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Research Article

Experimental Study on the Influence of Moisture Content during Gas Depressurization Extraction

Yuexia Chen,[1] Xuexi Chen ,[1] Jiang Xu,[2] and Tingxiang Chu[1]

[1]*School of Safety Engineering, North China Institute of Science and Technology, Beijing 101601, China*
[2]*State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400030, China*

Correspondence should be addressed to Xuexi Chen; chenxuexi1210@126.com

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Although there are many reports about the influence of moisture in the process of gas extraction, studies about the influence of moisture on gas flow, permeability, and coal deformation by experimental system analysis are lacking. Physical simulations of gas depressurization extraction using triaxial servo-controlled seepage equipment for hot-fluid-solid coupling were conducted. The gas flow rate, permeability, and strain were analysed during gas depressurization extraction. The relationship between gas flow rate and gas pressure was a quadratic polynomial. Permeability and strain changed continuously with the decrease of gas pressure and interacted with each other during gas depressurization extraction. In the initial stage, the effective permeability decreased. With the continuous decrease of gas pressure, the permeability gradually recovered. When the gas pressure dropped to about 0.6 MPa, the permeability increased rapidly and the corresponding volumetric strain increased gradually. With the increase of moisture content, the relationship between gas flow rate and gas pressure became less significant. The experiments showed that the higher the moisture content, the lower the effective permeability and the larger the volumetric strain.

1. Introduction

Coalbed methane reservoirs contain coal, gas, and water [1]. They are a dual porosity system medium consisting of pores and fractures [2] with large internal surface area and strong adsorption capacity: because of the change of moisture content in a coal seam, properties of coal seams change. Many experts have analysed the influence of moisture on adsorption and desorption, coal permeability, and gas extraction, through a large number of experiments, theoretical analyses, and numerical simulation.

Water in the coal plays an important role in adsorption isotherms and adsorption and desorption capacity of gas [3–5]. Gensterblum et al. [6] studied the influence of moisture on the sorption capacity of coals. They found that moisture reduced the gas sorption capacity of coals significantly with increasing coal rank. Huang et al. [7] studied the effect of organic content and moisture on CO_2/CH_4 competitive adsorption and found that the effect of moisture on CO_2 adsorption is greater than that on CH_4 adsorption. Wang et al. [8] showed that the presence of moisture in coal reduced gas absorption and studied the interaction of adsorbed/gaseous methane in coal under high pressure. Krooss et al. [9] studied the adsorption capacity of CH_4 and CO_2 on dry and moist coal and found that the larger the moisture content, the weaker the adsorption capacity. Low-permeability reservoirs make coalbed methane extraction difficult and its application is limited, so hydraulic fracturing is widely used. Fluid accumulates and migrates mainly in fractures, and the new discrete fractures caused by hydraulic fracturing may have changed: Chen et al. [10] analysed adsorption and desorption of gas in moisture coal and explored the mechanism of this two-phase flow. Pan et al. [11] analysed the effect of moisture content in a coal matrix on gas desorption and diffusion by experiment: the results show that the moisture content has a significant effect on gas desorption rates, and the influence of moisture content on gas diffusion rates varies greatly across different pore sizes. Zhong et al. [12] studied the influence of pore water on deformation of coal rock during swelling or shrinkage processes. Xu et al. [13] studied the influence of moisture on desorption, and the diffusion coefficient of granular coal is analysed. The results show that moisture has the ability to inhibit the diffusion of gas on the surface of the coal matrix.

Many scholars have studied the influence of moisture content on coalbed gas permeability. Wang et al. [14] studied the permeability of coal with different moisture contents through laboratory experiments and found that the porosity of coal decreases after moisture absorption and then the permeability decreases. The initial permeability to all gases for moisture-saturated coal is almost two orders of magnitude lower than that for dry coal, and the greater the pore pressure, the greater the permeability. The sorption capacities and swelling strains of moisture-saturated samples decreased significantly. Yin et al. [15, 16] investigated the influence of moisture content of coal reservoirs in coalbed methane seepage in the process of coalbed methane exploitation through experiment. The results showed that the effective permeability of methane increases with the decreasing moisture content of a coal sample under constant temperature and effective stress. The relationship between coal moisture content and methane effective permeability can be expressed by a linear function within the range of coal moisture contents assessed in these tests. Pan [17] analysed the swelling deformation of moisture coal adsorption and established a permeability model based on the coal swelling caused by gas adsorption. Chen et al. [18] modified the classical SD permeability model by considering the competitive adsorption effect of gas and moisture and established a solid-gas-liquid coupling model. Shaw et al. [19] studied the relative permeability during coal seam gas production. Thararoop et al. [20, 21] considered the effect of moisture on the expansion/contraction of adsorbed gas in a coal matrix and established a permeability model based on the adsorption expansion effect.

