure 8 MPa are shown in Figure 6. For a specific sample, under the same condition of confining pressure, temperature, and ScCO2 injection pressure, the sample permeability decreases with the ScCO2 injection time lapses, but the volumetric strain shows an opposite character with the injection time lapses (Figure 6A). After ScCO2 injection for 5000 minutes,
The volumetric strain of the ZZ sample is 3.26%, and its permeability declines from $4.37 \times 10^{-2}$ to $8.13 \times 10^{-5}$ mD. The volumetric strain of the CZ sample is 2.96%, and its permeability declines from $2.03 \times 10^{-2}$ to $3.52 \times 10^{-5}$ mD. The volumetric strain of the SH sample is 3.40%, and its permeability declines from $8.26 \times 10^{-3}$ to $1.81 \times 10^{-5}$ mD. The fitting formula for ZZ, CZ, and SH sample permeability and injection time are

$$y = 4.3696e^{-0.01622x}, \quad y = 2.027e^{-0.01691x}, \quad y = 0.8257e^{-0.01459x}$$

respectively. Their correlation coefficients ($R^2$) are 0.9882, 0.9897, and 0.9837, respectively. The correlation between anthracite permeability and volumetric strain presents a negative exponential curve. The anthracite permeability decreases rapidly, and the decline in the amplitude is large at the early period of ScCO$_2$ injection (Figure 6B). However, the variation amplitude of anthracite permeability decreases with ScCO$_2$ injection time lapses, and it tends to a minimal value. The permeability changes in the ZZ, CZ, and SH samples are consistent and regular.

### 3.3 The adsorption-swelling induced by ScCO$_2$ injection to different deep anthracite reservoirs

The adsorbed volume and volumetric strain of anthracite sample induced by ScCO$_2$ injection with 8 MPa to the depth of 800, 1000, 1200, and 1400 m are shown in Figure 7. For a specific sample, the adsorbed volume of sample decreases with the buried depth increase under the constant 8 MPa ScCO$_2$ injection pressure. The decline in the amplitude of adsorbed volume increases gradually. Having a case study of the SH4 sample, ScCO$_2$ with 8 MPa is injected to the anthracite reservoir in the depth of 800, 1000, 1200, and 1400 m, and the swelling strains are 3.50%, 2.95%, 2.65%, and 2.47%, respectively. The swelling strains were compared with the coal seam in the depth of 800 m, and the swelling strains of coal seams in the depth of 1000, 1200, and 1400 m decrease to 15.7%, 24.29%, and 29.43%, respectively. There is a linear correlation between swelling strain and ScCO$_2$ absolute adsorbed volumes under the condition of the same injection pressure, and the swelling strain increases with absolute adsorbed increase (Figure 8).

### 3.4 Anthracite permeability changes before and after ScCO$_2$ injection to different depths

The permeability changes before and after ScCO$_2$ injection to anthracite reservoir in the depth of 800, 1000, 1200, and 1400 m are shown in Figure 9. Before ScCO$_2$ injection to anthracite reservoir, the permeability variation presents a negative exponential decline with the buried depth increase (Figure 9(A)).
FIGURE 3  Schematic diagram of the testing system for measuring CO₂/ScCO₂ adsorption-induced swelling and permeability of the anthracite core (modified from44)

FIGURE 4  Flowchart of the experimental procedures; (A) simulating anthracite adsorption-swelling strain and permeability changes induced by ScCO₂ injection for different times; (B) simulating adsorption-swelling strain and permeability changes induced by ScCO₂ injection to different deep anthracite reservoirs
Having a case study of the SH4 sample, the depth of anthracite reservoir increases from 800 to 1000 m, its permeability will decrease from $4.59 \times 10^{-2}$ to $7.27 \times 10^{-3}$ mD, and the reduction is large. When anthracite reservoir is deeper than 1000 m, its permeability will decrease from $7.27 \times 10^{-3}$ to $8.04 \times 10^{-4}$ mD, and its reduction becomes small. After ScCO$_2$ injection to anthracite reservoir, its permeability will decrease sharply, and the variation also presents a negative exponential decline with the buried depth increase (Figure 9(B)). After ScCO$_2$ injection to the depth of 800 m, its permeability will decrease from $2.13 \times 10^{-5}$ to $3.34 \times 10^{-6}$ mD, and its reduction becomes small (Figure 9(B)).