Coalbed methane production can be divided into three stages: the first stage is a single-phase flow stage [22]. When the pressure near the bottom hole decreases, water drains out, the initial pressure reduction is relatively small, gas has not yet begun to desorb, and only water flows near the borehole. The second stage is an unsaturated one-phase flow stage. When the pressure at the bottom hole further decreases, a certain amount of gas is gradually desorbed from the pore surface of coal matrix and is diffused downwards to the fracture system because of the resulting concentration gradient. The third stage is a gas and water two-phase flow. As the pressure at the bottom hole continues to decrease, a large amount of gas is gradually desorbed and diffused into the fracture system, which forms a continuous flow of gas in the fracture. The whole process of gas extraction is affected by gas, water, coal, and temperature. The mechanism of gas extraction is the coupling of solid deformation, gas adsorption and desorption, diffusion, seepage, water seepage, and energy transformation. The migration of gas in the coal involves three phases: desorption from the internal surfaces, diffusion from the matrix, and flow in the fracture network. The free gas near the borehole flows from the fracture network to the borehole, and then, free gas in the matrix flows to the fractures because of the pressure drop along each fracture. Finally, due to the decreasing gas pressure in the matrix, gas is desorbed therefrom. The water in the coal occupies passages required for gas migration, and the gas relative permeability decreases. Many scholars analysed the solid deformation, adsorption, and desorption of gas [23, 24], the influence of moisture, and fluid- solid coupling characteristics [25], established multi-field coupling models, and studied the gas extraction process [21, 26–30].

Although many scholars have investigated the effect of water in the coal seam during gas extraction, thus providing theoretical support for gas extraction in aquifer coal seams, few scholars have studied the permeability and deformation of coal in gas pressure drop by experiments. In this study, the gas flow, permeability, and deformation during gas pressure drop tests (simulating gas extraction) are analysed. The effect of moisture content is also considered. This provides a theoretical basis for further understanding the gas extraction process in an aquifer coal seam and arranging boreholes for best effect.

2. Physical Simulation Experiments during Gas Pressure Drop

2.1. Experimental Apparatus. In this test, a triaxial servo-controlled seepage device for hot-fluid-solid coupling of coal containing methane is adopted (Figure 1). The device consists of a three-axis pressure chamber, hydraulic servo-system, water bath system, seepage control system, and data acquisition system.

The loading control mode can be chosen as either stress control or displacement control. The maximum axial pressure is 100 MPa, and the maximum confining pressure is 10 MPa. The axial deformation is monitored by using an axial displacement sensor, and the maximum displacement is 60 mm. The radial deformation in the middle position of coal sample is measured by using an Epsilon-3544-100M-060M-ST ring extensometer, and the maximum displacement is 6 mm.

Here, the deformation and permeability of coal with different moisture contents, in the process of gas depressurised extraction, are measured and analysed under triaxial stress regimes.

2.2. Processing of Experimental Coal Samples. The collected coal samples were crushed and screened to 60–80 mesh from which pulverised coal was screened out by using a vibrating screen and oven-dried for 24 h. After mixing the dried pulverised coal (about 173 g) and adding an appropriate amount of pure water according to the required moisture content, where the amount of pure water was calculated by using the moisture content formula (m_w is the quality of water in coal $(m_w/m_{dr}) \times 100\%$sample and m_{dr} is the drying quality of coal samples). Cylindrical briquette specimens measuring about 50 mm × 100 mm are pressed on the briquetting machine (Figure 2(a)) at a forming pressure of 100 MPa. A small amount of water would be extruded during the forming process; therefore, the moisture content of coal samples was adjusted to the exact value by using

Figure 1: Triaxial servo-controlled seepage equipment for hot-fluid-solid coupling of coal containing methane.

a curing box (Figure 2(d)). The precise water content of coal sample was obtained by weighing coal sample again and calculating formula. The specimens were wrapped in plastic film to prevent the evaporation of moisture.

2.3. Experimental Scheme. In the process of gas extraction, with the decrease of gas pressure, coal seam deformation, permeability, and other parameters change. To analyse the influence of moisture content in the gas extraction process, gas depressurised extraction experiments, at four different moisture contents, were conducted (Table 1). The experimental procedure was as follows:

(1) Test piece preparation: coal samples with a certain moisture content were evenly coated with 704 silica gel on the side and were loaded into a triaxial pressure chamber. Coal samples were sealed with thermoplastic tubes and metal hoops. The transverse extensometer was installed in the middle of the coal sample, the data acquisition joint was connected, and the intake pipe and three-axis pressure chamber top cover were installed.

(2) Vacuum pumping: after the specimen was sealed, the tightness of the test vessel was checked; the outlet valve was opened, and a vacuum pump was used to evacuate the sample for 2 h.

(3) Stress loading: when the axial and confining pressures were set to a predetermined value, methane gas was injected until the gas pressure was stabilised at 3.5 MPa.

(4) Adsorption equilibrium: the triaxial pressure chamber was placed into the constant temperature water bath and the gas in the coal sample was fully adsorbed.

(5) Gas depressurization extraction experiment: gas pressure which was adjusted by cylinder pressure valve decreased in the following order $3.5 \longrightarrow 3.0 \longrightarrow 2.5 \longrightarrow 2.1 \longrightarrow 1.8 \longrightarrow 1.5 \longrightarrow 1.2 \longrightarrow 0.9 \longrightarrow 0.6 \longrightarrow 0.3$ MPa. The outlet valve was opened after the gas pressure point was balanced, and after that, gas began to flow. When the flow rate was stable and gas desorption was balanced, the corresponding deformation and flow data were recorded at the same time. Then, the outlet valve was closed, cylinder pressure valve was adjusted, and the next pressure point test was conducted.

(6) Replace another coal sample with different moisture content, repeat the abovementioned operation, and carry out the next set of experiments.

3. Experimental Results

3.1. Gas Flow Rate, Permeability, and Deformation during Gas Depressurization Extraction. In the original state of a coal seam, gas is confined within the coal. When the equilibrium state is destroyed by gas extraction, free gas begins to flow from high pressure to low pressure regions. When the gas pressure decreases to the critical desorption pressure, the gas adsorbed on the surface of the micropores of the coal matrix is desorbed into free gas and is redistributed in the micropore space. In the process of gas extraction, gas flow rate, coal seam permeability, and deformation change because of the decreasing gas pressure. Gas in an aquifer coal seam flowing from matrix to production wells generally undergoes a three-stage process: unidirectional flow, an unsaturated unidirectional flow stage, and a gas-water two-phase flow stage. With the discharge of water, the moisture content and permeability of coal seam change over time.

Assuming that the coal sample used in the test is a homogeneous, isotropic material, the stress on the coal sample in the experiment is a pre-peak stress, changes in the methane in the test sample undergoing seepage are isothermal, and the seepage process of methane in coal samples conforms to Darcy's law. The effective permeability K is given by

$$K = \frac{2 \upsilon \mu L P_{\mathrm{n}}}{A\left(P_1^2 - P_2^2\right)}, \quad (1)$$

where υ is the gas seepage velocity in the coal sample (m^3/s), L is the length of the sample (m), μ is the coefficient of dynamic viscosity of methane (Pa. s), A is the cross-sectional area of the coal sample (m^2), P_{n} is standard atmospheric pressure (MPa), and P_1 and P_2 are the gas pressures at inlet and outlet (MPa), respectively.

Taking the coal sample with 3.5% moisture content as an example, the evolution of key parameters is analysed: Figures 3(a) and 3(b) show the evolution of the relationship between gas flow rate and gas pressure and the relationship between permeability and gas pressure in the process of gas depressurization extraction, respectively. It is found that the lower the gas pressure, the lower the gas flow rate: when the gas pressure initially decreases, the gas seepage flow rate decreases rapidly. When the pressure decreases to a certain extent, the curve in Figure 3(a) tends to be flat, and the relationship between gas flow rate and gas pressure is expressed by a quadratic polynomial.

During the process of gas depressurization extraction, the gas pressure decreases and the permeability decreases slightly. When gas pressure decreases to 2 MPa, the permeability begins to rise slowly, and when it decreases to about 0.6 MPa,

Figure 2: (a) Forming equipment, (b) moulds, (c) moulded coal, and (d) curing box.

Table 1: Experiments at different moisture contents.

Test type	Test gas	Moisture content (%)	Axial compression (MPa)	Confining pressure (MPa)	Gas pressure (MPa)
Different moisture contents	CH_4	3.5	6	6	3.5, 3.0, 2.5, 2.1, 1.8, 1.5, 1.2, 0.9, 0.6, 0.3
		6.3			→
		9.8			
		12.7			Reducing gas pressure

it increases rapidly because, in the initial stage of gas extraction, the external stress remains unchanged, and as the gas pressure decreases, the effective stress increases. Permeability is sensitive to effective stress: with the increase in effective stress, the permeability of coal decreases exponentially.

Water will change the adsorption and desorption performance of wetted coal and the viscous resistance of gas flow in wetted coal. The presence of water leads to the decrease of coalbed gas migration channel capacity and a decrease in effective permeability. With the discharge of gases, some of the water is discharged with gases, which increases the effective permeability. In the early stage of gas depressurization extraction, the permeability decreases because the increase of effective stress is greater than that caused by the drainage of water. The coal sample is soft, therefore, with the decrease of gas pressure, gas desorption and matrix shrinkage lead to the increase of gas transport channel capacity and, thence, permeability. When the gas pressure is very low, the average free distance of gas molecules is close to the pore size, and the Klinkenberg effect also increases the permeability.

Figure 4 shows the axial strain-time and radial strain-time relationships during gas depressurization extraction (ε_1 and ε_2 are the radial, and axial, strains respectively). There were three stages to the behaviour observed here: stress loading, aeration adsorption, and depressurization extraction. In the stress loading stage, the coal sample was subjected to the action of axial and confining pressures, the