4 | DISCUSSIONS

4.1 | Permeability changes in different deep anthracite reservoirs induced by ScCO$_2$ injection and evaluating models

The decrease in anthracite permeability was induced by ScCO$_2$ adsorption-swelling strain, and the correlation between
permeability and adsorption-swelling strain can be fitted by a negative exponential equation (Eq. 2 in Table 4). The correlation between anthracite permeability and buried depth also can be fitted by a negative exponential equation (Eq. 3 in Table 4). Namely, the variation of anthracite permeability presents a negative exponential decline with the buried depth increase. The main reasons that resulted in this phenomenon are the deep coal seams with high temperature and pressure. Coal matrix generates the thermal expansion induced by high temperature, and the matrix swells will reduce the channel for gas flowing. The increase in pressure will compress the space of pores and microfractures, resulted in the gas seepage channels tend to be closed. Therefore, high temperature and pressure produce dual influences in reducing the permeability of deep coal seam Figure 10. A large number of experiments have been conducted on the coal permeability changes induced by temperature and pressure.\textsuperscript{18,24} The experimental results also indicate that the coal permeability decreases with the increase in temperature and pressure in a function with a negative exponent.\textsuperscript{19-21,24,25,48} The temperature and pressure increase with the coal seam depth increase, and the depth changes are essentially the changes in temperature and pressure. The coal permeability variation induced by the buried depth will be consistent with the variation behavior of permeability induced by temperature and pressure. The experimental results are consistent with the theoretical analysis of permeability variation. Under

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{The changes in anthracite permeability induced by ScCO\textsubscript{2} injection for different times; (A) correlation between volumetric strain/permeability and ScCO\textsubscript{2} injection time; (B) correlation between permeability and volumetric strain.}
\end{figure}
the combined action of temperature and pressure, the reduction of coal seam permeability is large when the buried depth increases from 800 to 1000 m. When the buried depth is deeper than 1000 m, the coal seam seepage channel will be closed induced by the increase in temperature and pressure. The permeability variation becomes small with the buried depth increase.
The results also indicate that the permeability variation is more sensitive in shallow anthracite reservoir than the deep. After ScCO$_2$ injection to anthracite reservoir, its permeability will decrease sharply, and the variation also presents a negative exponential decline with the buried depth increase. The permeability changes induced by ScCO$_2$ injection are the combining effects of temperature, pressure, and adsorption-swelling strain Figure 10, and the variation of anthracite permeability presents the negative exponential declines induced by these factors. Therefore, the permeability changes in different deep anthracite reservoirs induced by ScCO$_2$ injection will remain the same with the effect of a single factor, so it will also follow a function with a negative exponent. The experimental results of permeability changes in the depth of 800, 1000, 1200, and 1400 m are consistent with the theoretical analysis results.

### 4.2 The permeability loss of anthracite reservoir in different depths induced by ScCO$_2$ injection

In this paper, the ratio of anthracite permeability nonadsorbed and saturated adsorbed ScCO$_2$ is defined as the permeability loss coefficient (Equation 4).

$$\eta = \frac{k_0}{k}$$  \hspace{1cm} (4)

where $\eta$ is the permeability loss coefficient, dimensionless; $k_0$ is the original permeability of coal seam, mD; $k$ is the permeability of coal seam with ScCO$_2$ injection, mD.

Having a case study of the SH4 sample, ScCO$_2$ with 8 MPa is injected to the anthracite reservoir in the depth of 800 m, its permeability decreases from $4.59 \times 10^{-2}$ to $7.46 \times 10^{-5}$ mD, and the permeability loss coefficient is up to 613.7. ScCO$_2$ with 8 MPa is injected to the anthracite reservoir in the depth of 1000 m, its permeability decreases from $7.27 \times 10^{-3}$ to $2.13 \times 10^{-5}$ mD, and the permeability loss coefficient is up to 339.6. ScCO$_2$ with 8 MPa is injected to the anthracite reservoir in the depth of 1200 m, its permeability decreases from $8.04 \times 10^{-4}$ to $9.51 \times 10^{-6}$ mD, and the permeability loss coefficient is up to 83.5. ScCO$_2$ with 8 MPa is injected to the anthracite reservoir in the depth of 1400 m, its permeability decreases from $9.30 \times 10^{-5}$ to $6.34 \times 10^{-6}$ mD, and the permeability loss coefficient is up to 13.7. The above results indicate the permeability loss sharply in shallow anthracite reservoir induced by ScCO$_2$ injection, but the permeability loss becomes small with the depth increase (Figure 11A). The permeability loss