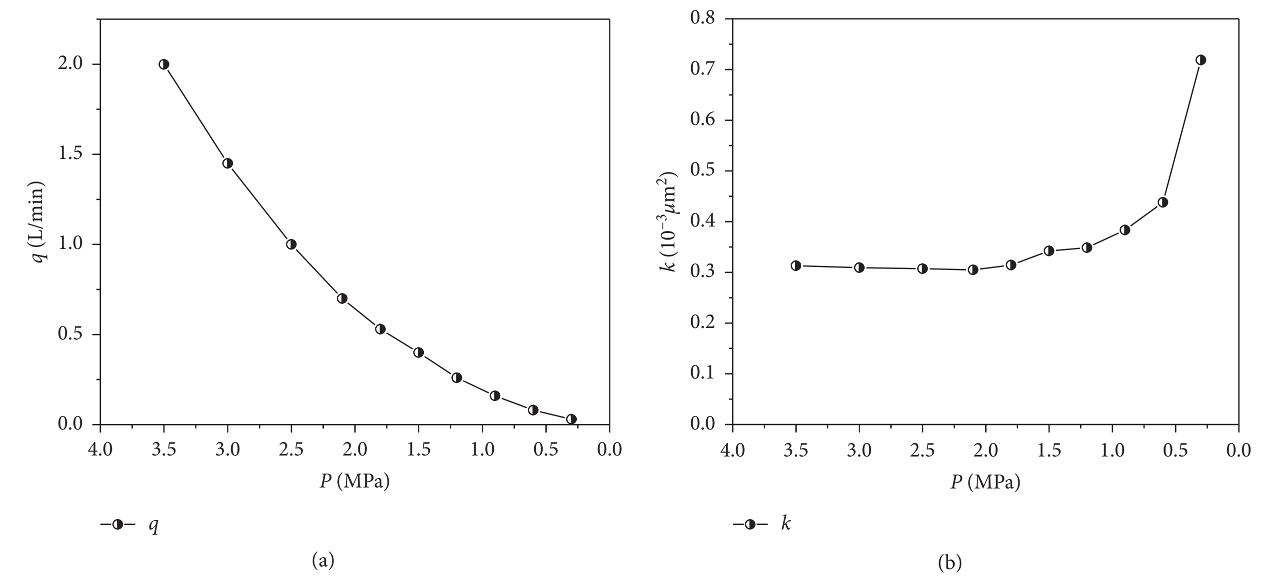

Figure 3: (a) Relationship between gas pressure and flow rate and (b) relationship between gas pressure and permeability during gas depressurization extraction.

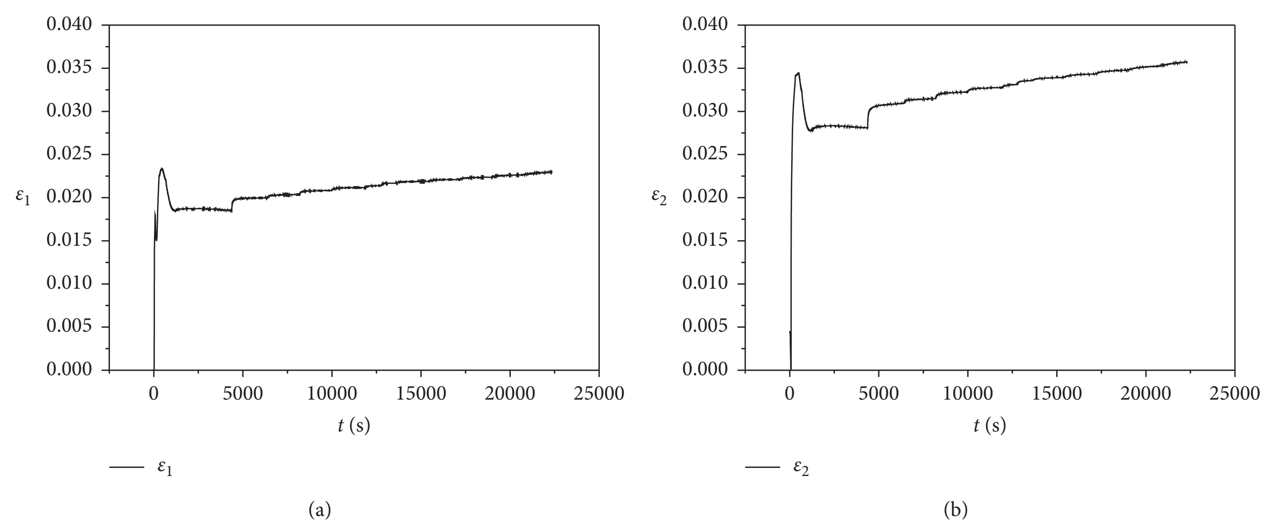

Figure 4: (a) Radial strain-time and (b) axial strain-time curves during gas depressurization extraction.

pores were extruded, and rapid axial and radial deformations occurred. The maximum axial and radial deformations were 0.034 and 0.023, respectively. In the process of gas filling of the coal sample, with increasing gas pressure, the coal body expanded and deformed and the axial and radial strains increased. When the gas pressure reached 3.5 MPa, the coal sample absorbed all available methane after stabilisation of the gas pressure. In the process of gas adsorption, the axial and radial strains recovered rapidly to about 0.007 and 0.005, respectively. With the increase of adsorption time, the deformation tended to be stable.

In the process of gas depressurization extraction, the gas was desorbed from the coal matrix because of the pressure gradient acting therein, but the external stress remained unchanged, which resulted in the decrease of pore volume and fissure size and an increase in effective stress. The compressive deformation of coal samples occurred, and the axial and radial strains increased. With the development of depressurization and extraction, the gas in the matrix was continuously desorbed, and the water therein was discharged. The deformation increased step-by-step, and the step boundary point was the time at which the gas pressure was changed.

3.2. Effect of Moisture Content on Gas Flow Rate, Permeability, and Deformation during Gas Depressurization Extraction. Figure 5 shows the relationship between gas flow rate and gas effective permeability with the decrease of gas pressure during gas depressurization extraction in coal samples with different initial moisture contents. The lower the gas pressure, the lower the gas content in the coal seam, and the

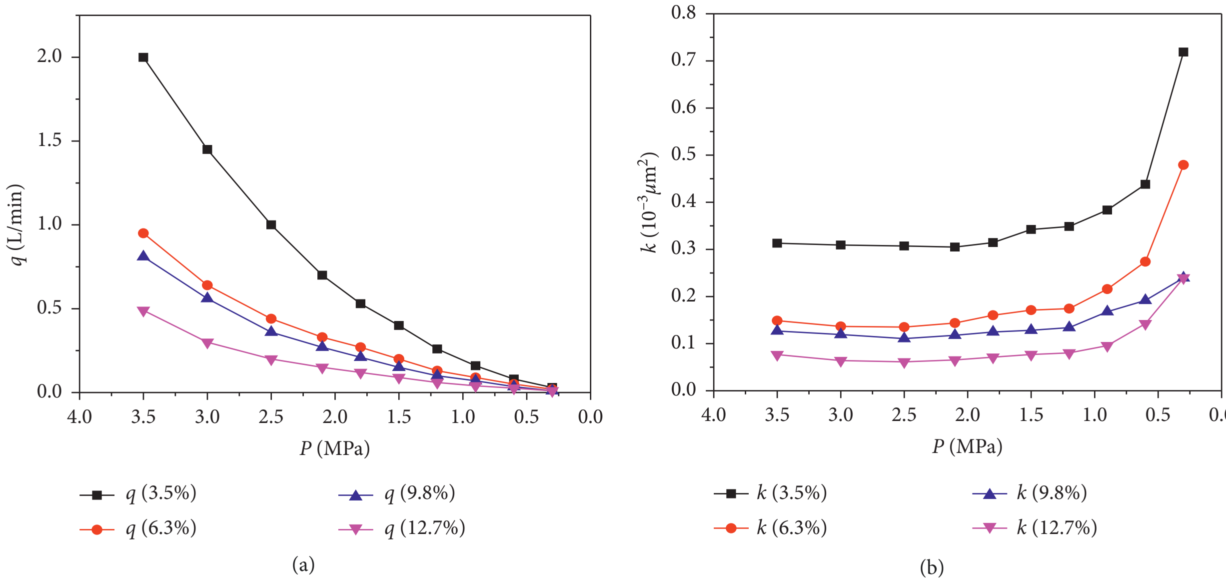

Figure 5: Plots of (a) gas pressure-flow rate and (b) gas pressure-permeability with different moisture contents during gas depressurization extraction.

lower the flow rate. After pressure reduction, the higher the moisture content, the lower the gas flow rate was under the same initial gas pressure.

The average flow rates in coal samples with moisture contents of 3.6%, 6.3%, 9.8%, and 12.8% were 0.6609 L/min, 0.3120 L/min, 0.2575 L/min, and 0.1486 L/min, respectively. The greater the moisture content, the smoother the plot of gas flow rate versus gas pressure. The relationship between gas flow rate and gas pressure was a quadratic polynomial function, as shown in Table 2 (the correlation coefficients were all above 0.98, indicating good correlation).

The permeability decreased slightly with the decrease of gas pressure. When the gas pressure was about 2 MPa, the permeability began to rise slowly. When the gas pressure dropped to about 0.6 MPa, the permeability increased rapidly. The reason for this was that the porosity of the coal seam affected the rate of gas migration. The pores in the coal seam were divided into fissures, visible pores, macropores, mesopores, small pores, and micropores. Fractures, visible holes, and small holes are collectively referred to as seepage pores. A seepage pore is the main migration channel for coal bed gas in the reservoir; therefore, the shape, size, and interconnections of seepage pores determine the ability of gas to migrate in the reservoir.

Water could not easily enter micropores in the coal matrix. Water in the coal seam was almost present in seepage pores. Gas in the coal seam was generally present in the form of free, dissolved, and adsorbed phases. For water-bearing coal samples, the force driving the adsorption of water was greater than the interactive force between the coal and the gas, which reduced the direct contact between methane molecules and the coal. In the process of coalbed methane exploitation, upon water discharge, the moisture content of the coal body decreased continuously, and the surface free energy of the coal body matrix increased continuously,

Table 2: Relationship between gas flow rate and gas pressure.

No.	Fitting function	R^2
1	$q = 0.1653p^2 - 0.0217p + 0.0360$	0.9995
2	$q = 0.0368p^2 - 0.0220p + 0.0782$	0.9994
3	$q = 0.0727p^2 - 0.0379p + 0.0317$	0.9960
4	$q = 0.0475p^2 - 0.0439p + 0.0345$	0.9858

which led to matrix shrinkage and the increase of pore size, the effective area of seepage passages, and the permeability.