### TABLE 3 Fitting formula of adsorption volume, volumetric strain, and buried depth during ScCO$_2$ being injected into anthracite

| Sample No. | Adsorbed volume and buried depth | Volumetric strain and buried depth | Volumetric strain and adsorbed volume |
|------------|---------------------------------|-----------------------------------|--------------------------------------|
| CZ4        | $y = -6E-05x^2 + 0.0916x + 27.372$ \hspace{1cm} $R^2 = 0.9994$ | $y = -3E-06x^2 + 0.0045x + 1.5705$ \hspace{1cm} $R^2 = 0.9998$ | $y = 0.0737x - 1.3797$ \hspace{1cm} $R^2 = 0.9587$ |
| ZZ4        | $y = -4E-05x^2 + 0.0456x + 47.241$ \hspace{1cm} $R^2 = 0.9838$ | $y = -4E-06x^2 + 0.0068x + 0.2975$ \hspace{1cm} $R^2 = 0.9976$ | $y = 0.0603x - 0.7385$ \hspace{1cm} $R^2 = 0.9953$ |
| SH4        | $y = -5E-05x^2 + 0.0757x + 41.883$ \hspace{1cm} $R^2 = 0.9968$ | $y = -3E-06x^2 + 0.0052x + 1.4245$ \hspace{1cm} $R^2 = 1.000$ | $y = 0.0654x - 1.0356$ \hspace{1cm} $R^2 = 0.997$ |

### FIGURE 8 Correlation between absolute adsorption and volumetric strain in different deep anthracite reservoirs

![Figure 8](image-url)
coefficient is up to three magnitudes when ScCO$_2$ injection to the anthracite reservoir is in the depth of 800 m. The permeability loss coefficient is about 2-3 magnitudes when ScCO$_2$ injection to the anthracite reservoir is in the depth of 1000 and 1200 m. The permeability loss coefficient is about 1-2 magnitudes when ScCO$_2$ injection to the anthracite reservoir is in the depth of 1400 m. Figure 11B shows that the permeability loss coefficient of different samples (ZZ, SH, and CZ) in the same depth exists difference. The reason for this phenomenon is that the nature fracture, porosity, and initial permeability are different among ZZ, SH, and CZ samples. Although the permeability loss coefficient of anthracite reservoirs in the same depth exists difference, it is interesting that the variation of permeability loss coefficient in different depths is almost the same order of magnitudes after ScCO$_2$ injection. Comparing the permeability loss coefficient of the anthracite reservoir in different depths, the permeability changes in the shallow coal seam are more sensitive than the deep induced by ScCO$_2$ injection (Figure 11).

4.3 | Implications for ScCO$_2$ storage in Qinshui Basin

The anthracite reservoirs deeper than 1000 m are developed in Qinshui Basin Figure 1, and the deep anthracite reservoirs with low permeability. The implementation of ScCO$_2$ storage in deep coal seam needs to focus on the coal permeability at three stages. The first is the in situ permeability (before injection stage), the second is the coal permeability during ScCO$_2$ injection process (injection stage), and the third is the coal permeability after ScCO$_2$ injection for a long time (storage stage). The influence factors of coal
TABLE 4 Models for evaluating the correlation between permeability and its influence factors

| Sample | Experimental schemes | Fitting formulas | Regression equations |
|--------|----------------------|------------------|----------------------|
| CZ3    | Changes of anthracite permeability induced by ScCO₂ adsorption-swelling strain | \( y = 4.360\text{exp}(−1.7105x); \) \( R^2 = 0.9968 \) | \( k = b_0 e^{−c\varepsilon} \) (2) |
| ZZ3    |                     | \( y = 2.023\text{exp}(−1.7868x); \) \( R^2 = 0.9969 \) |   |
| SH3    |                     | \( y = 0.824\text{exp}(−1.5374x); \) \( R^2 = 0.9971 \) |   |
| CZ4    | Changes of anthracite permeability in different depth | \( y = 25.914\text{exp}(−0.01x); \) \( R^2 = 0.9544 \) | \( k = b_0 e^{−cx} \) (3) |
| ZZ4    |                     | \( y = 78.328\text{exp}(−0.011x); \) \( R^2 = 0.9521 \) |   |
| SH4    |                     | \( y = 20.737\text{exp}(−0.01x); \) \( R^2 = 0.9985 \) |   |
| CZ4    | Changes of anthracite permeability induced by ScCO₂ injection to different depth | \( y = 0.1604\text{exp}(−0.004x); \) \( R^2 = 0.9495 \) |   |
| ZZ4    |                     | \( y = 0.1729\text{exp}(−0.004x); \) \( R^2 = 0.9705 \) |   |
| SH4    |                     | \( y = 0.2175\text{exp}(−0.005x); \) \( R^2 = 0.9977 \) |   |