To explore the relationships between gas pressure, permeability, strain, and moisture content during gas depressurization extraction, Figure 6 shows the relationship between permeability and volumetric strain (ε_V represents the volumetric strain) with the decrease of gas pressure when methane gas was injected into coal samples with initial moisture contents of 3.5%, 6.3%, 9.8%, and 12.7%. As can be seen from Figure 6, the effective permeability decreased when the gas pressure was decreased from 3.5 MPa to 2.5 MPa. With decreasing gas pressure, the permeability gradually recovered: when the gas pressure dropped to 0.6 MPa, the permeability increased rapidly and the corresponding volumetric strain increased gradually. The permeability and volumetric strain were affected by the moisture content: when the moisture contents were 3.5%, 6.3%, 9.8%, and 12.7%, and the gas pressure was 0.3 MPa, the permeabilities were $0.72 \times 10^{-3}\,\mu m^2$, $0.48 \times 10^{-3}\,\mu m^2$, $0.24 \times 10^{-3}\,\mu m^2$, and $0.239 \times 10^{-3}\,\mu m^2$, respectively, and the corresponding volumetric strains were 0.035, 0.044, 0.055, and 0.083. The higher the moisture content, the lower the effective permeability and the greater the volumetric strain. The reason for this was that, in the initial stage of gas depressurization extraction, with the decrease in gas pressure, the effective stress increased and the permeability decreased. On the contrary, upon the discharge of water,

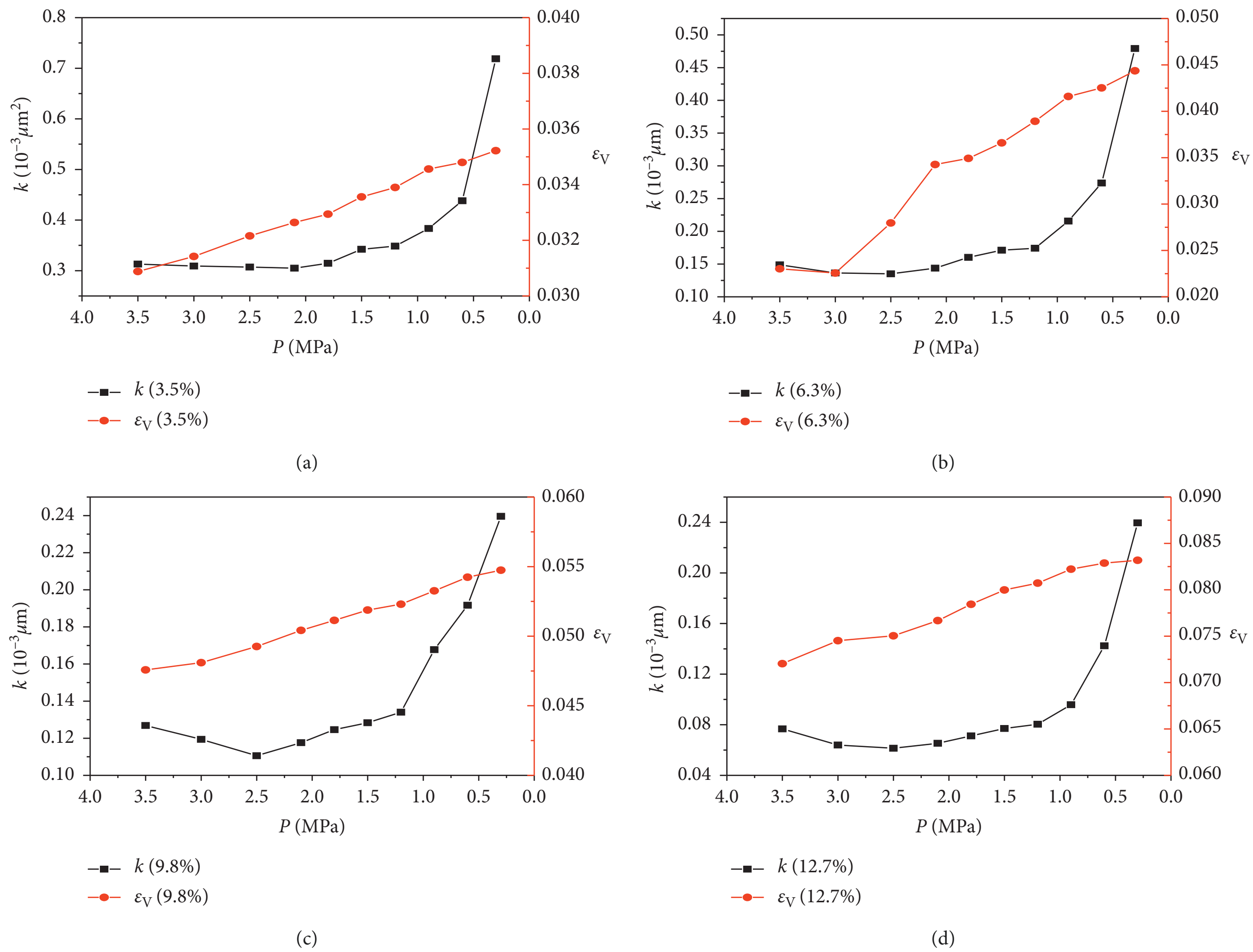

Figure 6: Relationships between volumetric strain-gas pressure and *K* during gas depressurization extraction for coal samples with moisture contents of (a) 3.5%, (b) 6.3%, (c) 9.8%, and (d) 12.7%.