Seam permeability are different at each stage. For example, the in situ permeability of coal seam is mainly affected by the buried depth at the area with simple geological structure. The permeability of coal seam is affected by the buried depth and adsorption-swelling during ScCO₂ injection. The permeability of coal seam is affected by the geochemical reaction of ScCO₂-H₂O with minerals in coal after ScCO₂ injection for a long time. The ScCO₂ injection has a negative effect on decreasing the permeability induced by adsorption-swelling during injection stage. However, the injected ScCO₂ plays a role in improving permeability caused by the geochemical reaction of ScCO₂-H₂O with minerals in coal during storage stage. Lots of experimental results indicate that the permeability of coal seam will recover to the in situ permeability, even greater than it, after ScCO₂ injection for a long time.²,¹¹ From the perspective of engineering implementation on ScCO₂ storage, the initial permeability and the permeability during ScCO₂ injection are the critical parameters for storing ScCO₂. The permeability of deep coal seam is influenced by temperature, pressure, and ScCO₂ adsorption-swelling strain. The seepage channels of coal seam are almost closed induced by these factors. The permeability changes in coal seam become small when the depth is deeper than 1000 m. The ScCO₂ injection rate is directly affected by the permeability variation, so the difference of ScCO₂ injection rate is small when the coal seam is deeper than 1000 m at the same injection pressure. To ensure the security of ScCO₂ storage in the coal seam, the ScCO₂ injection pressure should be less than the fracture pressure of the coal seam. The deep coal seam has a relatively large fracture pressure (Figure 12), so the allowable ScCO₂ injection pressure in the deep coal seam is greater than the shallow. It is obvious that the increases in ScCO₂ injection pressure will reduce the effective pressure of the coal seam. The permeability of deep coal seam increases with the effective pressure decrease.¹⁵,²⁰,²¹,²³ Therefore, the deep coal seam with low permeability is one of the geological media to potentially store huge amounts of ScCO₂.

5 | CONCLUSIONS

In this paper, the permeability changes in anthracite reservoirs in different depths of Qinshui Basin induced by ScCO₂ injection were studied by an independent development apparatus. The research results demonstrated that:

1. The variation of anthracite permeability presents a negative exponential decline with the buried depth increase. The depth of anthracite reservoir increases from 800 to 1000 m, and its permeability will decrease from \( 4.59 \times 10^{-2} \) to \( 7.27 \times 10^{-3} \) mD. If anthracite reservoir is deeper than 1000 m, its permeability will decrease from \( 7.27 \times 10^{-3} \) to \( 8.04 \times 10^{-4} \) mD.

2. The permeability change induced by ScCO₂ injection is the combining effects of temperature, pressure, and adsorption-swelling, and the variation of anthracite permeability presents the negative exponential declines induced by these factors. The permeability changes can be described by the model of \( k = k_0 e^{−c\varepsilon} \) during ScCO₂ injection to different deep anthracite reservoirs in Qinshui Basin.
3. The permeability loss coefficient is up to three magnitudes induced by ScCO₂ injection to the anthracite reservoir in the depth of 800 m, 2-3 magnitudes in the depth of 1000 and 1200 m, and 1-2 magnitudes in the depth of 1400 m. Although the initial permeability of anthracite reservoirs in the same depth exists differences, the permeability loss coefficient almost has the same magnitudes induced by ScCO₂ injection.

4. Comparing with the permeability loss coefficient of the anthracite reservoir in different depths, the permeability

FIGURE 10 Schematic diagram of coal seam permeability loss in different depths induced by ScCO₂ injection

FIGURE 11 Permeability loss coefficient of anthracite reservoirs in different depths induced by ScCO₂ injection; (A) the permeability loss coefficient in different depths; (B) the error analysis of permeability loss coefficient in different depths
variation of the shallow coal seam is more sensitive than the deep induced by ScCO2 injection. However, the deep coal seam has a relatively large fracture pressure, so the allowable ScCO2 injection pressure in the deep coal seam is greater than the shallow.

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