the gas permeability increased and the one offset the other. In the initial stage of gas depressurization extraction, the effect of changes in the effective stress was more obvious, and the permeability decreased slightly. With the further decrease in gas pressure, gas desorption in the matrix, matrix shrinkage, widening of coal pores and fissure channels, and the permeability increased. When the gas pressure decreased to a certain extent, slippage effects arose, and the permeability was thus further increased.

4. Conclusion

The gas depressurization extraction experiments on coal containing gas and water were carried out using triaxial servo-controlled seepage test equipment for hot-fluid-solid coupling. The variations in key parameters in the process of gas depressurization extraction were analysed. The main conclusions may be drawn as follows:

(1) In the process of gas depressurization extraction experiment, the flow rate decreased with the decrease of gas pressure. In the initial stage, the gas seepage flow rate decreased rapidly. When the pressure decreased to a certain extent, the curve tended to be flat. The relationship between gas flow rate and gas pressure could be described by using a quadratic polynomial.

(2) Permeability and strain changed continuously with decreasing gas pressure and they interacted with each other during gas depressurization extraction. In the initial stage, the effective permeability decreased. Upon the continuous decrease of gas pressure, the permeability gradually recovered: when the gas pressure dropped to about 0.6 MPa, the permeability rose rapidly and the corresponding volumetric strain increased.

(3) For coal samples containing water and gas, the lower the gas pressure, the lower the gas content in the coal seam, and the lower the gas flow rate were during gas depressurization extraction. Under the same gas pressure, the higher the moisture content was, the lower the flow rate was during gas depressurization extraction. With the increase in moisture content,

the relationship between gas flow rate and gas pressure became less significant. The experiments showed that the higher the moisture content, the lower the effective permeability and the larger the volumetric strain were, which provide a realistic basis for further understanding the law of gas migration in aquifer coal seam.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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References

[1] J. Zhao, D. Tang, H. Xu, Y. Meng, Y. Lv, and S. Tao, "A dynamic prediction model for gas-water effective permeability in unsaturated coalbed methane reservoirs based on production data," *Journal of Natural Gas Science and Engineering*, vol. 21, pp. 496–506, 2014.

[2] W. C. Zhu, C. H. Wei, J. Liu, T. Xu, and D. Elsworth, "Impact of gas adsorption induced coal matrix damage on the evolution of coal permeability," *Rock Mechanics and Rock Engineering*, vol. 46, no. 6, pp. 1353–1366, 2013.

[3] B. Nie, X. Liu, S. Yuan et al., "Sorption charateristics of methane among various rank coals: impact of moisture," *Adsorption*, vol. 22, no. 3, pp. 315–325, 2016.

[4] J. Yue, Z. Wang, and J. Chen, "Investigation of timing characteristics of the imbibition height of remolded coal without gas," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 41, no. 2, pp. 156–166, 2019.

[5] J. Yue, Z. Wang, and J. Chen, "Dynamic response characteristics of water and methane during isobaric imbibition process in remolded coal containing methane," *Energy Exploration & Exploitation*, vol. 37, no. 1, pp. 83–101, 2019.

[6] Y. Gensterblum, A. Merkel, A. Busch, and B. M. Krooss, "High-pressure CH_4 and CO_2 sorption isotherms as a function of coal maturity and the influence of moisture," *International Journal of Coal Geology*, vol. 118, pp. 45–57, 2013.

[7] L. Huang, Z. Ning, Q. Wang et al., "Effect of organic type and moisture on CO_2/CH_4 competitive adsorption in kerogen with implications for CO_2 sequestration and enhanced CH_4 recovery," *Applied Energy*, vol. 210, pp. 28–43, 2018.

[8] Z. Wang, W. Su, X. Tang, and J. Wu, "Influence of water invasion on methane adsorption behavior in coal," *International Journal of Coal Geology*, vol. 197, pp. 74–83, 2018.

[9] B. M. Krooss, F. Van Bergen, Y. Gensterblum, N. Siemons, H. J. M. Pagnier, and P. David, "High-pressure methane and carbon dioxide adsorption on dry and moisture-equilibrated Pennsylvanian coals," *International Journal of Coal Geology*, vol. 51, no. 2, pp. 69–92, 2002.

[10] S. Chen, T. Yang, P. G. Ranjith, and C. Wei, "Mechanism of the two-phase flow model for water and gas based on adsorption and desorption in fractured coal and rock," *Rock Mechanics and Rock Engineering*, vol. 50, no. 3, pp. 571–586, 2017.

[11] Z. Pan, L. D. Connell, M. Camilleri, and L. Connelly, "Effects of matrix moisture on gas diffusion and flow in coal," *Fuel*, vol. 89, no. 11, pp. 3207–3217, 2010.

[12] C. Zhong, Z. Zhang, P. G. Ranjith, Y. Lu, and X. Choi, "The role of pore water plays in coal under uniaxial cyclic loading," *Engineering Geology*, vol. 257, Article ID 105125, 2019.

[13] H. Xu, D. Tang, J. Zhao, S. Li, and S. Tao, "A new laboratory method for accurate measurement of the methane diffusion coefficient and its influencing factors in the coal matrix," *Fuel*, vol. 158, pp. 239–247, 2015.

[14] S. Wang, D. Elsworth, and J. Liu, "Permeability evolution in fractured coal: the roles of fracture geometry and water-content," *International Journal of Coal Geology*, vol. 87, no. 1, pp. 13–25, 2011.

[15] G. Z. Yin, C. B. Jiang, and X. U. Jiang, "Experimental study of influences for water content in coalbed gas reservoirs on methane seepage," *Chinese Journal of Rock Mechanics and Engineering*, vol. 30, pp. 1–6, 2011.

[16] G. Z. Yin, C. B. Jiang, J. Xu, L. Guo, S. J. Peng, and W. Li, "An experimental study on the effects of water content on coalbed gas permeability in ground stress fields," *Transport in Porous Media*, vol. 94, no. 1, pp. 87–99, 2012.

[17] Z. Pan, "Modeling of coal swelling induced by water vapor adsorption," *Frontiers of Chemical Science and Engineering*, vol. 6, no. 1, pp. 94–103, 2012.

[18] D. Chen, Z. Pan, J. Liu, and L. D. Connell, "Modeling and simulation of moisture effect on gas storage and transport in coal seams," *Energy & Fuels*, vol. 26, no. 3, pp. 1695–1706, 2012.

[19] D. Shaw, P. Mostaghimi, and R. T. Armstrong, "The dynamic behaviour of coal relative permeability curves," *Fuel*, vol. 253, pp. 293–304, 2019.

[20] P. Thararoop, Z. T. Karpyn, and T. Ertekin, "Development of a material balance equation for coalbed methane reservoirs accounting for the presence of water in the coal matrix and coal shrinkage and swelling," *Journal of Unconventional Oil and Gas Resources*, vol. 9, pp. 153–162, 2015.

[21] P. Thararoop, Z. T. Karpyn, and T. Ertekin, "Development of a multi-mechanistic, dual-porosity, dual-permeability, numerical flow model for coalbed methane reservoirs," *Journal of Natural Gas Science and Engineering*, vol. 8, no. 9, pp. 121–131, 2012.

[22] K. Sun, B. Liang, and J. Wang, "The fluid–solid-coupling seepage of two phase fluid (gas and water) in coal seams gas reservoir," *Journal of Liaoning Technical University: Natural Science*, vol. 20, no. 1, pp. 36–39, 2001.

[23] B. Nie, P. Fan, and X. Li, "Quantitative investigation of anisotropic characteristics of methane-induced strain in coal based on coal particle tracking method with X-ray computer tomography," *Fuel*, vol. 214, pp. 272–284, 2018.

[24] B. Nie, J. Zhang, X. Liu, S. Liu, and J. Meng, "Research on nanopore characteristics and gas diffusion in coal seam," *Journal of Nanoscience and Nanotechnology*, vol. 17, no. 9, pp. 6765–6770, 2017.

[25] Q. Zou and B. Lin, "Fluid-solid coupling characteristics of gas-bearing coal subjected to hydraulic slotting: an experimental investigation," *Energy & Fuels*, vol. 32, no. 2, pp. 1047–1060, 2018.

[26] J. Rutqvist, Y.-S. Wu, C.-F. Tsang, and G. Bodvarsson, "A modeling approach for analysis of coupled multiphase fluid flow, heat transfer, and deformation in fractured porous rock," *International Journal of Rock Mechanics and Mining Sciences*, vol. 39, no. 4, pp. 429–442, 2002.
[27] F. Gu and R. Chalaturnyk, "Permeability and porosity models considering anisotropy and discontinuity of coalbeds and application in coupled simulation," *Journal of Petroleum Science and Engineering*, vol. 74, no. 3-4, pp. 113–131, 2010.
[28] S. Li, C. Fan, J. Han, M. Luo, Z. Yang, and H. Bi, "A fully coupled thermal-hydraulic-mechanical model with two-phase flow for coalbed methane extraction," *Journal of Natural Gas Science and Engineering and Engineering*, vol. 33, pp. 324–336, 2016.
[29] Z. Ge, K. Deng, Y. Lu, L. Cheng, S. Zuo, and X. Tian, "A novel method for borehole blockage removal and experimental study on a hydraulic self-propelled nozzle in underground coal mines," *Energies*, vol. 9, no. 9, p. 698, 2016.
[30] S. Zuo, Z. Ge, Z. Zhou, L. Wang, and H. Zhao, "A novel hydraulic mode to promote gas extraction: pressure relief technologies for tectonic regions and fracturing technologies for nontectonic regions," *Applied Sciences*, vol. 9, no. 7, p. 1404, 2019.